Wall patterns influence the perception of interior space

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Title

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Pattern matters

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Abstract

The texture of an object's surface influences its perceived spatial extent. For example, von Helmholtz (1867) reported that a square patch with black and white stripes appears elongated perpendicular to the stripes' orientation. This time-honored finding stands in contrast with more recent recommendations by interior design experts who suggest that stripe wall patterns make rooms appear elongated in the direction parallel to the stripes' orientation. In a series of four experiments, we presented stripe wall patterns and varied the orientation of the stripes (horizontal versus vertical) and their density (number of stripes per degree of visual angle). Subjects estimated the width and height of stereoscopically presented interior spaces. Stripe patterns with higher densities made rooms appear both wider and higher than did stripe patterns with lower densities or plain walls. In contrast to both the predictions from the Helmholtz-square and the design guidelines, this effect was only weakly modulated by pattern orientation, in the sense that rooms appeared elongated in the direction parallel to the stripes' orientation. We conclude that object-based texture effects cannot be generalized to interior space perception. For a room's perceived spatial extent, pattern density is more important than pattern orientation.

Keywords: perceived spatial extent, stripe wall pattern, interior space perception, interior design.

INTRODUCTION

When attempting to manipulate the perceived spatial layout of a room, it is often recommended to paint the walls with a stripe pattern. In architectural textbooks (e.g., Heuser, 1989; Neufert & Kister, 2009) as well as on interior-design websites (e.g., Davis, 2012; Morris, 2012; Smart, n.y.), there is broad consensus that such wall patterns lead to a visual expansion *along the orientation of the stripes*. For example, Neufert and Kister (2009) suggest that vertically striped wall patterns increase the perceived height of a given interior room while horizontally striped wall patterns should decrease perceived height for the benefit of an increase in perceived width.

Yet, the empirical evidence for these recommendations is weak at best. We are aware of only one study examining the influence of the orientation of wall elements on the perceived spatial extent of a room: Matusiak (2006) constructed full-scale rooms painted in light-gray and equipped either with windows or with dark-gray segments. Both were presented in vertical or horizontal orientation. Subjects judged the width, depth, and height as well as the overall size of each room on categorical rating scales. Descriptively, the results were largely in line with the experts' suggestions. Vertical window arrangements and vertical dark-gray painted segments led to somewhat larger height ratings and somewhat smaller width ratings, whereas horizontal orientations led to somewhat lower height ratings and somewhat larger width ratings. However, because the ratings were performed on a rather coarse scale and the results were only reported descriptively, the statistical meaningfulness of the effects remains unclear. Besides this study, other surface characteristics have been explored with respect to their effects on the perception of the spatial layout of interior space. Von Castell, Hecht, and Oberfeld (2017, 2018a, 2018b), Oberfeld and Hecht (2011), and Oberfeld, Hecht, and Gamer

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(2010) used three-dimensional room simulations and reported that bright room surfaces look farther away or farther apart than dark room surfaces. For instance, a bright ceiling makes a room look higher, a bright rear wall makes a room look deeper, and bright side walls make a room look wider. In terms of a more holistic impression of the perceived extent of interior spaces, Stamps and Krishnan (2006) reported higher spaciousness ratings for interior room simulations with rough wall surface structure (fractal patterns or book shelves) than for rooms with smooth walls.

Based on studies regarding the perceived spatial extent of small objects observed from the outside, one would expect that both surface segmentation and orientation likewise affect the perceived dimensions of interior spaces observed from the inside. With regard to *segmentation*, according to the Oppel-Kundt-illusion (OKI; Kundt, 1863; Oppel, 1861), an exocentric distance between two vertical lines in the frontoparallel plane appears larger when divided by additional vertical lines. Studies dealing with determinants of this illusion reported various effects of the number of dividing lines on the size and the direction of the illusion (Bulatov, Bertulis, & Mickiene, 1997; Erdfelder & Faul, 1994; Long & Murtagh, 1984; Mikellidou & Thompson, 2013, 2014; Obonai, 1933; Piaget & Osterrieth, 1953; Rentschler, Hilz, Sütterlin, & Noguchi, 1981; Wackermann & Kastner, 2010). Taking these effects together, we picture an inverted U-shaped relationship between the perceived extent and the number of dividing lines (see also Robinson, 1998, pp. 49-52). Here, we define *number of stripes* as the absolute quantity of segmenting elements within a given pattern, whereas (retinal) *stripe density* describes the spatial frequency of the pattern in terms of full cycles per degree of visual angle (c/deg), where one full cycle is given by the sequence of two adjacent regions of the pattern (e.g., one adjacent black and white stripe of a black and white striped pattern; cf. Giora & Gori, 2010). Across all above-mentioned studies, a number of six to 15 dividing lines (depending on the particular study) produced a maximal overestimation of the filled extent, whereas lower and larger numbers of lines resulted in a less overestimation. For

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example, Obonai (1933) reported a reversal of the illusion (i.e., the filled extent looked smaller than the unfilled extent) for one dividing line, an increase in the perceived extent reaching its maximum at seven to 12 dividing lines, and then a decrease again leading to perceived equality of the empty and the filled extent for 16 lines. Giora and Gori (2010) varied the number of the segmenting elements of square checkerboard-like patterns independently of their density. Consistent with the studies on the OKI, they reported an inverted U-shaped relationship between the patterns' perceived area and the number of segmenting elements.

With regard to pattern *orientation*, von Helmholtz (1867, p. 563) described an illusion that is closely related to the OKI. According to the so-called Helmholtz-square, the perceived horizontal and vertical extent of two-dimensional squares made up of alternating black and white stripes depends on the orientation of the stripe pattern. A horizontally striped square appears taller than wide, whereas a vertically striped square appears wider than tall (see Figure 1; for a nice demonstration using a coin stack, see Zanforlin, 1967). Together, the OKI and the Helmholtz-square suggest that the spatial extent of small objects appears visually expanded in the direction *perpendicular to the orientation of the stripe pattern* and that the number / density of the stripes influences both the size and the direction of this visual expansion. Von Helmholtz (1867, p. 563) assumed the principle of the Helmholtz-square to be also applicable to larger surfaces in three-dimensional contexts. With regard to women's clothing, he suggested horizontally striped skirts in order to make women look taller and thinner. Several studies reported results in line with von Helmholtz's assumptions (e.g., Ashida, Kuraguchi, & Miyoshi, 2013; Maehara, Saida, & Wake, 2015; Thompson & Mikellidou, 2011). However, one study (Swami & Harris, 2012) reported the opposite effect: a woman appeared thinner when wearing a vertically striped (or plain) skirt as compared to a horizontally striped skirt. With regard to the perceived extent of interior spaces, von Helmholtz (1867, p. 563) assumed that his observations with small squares also apply to

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wallpaper patterns in interior spaces. Horizontally striped walls should lead to an increase in perceived ceiling height accompanied by a decrease in perceived room width while vertical stripes should lead to an increase in perceived width accompanied by a decrease in perceived height. However, we are not aware of any studies on the effect of stripes in interior spaces.

[insert Figure 1 here]

In sum, there is a discrepancy between the reported effects of segmentation and pattern orientation on the perceived extent of small objects on the one hand, and architects' guidelines for the application of striped wall patterns in interior spaces on the other hand. With reference to this discrepancy, the present study is aimed at answering the following questions: Does a pattern's orientation influence the perceived spatial layout of interior spaces at all – as assumed by both von Helmholtz (1867) and today's interior design experts? And if so, do vertically striped wall patterns make a room look wider, as suggested by von Helmholtz (1867), or higher, as suggested by today's interior design experts? Finally, does pattern density moderate possible effects on an interior room's perceived spatial layout, as suggested by several studies on determinants of the size and direction of the OKI (e.g., Mikellidou & Thompson, 2013)? To put these questions more generally, to our knowledge, the present study is the first to attempt to empirically test whether the regularities of the Oppel-Kundt illusion and the Helmholtz square still hold true when applied to large visual angles in a three-dimensional context.

We conducted a series of four experiments in order to answer these questions empirically. In Experiments 1 and 2, we varied the density of vertically striped wall patterns. In Experiment 3, we manipulated the orientation and density of striped wall patterns independently of each other. In Experiment 4, we additionally varied the contrast of the stripe patterns and the availability of depth and context information.

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EXPERIMENT 1: VERTICAL LOW-DENSITY PATTERNS

For a small number of segmenting elements (1 to 4), Obonai (1933) and Mikellidou and Thompson (2014) reported an inversion of the OKI, that is a visual compression of the segmented half of the figure relative to the unsegmented half of the figure. Thus, we hypothesized that, in comparison to interior spaces with plain walls, interior spaces with low-density wall patterns should look compressed in the direction perpendicular to the stripe pattern.

Method

Subjects

20 observers (14 women, six men), aged from 20 to 35 years (M = 25.40, SD = 5.60), participated voluntarily in Experiment 1. 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 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 using 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 Titmus-test, the criterion for participation in the experiment was that at least six of the nine trials had been answered correctly. All subjects were familiar with the metric system.

Stimuli and apparatus

On each trial, we presented one simulated room stereoscopically on a large rear-projection screen. We varied the number of stripes on the rear wall in four steps: 0 (plain), 4, 12, and 36 stripes. The stripe patterns consisted of alternating light- and medium-gray stripes. For the medium wide room (4.50 m room width), the pattern densities were 0.05, 0.14, and

0.41 c/deg for the 4-stripes, 12-stripes, and 36-stripes condition, respectively. The orientation of the pattern was set constant at vertical. The mean luminance of the rear wall was kept constant. We adapted the stripes' thickness to the pattern's density, so that 50% of the rear wall was covered by light-gray and 50% by medium-gray stripes. For example, in the 4-stripes condition, each stripe covered 25% of the rear wall's surface, in the 36-stripes condition, each stripe covered only 2.78% of the rear wall's surface. In order to avoid an asymmetrical arrangement of the stripes in terms of the horizontal extension of the pattern, the centers of the outermost stripes were made to coincide with the rear corners of the room (see Figure 2). Thus, the 4-stripes condition consisted of two medium-gray stripes, one light-gray-stripe, and two halves (one on either end) of the remaining light-gray stripe. We presented the stripe pattern only on the rear wall. The side walls remained plain across all conditions. The colorimetric values (Commission Internationale de l'Éclairage, 2006) of the surfaces were Y = 15.98 cd m^{-2}, x = 0.35, y = 0.36 for the medium-gray stripes, Y = 33.16 cd m^{-2}, x = 0.36, y = 0.37 for the light-gray stripes, and Y = 24.84 cd m^{-2}, x = 0.36, y = 0.36 for the plain rear wall. The mean luminance of the medium-gray and light-gray stripes (Y = 24.57 cd m^{-2}) was matched to the luminance of the plain surface (cf. Giora & Gori, 2010). The ceiling and the floor were overlaid with a light-gray and a medium-gray fine-grained texture, respectively.

Room width (4.30, 4.50, and 4.70 m) and ceiling height (2.70, 2.90, and 3.10 m) were varied independently (see Figure 3). The depth of the simulated rooms was constant at 6.00 m. The observer’s virtual position was 20 cm in front of the simulated room’s invisible front wall (see Figure 3), horizontally centered between the left and the right side wall such that the distance between the observer's eyes and the rear wall was 5.80 m. Thus, an increase in the number of stripes of the rear-wall pattern automatically led to an increase in pattern density and vice versa. The virtual eye height was set to 1.30 m. The virtual viewing direction was horizontally centered facing the room’s rear wall. Subjects were instructed that their virtual position was like sitting on a chair and leaning with their back against the horizontal center of

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the simulated room's front wall. The observer's virtual position remained constant across all experiments in this paper.

[insert Figure 2 here]

The stimuli were generated with Vizard 3 (WorldViz, 2010) on a Core i5 computer with an NVIDIA QuadroFX5500 graphics board and presented on a 2.60 m × 1.95 m (horizontal × vertical) rear-projection screen (aspect ratio 4:3) with a 3D-projector (projectiondesign F10 AS3D). It had a resolution of 1,400 × 1,050 pixels (horizontal × vertical), a color 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. Each eye received 60 frames per second. The individual inter-pupillary distance of each subject was measured with the aid of a pupil distance meter (bon PD-2) 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. The eye position was centered at a distance of 2.00 m from the projection screen by means of a chin rest. The geometric field of view (enclosed visual angle of the projection) was 66° horizontally × 52° vertically. The virtual field of view (visible area of the simulated room) corresponded to the geometric field of view (see Figure 3). The experiment was conducted in a darkened rectangular room with 105 m² surface area and 2.90 m ceiling height. Subjects were tested individually.

[insert Figure 3 here]

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Design and procedure

On each trial, the stimulus was presented for 5 seconds. Then, subjects estimated the ceiling height or room width (depending on the condition) in units of meters and centimeters. No time limit was given for the response. The experimenter entered the estimates using the computer keyboard and advanced to the next trial.

We presented all factorial combinations of pattern density (4), room width (3), and ceiling height (3) to each observer. In two blocks of 108 trials each, the 36 factorial combinations were presented three times each in random order. In order to facilitate the task, in one block, subjects estimated the width of the simulated rooms, in the other block they estimated the height. The order of the two blocks was balanced between subjects. Prior to each block, subjects completed six training trials (drawn at random from the 108 trials), which were not taken into account in the data analyses. Experiment 1 consisted of 216 trials and lasted approximately 60 minutes.

Results and discussion

For both dependent measures (perceived height, perceived width), the data were analyzed on the basis of the subjects' estimates for the 36 experimental conditions, averaged across the three presentations of each stimulus. This averaging procedure was also used in the subsequent experiments.

The mean height and width estimates are depicted in Figure 4. We computed a pattern density × room width × ceiling height MANOVA (doubly multivariate repeated-measures analysis of variance) with the mean width and height estimates as dependent variables. As a post-hoc analysis, we calculated rmANOVAs (univariate approach) separately for each dependent variable, using the Huynh and Feldt (1976) correction for the degrees of freedom (correction factor $\tilde{\varepsilon}$; this correction was applied to all subsequent rmANOVAs in this paper). The MANOVA showed a significant main effect of pattern density, V = .664, F(6,14) =

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4.612, p = .009[1]. According to the post-hoc rmANOVAs, pattern density influenced both the width and the height estimates significantly, $F(3,57) = 14.516$, $p < .001$, $\eta^2_p = .433$, $\tilde{\varepsilon} = .520$ and $F(3,57) = 3.676$, $p = .049$, $\eta^2_p = .162$, $\tilde{\varepsilon} = .505$, respectively. As can be seen in Figure 4, low-density patterns (up to 12 stripes; 0.14 c/deg) produced smaller width (panel A) and height (panel C) estimates than the plain condition. The width and height estimates for the highest-density pattern (36 stripes; 0.41 c/deg) were comparable in size with the plain condition. To answer the question of which patterns differed significantly from the plain condition, we calculated paired-samples t-tests (two-tailed) for the comparisons of the three striped conditions with the plain baseline condition separately for each dependent variable (averaged across the levels of room width and ceiling height). We corrected for multiple testing using the procedure by Hochberg (1988) with an α-level of .05. Note that this correction was also applied to all further post-hoc comparisons in this paper. Significant differences are indicated in panels A and C of Figure 4.

The MANOVA showed also a significant main effect of room width and ceiling height, $V = .709$, $F(4,16) = 9.749$, $p < .001$ and $V = .767$, $F(4,16) = 13.155$, $p < .001$, respectively. The post-hoc rmANOVAs showed that perceived width increased with actual room width, $F(2,38) = 32.894$, $p < .001$, $\eta^2_p = .634$, $\tilde{\varepsilon} = .674$, and decreased with increasing ceiling height, $F(2.38) = 32.482$, $p < .001$, $\eta^2_p = .631$, $\tilde{\varepsilon} = .670$ (see panel B of Figure 4). Perceived height increased with actual ceiling height, $F(2,38) = 41.005$, $p < .001$, $\eta^2_p = .683$, $\tilde{\varepsilon} = .561$, and decreased with increasing room width, $F(2.38) = 21.138$, $p < .001$, $\eta^2_p = .527$, $\tilde{\varepsilon} = .935$ (see panel D of Figure 4). In addition, our data show an underestimation of the simulated rooms' spatial extent. This finding is compatible with results from previous studies that also collected size estimates of stereoscopically presented interior spaces on a metric scale (cf. von Castell et al., 2017; von Castell, Oberfeld, & Hecht, 2014).

[1] For fully crossed repeated-measures designs, Pillai's trace and η^2_p are identical in value. We therefore only report Pillai's trace for multivariate effects.

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Note that we did not include the density × room width × ceiling height three-way interaction in the MANOVA in order to reduce the needed degrees of freedom of the multivariate model. According to the rmANOVAs, this interaction was not significant for the width nor the height estimates (*p*-values ≥ .123). In the MANOVA, the remaining effects were not significant (all *p*-values ≥ .202).

[insert Figure 4 here]

In sum, rooms with vertically striped low-density rear-wall patterns appeared narrower and lower than equally sized rooms with plain rear walls or higher-density rear-wall patterns. However, as we have not exceeded densities above 0.41 c/deg, we do not know if still higher stripe densities will produce a continued effect beyond the perceived width of the uniformly colored background, and this aspect was investigated in Experiment 2.

EXPERIMENT 2: VERTICAL HIGH-DENSITY PATTERNS

Do patterns with densities above 0.41 c/deg continue to increase perceived spatial extent? If so, one could use such patterns to enhance, rather than merely reduce the interior space experience. To answer this question, Experiment 2 presented the same room configurations as Experiment 1, albeit with higher-density stripe patterns on the rear wall.

Method

Subjects

20 observers (11 women, nine men), aged from 18 to 49 years ($M = 25.50$, $SD = 7.07$), volunteered for Experiment 2. None of them had participated in Experiment 1. They were tested for normal vision, briefed, and debriefed as before.

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Stimuli and apparatus

In Experiment 2, we used wall patterns with 0 (plain wall) 36, 72, 144, and 288 stripes on the rear wall. For the medium-wide room (4.50 m room width), the densities were 0.41, 0.81, 1.62 and 3.24 c/deg for the 36-stripes, 72-stripes, 144-stripes, and 288-stripes condition, respectively. Apart from that, the stimuli were identical to those of Experiment 1.

Design and procedure

We used a 5 (pattern density) × 3 (room width) × 3 (ceiling height) factorial design amounting to 45 cells, according to the same procedure as in Experiment 1. Experiment 2 consisted of 270 trials and lasted approximately 70 minutes.

Results and discussion

Figure 5 displays the mean width and height estimates. We computed a pattern density × width × height MANOVA with the mean width and height estimates as dependent variables and, as a post-hoc analysis, calculated rmANOVAs separately for each dependent variable. The effect of pattern density was significant, $V = .772$, $F(8,12) = 5.080$, $p = .006$. The post-hoc rmANOVAs showed that pattern density had a significant effect on both the width estimates, $F(4,76) = 19.100$, $p < .001$, $\eta^2_p = .501$, $\tilde{\varepsilon} = .333$, and the height estimates, $F(4,76) = 23.506$, $p < .001$, $\eta^2_p = .553$, $\tilde{\varepsilon} = .355$.

The mean *width estimates* are shown in panel A of Figure 5. Descriptively, compared with the plain condition, we found smaller mean width estimates in the 36-stripes condition (0.41 c/deg) and higher mean width estimates in the 144-stripes condition (1.62 c/deg) and the 288-stripes condition (3.24 c/deg). The mean estimate in the 72-stripes condition (0.81 c/deg) was comparable in size with the plain condition. The mean *height estimates* are depicted in panel C of Figure 5. Descriptively, similar to the width estimates, we found the lowest mean estimate in the 36-stripes condition and the highest mean estimate in the 288-stripes

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condition. Taken together, Experiment 2 showed that a vertical stripe pattern with high density on the rear-wall can make a room look wider and higher than an equally-sized room with a plain rear wall. Note, however, in the 36-stripes condition, there was an unexpected difference in the mean width and height estimates between Experiment 1 and Experiment 2. In Experiment 1, we found comparable width estimates and height estimates for the plain and the 36-stripes condition, whereas, in Experiment 2, both width and height estimates were smaller for the 36-stripes condition than for the plain condition (see also General Discussion).

The MANOVA likewise showed significant effects of room width and ceiling height, $V = .750$, $F(4,16) = 11.994$, $p < .001$ and $V = .768$, $F(4,16) = 13.216$, $p < .001$, respectively. According to the post-hoc rmANOVAs, room width as well as ceiling height influenced both perceived width and perceived height in the same way as in Experiment 1: mean width estimates increased with increasing room width and decreased with increasing ceiling height, $F(2,38) = 27.135$, $p < .001$, $\eta^2_p = .588$, $\tilde{\varepsilon} = .610$ and $F(2,38) = 11.724$, $p = .002$, $\eta^2_p = .382$, $\tilde{\varepsilon} = .538$, respectively (see panel B of Figure 5). Mean height estimates increased with increasing ceiling height and decreased with increasing room width, $F(2,38) = 38.499$, $p < .001$, $\eta^2_p = .670$, $\tilde{\varepsilon} = .530$ and $F(2,38) = 15.382$, $p < .001$, $\eta^2_p = .447$, $\tilde{\varepsilon} = 1.000$, respectively (see panel D of Figure 5).

In contrast to Experiment 1 (and also Experiment 3; see panel A of Figures 7 and 8, respectively), the mean width and height estimates were close to the rooms' simulated spatial extent. However, a closer look at the individual data of the 20 subjects revealed that three subjects produced noticeably higher width and height estimates than the remaining 17 subjects whose range of estimates matched Experiment 1. However, relative to the plain baseline condition, the experimental manipulations affected the mean estimates of both subgroups ($n = 3$ and $n = 17$) in the same way as the complete data set ($n = 20$). Be reminded that all reported results are based on repeated-measures analyses and, thus, are unaffected by the subjects' individual baseline.

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As in Experiment 1, we did not include the density × room width × ceiling height three-way interaction in the MANOVA. In the rmANOVAs, this interaction was not significant for both the width and the height estimates (p-values ≥ .310). In the MANOVA, the remaining effects were not significant (all p-values ≥ .610).

In sum, we found that high-density patterns enhanced perceived spatial extent beyond the reference provided by the uniformly textured rear wall.

[insert Figure 5 here]

EXPERIMENT 3: INDEPENDENT VARIATION OF PATTERN DENSITY AND PATTERN ORIENTATION

As Experiments 1 and 2 presented only vertical patterns, it remains unclear whether the observed effect of pattern density generalizes to stripe patterns with horizontal orientation. For this reason, in Experiment 3, we varied both the pattern density and the pattern orientation (vertical vs. horizontal) on the rear wall.

Method

Subjects

20 observers (17 women, 3 men), aged from 18 to 46 years (M = 23.85, SD = 6.41), participated in Experiment 3. None of them had participated in the previous experiments. Subjects were tested for normal vision, briefed, and debriefed as before.

[insert Figure 6 here]

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Stimuli and apparatus

The stimuli had the same basic configuration as in Experiments 1 and 2. Room width and ceiling height were varied in two steps, 4.40 to 4.60 m and 2.90 to 3.10 m, respectively, such that the rooms' mean width-to-height ratio was 1.5:1. Unlike in Experiments 1 and 2, we additionally varied the orientation of the stripe patterns (vertical, horizontal) on the rear wall. With regard to the density of the vertical patterns, we used the patterns that had already produced significant differences from the plain condition in Experiments 1 or 2: 4, 36, and 288 stripes. In addition, we presented an additional pattern with 6 stripes. With regard to the density of the horizontal patterns, we used patterns with 4, 24, 36, 192, and 288 stripes (see Table 1). Figure 6 depicts the vertical and horizontal patterns with up to 36 stripes. Apart from the orientation of the stripes, the horizontal patterns complied with the same construction rules as the vertical patterns (see Experiment 1). Note that the number of stripes in each vertical pattern was either equal to or 1.5 times higher than the number of stripes in one of the horizontal patterns. Thus, the stimulus set contained pairs of vertical and horizontal patterns with the same number of stripes and others equal in density. In total, we presented each room with nine different rear-wall patterns and an additional plain rear wall, using the same rear-projection setup as before.

[insert Table 1 here]

Design and procedure

We presented all factorial combinations of pattern [10; 4 (vertical) + 5 (horizontal) + 1 (plain)], room width (2), and ceiling height (2) using the same design and basic procedure as in the previous experiments. In two blocks of 120 trials each, the 40 factorial combinations were presented three times in random order. In one block, subjects estimated the width of the

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simulated rooms, in the other block, subjects estimated the ceiling height. Order of blocks was balanced between subjects. Prior to each block, subjects completed six training trials (drawn at random from the 120 trials), which were not taken into account in the data analyses. In total, Experiment 3 consisted of 240 trials and lasted approximately 65 minutes.

Results and discussion

We first report the analysis of effects of the *density of vertical and horizontal patterns* and then the analysis of effects of *pattern orientation*.

Density of vertical patterns

Figure 7 shows the mean width and height estimates for rooms with vertically striped or plain rear walls. We calculated a pattern density × room width × ceiling height MANOVA. We included all vertically striped conditions and the plain condition in the analysis. The mean width and height estimates were the dependent variables. As a post-hoc analysis, we calculated rmANOVAs (univariate approach) separately for each dependent variable. The MANOVA showed a significant effect of pattern density, $V = .707$, $F(8,12) = 3.617$, $p = .023$. According to the rmANOVAs, there was a significant effect of pattern density on both perceived width, $F(4,76) = 18.497$, $p < .001$, $\eta_p^2 = .493$, $\tilde{\varepsilon} = .572$, and perceived height, $F(4,76) = 7.431$, $p = .003$, $\eta_p^2 = .281$, $\tilde{\varepsilon} = .453$. Descriptively, pattern density influenced the width (panel A) and height (panel C) estimates in a very similar way as in Experiments 1 and 2: rooms with low-density patterns (up to 36 stripes; 0.41 c/deg) were judged narrower and lower than rooms with plain walls, whereas rooms with high-density patterns (288 stripes; 3.24 c/deg) were judged wider and higher than rooms with plain walls (see Figure 7). However, according to the paired comparisons, the decrease in perceived spatial extent due to low-density patterns was more pronounced for the width estimates compared to the height

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estimates and the increase in perceived spatial extent due to high-density patterns was more pronounced for the height estimates compared to the width estimates.

Consistent with the previous experiments, the multivariate effects of physical room width and ceiling height were significant, $V = .761$, $F(2,18) = 28.679$, $p < .001$ and $V = .808$, $F(2,18) = 37.874$, $p < .001$, respectively. According to the rmANOVAs, perceived width increased with increasing room width, $F(1,19) = 52.473$, $p < .001$, $\eta^2_p = .734$, and decreased with increasing ceiling height, $F(1,19) = 27.098$, $p < .001$, $\eta^2_p = .588$ (see panel B of Figure 7), perceived height increased with increasing ceiling height, $F(1,19) = 47.375$, $p < .001$, $\eta^2_p = .714$, and decreased with increasing room width, $F(1,19) = 9.661$, $p = .006$, $\eta^2_p = .337$ (see panel D of Figure 7). The MANOVA showed no further significant effects (all *p*-values ≥ .278).

[insert Figure 7 here]

Density of horizontal patterns

The mean width and height estimates for rooms with horizontally striped or plain rear walls are depicted in Figure 8. We conducted the same analyses as for the vertical patterns. Here, all horizontally striped conditions as well as the plain condition were included in the analysis. In the MANOVA, the effect of pattern density reached significance, $V = .818$, $F(10,10) = 4.504$, $p = .013$. The rmANOVAs showed that pattern density influenced the width estimates as well as the height estimates, $F(5,95) = 9.354$, $p = .002$, $\eta^2_p = .330$, $\tilde{\varepsilon} = .312$, and $F(5,95) = 17.550$, $p < .001$, $\eta^2_p = .480$, $\tilde{\varepsilon} = .494$, respectively. The mean width (panel A) and height (panel C) estimates as a function of pattern density are shown in Figure 8. Subjects judged rooms with low-density stripe patterns to be narrower and lower than rooms with a plain rear wall. Also, rooms with high-density patterns appeared wider and higher than plain

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rooms without stripes on the rear wall. Note that this is the same relationship between pattern density and the rooms' perceived extent that we observed in Experiments 1 and 2 for vertical stripe patterns.

The MANOVA showed significant effects of room width, $V = .649$, $F(2,18) = 16.674$, $p < .001$, and ceiling height, $V = .685$, $F(2,18) = 19.553$, $p < .001$. According to the rmANOVAs, perceived width increased with increasing room width, $F(1,19) = 34.851$, $p < .001$, $\eta_p^2 = .647$ and decreased with increasing ceiling height, $F(1,19) = 29.238$, $p < .001$, $\eta_p^2 = .606$ (see panel B of Figure 8). Regarding the height estimates (see panel D of Figure 8), we found that perceived height increased with increasing ceiling height, $F(1,19) = 31.279$, $p < .001$, $\eta_p^2 = .622$. The decrease of perceived height with increasing room width just missed significance, $F(1,19) = 3.638$, $p = .072$, $\eta_p^2 = .161$. Taken together, notwithstanding the non-significant effect of room width on perceived height, we replicated the results from Experiments 1 and 2. In the MANOVA, the remaining effects were not significant (all *p*-values ≥ .311).

[insert Figure 8 here]

Pattern orientation

To answer the question whether pattern orientation influenced the mean width or height estimates, we analyzed the pairs of vertical and horizontal stripe patterns with matching densities. We included only trials from the 6-, 36-, and 288-stripes vertical conditions and from the 4-, 24-, and 192-stripes horizontal conditions in the analysis, such that, irrespective of pattern orientation, mean densities were matched at 0.07, 0.41, and 3.24 c/deg. Since both current interior-design experts and von Helmholtz (1867) suggested a differential influence of pattern orientation, we entered the dimension to be judged (width and

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height) as an additional within-subjects factor into the model. In order to reduce the complexity of the model, we averaged across the experimental manipulations of room width and ceiling height. Hence, we used a 3 (pattern density) × 2 (pattern orientation) × 2 (judged room dimension) rmANOVA (univariate approach). As the dependent variable, we used the relative difference between the estimate for the respective patterned condition and the estimate for the plain baseline condition. For each subject and factorial combination, this difference is given by $(\text{meanEst}_{\text{patterned}} - \text{meanEst}_{\text{plain}}) / \text{meanEst}_{\text{plain}} \cdot 100\%$, where $\text{meanEst}_{\text{patterned}}$ is the mean estimate by the given subject across all trials presenting the patterned condition, and $\text{meanEst}_{\text{plain}}$ is the mean estimate for the plain baseline condition. Analyzing the estimates for the patterned conditions relative to the estimates for the plain baseline condition enabled a direct comparison of both judged dimensions on the same scale. Irrespective of the judged dimension (i.e., width or height), a value of −5%, for example, indicates that the respective patterned room was judged to be 5% smaller, i.e., narrower or lower, than the plain room.

The main effect of pattern orientation was not significant, $F(1,19) = 0.326$, $p = .575$, $\eta^2_p = .017$. However, the pattern orientation × judged room dimension interaction was, $F(1,19) = 9.286$, $p = .007$, $\eta^2_p = .328$. As depicted in Figure 9, horizontal patterns made the rooms appear wider but lower than vertical patterns, and vertical patterns made the rooms appear higher but narrower than did horizontal patterns. In sum, we found a visual expansion of perceived spatial extent in the direction of the stripe pattern rather than in the direction perpendicular to the stripe pattern. This result widely matches the predictions of pattern-orientation effects made by experts in architecture and interior design, but contradicts the assumptions of von Helmholtz (1867).

The rmANOVA also showed a significant effect of pattern density, $F(2,38) = 24.783$, $p < .001$, $\eta^2_p = .566$, $\tilde{\varepsilon} = .654$. The perceived extent of both room dimensions increased with increasing pattern density (see Figure 9). In addition, there was also a significant effect of the

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judged room dimension, $F(1,19) = 10.700$, $p = .004$, $\eta^2_p = .360$. As shown in Figure 9, relative to the plain condition (as indicated by the dashed lines), height estimates (panel B) showed a smaller decrease due to the low-density patterns (0.07 and 0.41 c/deg) and a higher increase due to the high-density pattern (3.24 c/deg) as compared to width estimates (panel A). All remaining effects were not significant (all p-values $\geq .146$). In particular, the difference in the height or width estimates between conditions with vertical and horizontal stripes did not change significantly as a function of pattern density.

[insert Figure 9 here]

EXPERIMENT 4: VARIATION OF PATTERN CONTRAST AND SPATIAL CONTEXT

The results of Experiment 3 indicate that striped patterns on the rear wall visually expand the perceived spatial extent of interior spaces in the direction of the stripe pattern more so than in the direction perpendicular to the stripe pattern. This finding is not compatible with the predictions derived from the Helmholtz-square. We conducted Experiment 4 in order to examine two possible reasons for this incompatibility. First, in Experiments 1 – 3, we used stripe patterns with a comparably low luminance contrast between the dark and the bright stripes. Depictions of the Helmholtz-square typically consist of a sequence of black and white stripes, which maximizes the luminance contrast between two adjacent stripes (see Figure 1). Second, even though von Helmholtz (1867) expected his finding to apply also to wall patterns, his observations were based on a small two-dimensional stimulus without any depth cues. Following this consideration, both pictorial depth cues, such as the linear perspective provided by the spatial context (i.e., the remaining room surfaces), and the binocular disparity

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of the stereoscopic simulation might have caused our divergent findings. To investigate this question, in Experiment 4, we used the same rear-wall patterns as in Experiment 3 but additionally varied the luminance contrast of the stripe patterns and the availability of spatial context.

Method

Subjects

20 participants (12 women, 8 men), aged from 22 to 32 years (M = 24.85, SD = 2.48), completed Experiment 4. None of them had participated in Experiments 1-3. Subjects were tested for normal vision, briefed, and debriefed as before.

Stimuli and apparatus

Experiment 4 consisted of three display conditions in which we gradually increased the availability of spatial context information. In each display condition, we varied the pattern density and the pattern orientation on the rear wall. Following the construction rules of Experiment 3, we presented horizontal patterns with 4, 24, and 192 stripes and vertical patterns with 6, 36, and 288 stripes and varied the simulated width and height in two steps between 4.40 and 4.60 m and 2.90 and 3.10 m. Thus, we used three pairs of vertical and horizontal stripe patterns with matching densities: 0.07. 041, and 3.24 c/deg (cf. Table 1). In display condition *2D rear wall* (shown in Figure 10), we presented only the rear wall without any spatial context (i.e., no side walls, ceiling, or floor) in front of a dark background (i.e., the surrounding screen area remained unlit) and set the binocular disparity of the projection (see Experiment 1) to zero. In terms of spatial context, this display condition is similar to the typical viewing conditions in studies presenting the Helmholtz-square, albeit with a larger visual angle. In addition, we varied the luminance contrast (low, high) of the stripe patterns (see Figure 12). The colorimetric values (Commission Internationale de l'Éclairage, 2006) of

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the bright and dark stripes were $Y = 27.00$ cd m^{-2}, $x = 0.37$, $y = 0.38$ and $Y = 12.28$ cd m^{-2}, $x = 0.37$, $y = 0.36$ for the low-contrast patterns, $Y = 27.00$ cd m^{-2}, $x = 0.37$, $y = 0.38$ and $Y = 0.97$ cd m^{-2}, $x = 0.37$, $y = 0.37$ for the high-contrast patterns. The Weber contrast $((L_{max} - L_{min}) / L_{max}) \cdot 100\%$, where L_{max} is the maximum luminance and L_{min} is the minimum luminance in the stimulus, was 55% in the low-contrast patterns and 96% in the high-contrast patterns. The colorimetric values of the plain surfaces were $Y = 19.65$ cd m^{-2}, $x = 0.37$, $y = 0.37$ for the low-contrast patterns and $Y = 14.02$ cd m^{-2}, $x = 0.37$, $y = 0.36$ for the high-contrast patterns, such that the mean luminance of the low-contrast patterns ($Y = 19.64$ cd m^{-2}) and the high-contrast patterns ($Y = 13.99$ cd m^{-2}) were matched to the luminance of the respective plain surfaces. Note that the colorimetric values of the low-contrast patterns approximately corresponded to the patterns presented in Experiments 1-3. In display condition *2D room*, we presented the low-contrast rear-wall patterns from display condition 2D rear wall and added pictorial depth cues by virtue of the side walls, ceiling, and floor. The binocular disparity of the projection remained zero. Thus, the stimuli corresponded to the 2D screenshots shown in Figure 6. In display condition *3D room*, we used the same stimuli as in display condition 2D room but added stereoscopic depth information. We adjusted the binocular disparity of the images presented to the left and right eye to the subject's individual inter-pupillary distance. This corresponds to the stereoscopic displays presented in Experiments 1 – 3. In sum, we presented two-dimensional rectangular surfaces on a uniformly dark background in display condition 2D rear wall, two-dimensional perspective drawings of interior spaces in display condition 2D room, and three-dimensional stereoscopic simulations of interior spaces in display condition 3D room. The luminance contrast of the bright and dark stripes was varied in display condition 2D rear wall, while in the remaining display conditions it was set to a comparable value as in Experiments 1-3. In display conditions 2D rear wall and 2D room, the observers viewed the stimuli without shutter glasses, corresponding to natural viewing of the 2D stimuli. In display condition 3D room, subjects wore the same shutter glasses as in Experiments 1-3

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(stereoscopic presentation). Apart from that, the experimental parameters remained constant across all display conditions of Experiment 4, and unchanged compared to Experiment 3. Most importantly, the visual angle of the rear wall and its position relative to the observer did not change as a function of the display condition. The visual angle of the rear wall in the 4.40 m wide and 2.90 m high room, for example, remained constant at 41.54° horizontally and 28.07° vertically.

[insert Figure 10 here]

Design and procedure

Display condition 2D rear wall was presented in two sessions while conditions 2D room and 3D room were presented in one session each. In each session, we presented all factorial combinations of pattern (7; 3 vertical + 3 horizontal + 1 plain), room width (2), and ceiling height (2) using the same design and procedure as in Experiment 3. In two blocks of 84 trials each, the 28 factorial combinations were presented three times in random order. In one block, subjects estimated the width of the simulated rooms in metric units. In the other block, subjects estimated the ceiling height. In display condition 2D rear wall, the pattern's luminance contrast was varied between sessions. The high-contrast patterns were presented in one session and the low-contrast patterns in the other. The order of width and depth blocks within each session and (in the case of display condition 2D rear wall) the order of luminance contrasts were balanced between subjects. Prior to each block, subjects completed six training trials (drawn at random from the 84 trials), which were excluded from the data analyses. The order of the display conditions was 2D rear wall – 2D room – 3D room and identical for each participant, such that the amount of spatial context information increased gradually during the course of the experiment. In total, Experiment 4 consisted of 672 trials, evenly distributed

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among four sessions, and lasted approximately 3 hours. The time interval between two successive sessions was minimally one hour and maximally one week.

Results and discussion

We conducted Experiment 4 in order investigate influences of pattern luminance contrast and availability of spatial context on the observed effects of pattern density and pattern orientation on the perceived width and depth. We first analyze the data of display condition 2D rear wall with regard to effects of the pattern contrast and then report an analysis concerning effects of spatial context across all of the three display conditions (2D rear wall, 2D room, 3D room).

Display condition 2D rear wall: Effects of pattern contrast

Data were analyzed in an analogous manner to the analysis of pattern orientation in Experiment 3. We calculated a 3 (pattern density) × 2 (pattern orientation) × 2 (pattern contrast) × 2 (judged room dimension) rmANOVA (univariate approach). Again, the relative difference between the estimate for the patterned condition and the estimate for the respective plain baseline condition was the dependent variable (for details see Experiment 3). The relative differences were aggregated across the levels of room width and ceiling height in order to reduce the complexity of the model.

[insert Figure 11 here]

Figure 11 shows the relative deviation from the plain baseline condition as a function of pattern density, pattern orientation, and pattern contrast for the width estimates (panels HC_W and LC_W) and the height estimates (panels HC_H and LC_H) from display condition 2D rear wall. Descriptively, the effects of pattern density and pattern orientation

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were largely independent of pattern contrast. The rmANOVA showed neither a significant main effect of pattern contrast, $F(1,19) = 0.115$, $p = .738$, $\eta^2_p = .006$, nor significant interaction effects involving pattern contrast (all p-values $\geq .321$). Most importantly, the pattern density × pattern contrast interaction and the pattern orientation × pattern contrast interaction were clearly not significant (p-values $\geq .898$). We therefore averaged the relative differences from display condition 2D rear wall across the two levels of pattern contrast and then conducted an analysis across display conditions 2D rear wall, 2D room, and 3D room in order to examine whether our findings regarding effects of pattern density (see Experiments 1-3) and pattern orientation (see Experiment 3) change as a function of spatial context.

Spatial context

Figure 12 shows the mean relative differences to the plain baseline condition for the width and height estimates as a function of pattern density, pattern orientation, and display condition. We conducted a 3 (pattern density) × 2 (pattern orientation) × 3 (display condition) × 2 (judged room dimension) rmANOVA (univariate approach) on the relative estimation error.

[insert Figure 12 here]

The main effect of display condition was significant, $F(2,38) = 11.925$, $p < .001$, $\eta^2_p = .386$, $\tilde{\varepsilon} = 1.000$. As shown in Figure 12, the successive increase of spatial context from the 2D rear walls (panels 2D rear wall_W and 2D rear wall _H) to the 2D rooms (panels 2D room_W and 2D room_H) to the 3D rooms (panels 3D room_W and 3D room_H) led to a general decrease of the perceived width and height of the patterned rear walls relative to the plain rear wall (see also General Discussion).

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The main effect of pattern density was also significant, $F(2,38) = 25.619$, $p < .001$, $\eta^2_p = .574$, $\tilde{\varepsilon} = .597$. Consistent with Experiments 1 – 3, perceived width and perceived height increased with increasing pattern density. Across all variations of display condition (see Figure 12), we found the lowest width (left column) and height (right column) estimates for the lowest-density pattern (0.07 c/deg) and the highest width and height estimates for the highest-density pattern (3.24 c/deg). Accordingly, the pattern density × display condition interaction and the pattern density × display condition × judged room dimension three-way interaction were not significant, $F(4,76) = 2.039$, $p = .111$, $\eta^2_p = .097$, $\tilde{\varepsilon} = .834$ and $F(4,76) = 0.982$, $p = .419$, $\eta^2_p = .049$, $\tilde{\varepsilon} = .935$, respectively. Thus, the increase in perceived width and height with increasing pattern density was largely independent of the display condition.

The main effect of pattern orientation was not significant, $F(1,19) = 1.040$, $p = .321$, $\eta^2_p = .052$. In contrast to Experiment 3, the pattern orientation × judged room dimension interaction was also not significant, $F(1,19) = 1.615$, $p = .219$, $\eta^2_p = .078$. However, the effect of pattern orientation changed as a function of *display condition* and *pattern density*, additionally modulated by judged room dimension.

With regard to *display condition*, there was a marginally significant pattern orientation × display condition interaction, $F(2,38) = 3.143$, $p = .077$, $\eta^2_p = .142$, $\tilde{\varepsilon} = .674$, combined with a significant pattern orientation × display condition × judged room dimension three-way interaction, $F(2,38) = 5.020$, $p = .019$, $\eta^2_p = .209$, $\tilde{\varepsilon} = .789$. For the width estimates, descriptively, the effect of pattern orientation changed as a function of the available spatial context (see panel DC_W of Figure 13): When only the 2D rear wall was presented, we found the average width estimates to be somewhat larger when the pattern orientation was vertical as compared to horizontal (as suggested by von Helmholtz, 1867). In contrast, in the 2D room and, even more pronounced, in the 3D room, we found the average width estimates to be somewhat larger when the pattern orientation was horizontal as compared to vertical (as suggested by interior-design experts). For perceived height, no such systematic relationship

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between pattern orientation and display condition emerged (see panel DC_H of Figure 13). According to two post-hoc pattern density × pattern orientation × display condition rmANOVAs (univariate approach) conducted separately for each judged dimension, the pattern orientation × display condition interaction was significant for the width estimates, $F(2,38) = 5.732$, $p = .009$, $\eta^2_p = .232$, $\tilde{\varepsilon} = .877$, but not for the height estimates, $F(2,38) = 1.865$, $p = .173$, $\eta^2_p = .089$, $\tilde{\varepsilon} = .918$.

With regard to *pattern density*, the overall rmANOVA showed a marginally significant pattern orientation × pattern density interaction, $F(2,38) = 3.038$, $p = .063$, $\eta^2_p = .138$, $\tilde{\varepsilon} = .948$, in combination with a significant pattern orientation × pattern density × judged room dimension three-way interaction, $F(2,38) = 10.006$, $p < .001$, $\eta^2_p = .345$, $\tilde{\varepsilon} = .944$. With regard to perceived width (see panel PD_W of Figure 13), for the medium-density pattern (0.41 c/deg) and the highest-density pattern (3.24 c/deg), the estimates were larger when the pattern orientation was vertical as compared to horizontal, whereas, for the lowest-density pattern (0.07 c/deg), the estimates were larger when the pattern orientation was horizontal as compared to vertical. With regard to the height estimates (see panel PD_H of Figure 13), for the highest-density pattern (3.24 c/deg), the vertical pattern resulted in slightly larger height estimates than the horizontal pattern, whereas for the lowest-density pattern (0.07 c/deg) and the medium-density pattern (0.41 c/deg), we found the reversed effect as compared to the width estimates. The post-hoc rmANOVAs showed that the pattern orientation × pattern density interaction was significant for both the width and the height estimates, $F(2,38) = 7.429$, $p = .004$, $\eta^2_p = .281$, $\tilde{\varepsilon} = .831$ and $F(2,38) = 5.182$, $p = .010$, $\eta^2_p = .214$, $\tilde{\varepsilon} = 1.000$, respectively.

In the overall rmANOVA, the pattern orientation × pattern density × display condition × judged room dimension four-way interaction also reached significance, $F(4,76) = 2.874$, $p = .037$, $\eta^2_p = .131$, $\tilde{\varepsilon} = .944$. According to the post-hoc rmANOVAs, the pattern orientation × pattern density × display condition three-way interaction was significant for the width

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estimates, $F(4,76) = 3.027$, $p = .043$, $\eta^2_p = .137$, $\tilde{\varepsilon} = .671$, but not for the height estimates, $F(4,76) = 1.013$, $p = .400$, $\eta^2_p = .051$, $\tilde{\varepsilon} = .869$. As can be seen in the left column of Figure 12, when only the rear wall was presented (panel 2D rear wall_W), the overestimation of the width of vertical relative to horizontal patterns was maximal for the medium (0.41 c/deg) and the highest (3.24 c/deg) pattern density. When spatial context was provided (panels 2D room_W and 3D room_W), we found the maximal underestimation of the width of vertical relative to horizontal patterns for the lowest (0.07 c/deg) pattern density. Note that the latter fits well into the corresponding results from Experiment 3 (see panel A of Figure 9).

[insert Figure 13 here]

The overall rmANOVA showed also a significant effect of the judged room dimension, $F(1,19) = 14.088$, $p = .001$, $\eta^2_p = .426$. Across all display conditions (see Figure 12), we found the perceived deviation in the spatial extent of the patterned condition relative to the plain baseline condition to be more positive for the height estimates (right column) as compared to the width estimates (left column). Perceived height therefore generally benefited more from the stripe patterns than perceived width. Be reminded that Experiment 3 yielded the same result (see Figure 9). In the overall rmANOVA, all remaining effects were not significant (p-values $\geq .212$).

Taken together, Experiment 4 showed a relatively weak effect of pattern orientation consistent with the findings for the Helmholtz-square (larger perceived height with horizontal stripes, larger perceived width with vertical stripes) only for the 2D display condition without spatial context (2D rear wall), which most closely corresponds to the typical viewing condition in an experiment presenting the Helmholtz-square. When exactly the same rear-wall patterns were presented with pictorial depth cues (2D room) or in the context of a stereoscopically presented 3D room, the results confirmed the finding from Experiment 3.

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Interior spaces appear extended in height and width in the presence of high-density patterns regardless of pattern orientation, albeit more so when the stripes are aligned with the dimension to be judged. As in Experiment 3, the effect of pattern orientation was rather weak and, in case of the height estimates, non-significant. Also compatible with the results from Experiments 1 to 3, in all of the three display conditions we observed an increase of both width and height estimates with increasing stripe density.

GENERAL DISCUSSION

We conducted four experiments in order to investigate the effects of wall-pattern density and wall-pattern orientation on the perceived width and height of stereoscopically presented simulated interior spaces. The motivation for this study came from architectural design guidelines as well as from effects of segmentation and pattern orientation on perceived extent, which had been reported for small two-dimensional objects, such as the Oppel-Kundt-illusion (OKI; Kundt, 1863; Oppel, 1861) and the Helmholtz-square (von Helmholtz, 1867). The latter partially contradict the architects' guidelines, suggesting that effects observed in size judgments of small two-dimensional objects do not necessarily generalize to judgments of the spatial layout of rooms.

Overview of pattern-density and pattern-orientation effects in the present study

Figure 14 shows the mean relative differences to the plain condition (no stripe patterns presented on the walls of the simulated interior spaces), across all experiments, as a function of pattern density and pattern orientation. With regard to Experiment 4, we only used the data from display condition C (full availability of spatial information) which is directly comparable to the displays presented in Experiments 1 – 3.

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Let us first take a closer look at the effects of *pattern density*. Comparing panels W and H, we see a similar pattern for the width and height estimates. An increase in perceived width was always accompanied by an increase in perceived height and vice versa.

[insert Figure 14 here]

In comparison to the plain condition, each of the four experiments showed a considerable underestimation of the spatial extent of the rooms with the lowest-density stripe pattern, followed by a monotonic increase in perceived extent with increasing pattern density, leading to an approximately equivalent estimate as in the plain condition (Experiment 1), or to an overestimation (Experiments 2 – 4) of the spatial extent of the interior spaces, for the high-density patterns on the rear wall. Also, the consistency of the estimates across the four experiments depended on the pattern density. In comparison to the plain condition, patterns with low densities (up to 12 stripes or 0.14 c/deg) led to an underestimation of the room's spatial extent in all of the four experiments. Patterns with high densities (equal or above 144 stripes or 1.62 c/deg) consistently led to an overestimation of the room's spatial extent as compared to the plain condition. For the intermediate range of pattern densities, i.e., patterns with 24 to 72 stripes (0.41 to 0.81 c/deg), we found less consistent results. At the level of single experiments, we found underestimation as well as overestimation of the medium-density patterns relative to the plain baseline condition. For instance, subjects judged the rooms with the 36-stripes pattern to be either narrower and lower than the plain rooms (Experiment 2) or approximately as wide and high as the plain rooms (Experiment 1). Averaged across Experiments 1 – 4, however, the width and height estimates for the medium-density patterns were close to the plain condition. Note that the estimates for the low-density patterns (< 0.41 c/deg) and the high-density patterns (> 0.81 c/deg) varied comparably between experiments, but remained consistently lower (in the case of low-density patterns) or

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higher (in the case of high-density patterns) than the estimates for the plain baseline condition. Thus, given the overall profile of our results, it seems plausible that between-samples variation has caused the mixed results for the medium-density patterns. Be reminded that each subject participated only in one of the four experiments.

Next, we consider effects of *pattern orientation*. In Experiment 3, vertical patterns made the rooms appear higher but narrower than horizontal patterns with the same density, and horizontal patterns made the rooms appear wider but lower than vertical patterns with the same density (see Figure 9). Thus, the interior spaces appeared to be extended in the direction of the stripes.

In Experiment 4, when we presented the 2D room or the 3D room (see Figure 12, panels 2D room_W and 3D room_W), we could replicate this finding, albeit only when asking for width estimates. The height estimates remained largely unaffected by the variation of pattern orientation. When we presented the 2D rear wall without spatial context (see Figure 12, panel 2D rear wall_W), we found essentially the opposite pattern as for the 2D rooms and the 3D rooms: rear walls with vertical patterns appeared wider than walls with horizontal patterns, consistent with the original demonstrations of the Helmholtz-square. That is, if the context suggests the inside of room, the pattern has a different effect compared to when the context suggests an object. Taken together, at least in the case of perceived width, the effect of pattern orientation was moderated by the available spatial context.

How do our results compare to previous results on visual illusions and architectural guidelines?

With respect to *segmentation*, previous studies on the Oppel-Kundt illusion (Bulatov et al., 1997; Mikellidou & Thompson, 2013, 2014; Obonai, 1933; Piaget & Osterrieth, 1953; Rentschler et al., 1981; Wackermann & Kastner, 2010) reported the relationship between perceived extent and the number of lines to be inverted U-shaped. An arrangement of 6 to 15

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lines produced a maximal overestimation of the filled extent in comparison to the unfilled extent. While the published studies on the OKI did not report the stripe densities of the filled extent, some of these studies specified the visual angle of the segmented extent such that the density of the patterns could be calculated from the number of segmenting lines and the visual angle. Analogous to the calculation of pattern density in the present study, we defined one full cycle as the distance from the left edge of one line to the left edge of the right adjacent line. Taking the end lines of the filled extent into consideration, ten dividing lines (cf. Figure 1), for example, resulted in 11.5 full cycles. In contrast to the stripe patterns that we used in the present study, in most studies on the OKI, the darker lines remained constant in width, whereas the brighter spaces between the lines varied in width (the more lines, the narrower the spaces between the lines). Therefore, this approach should be understood as a rough description of these stimuli in terms of spatial frequency, in order to make the previous results on the OKI comparable to ours. Despite these limitations, we found a good match between our results and the calculated densities of the local maxima reported for the OKI. For instance, the calculated optimum densities lay within ranges of 4.46 – 5.18 c/deg (2.8° visual angle, 12.5 – 14.5 full cycles) in a study by Wackermann and Kastner (2010), within 6.43 – 14.14 c/deg (1.17° visual angle, 7.5 – 16.5 full cycles) in a study by Bulatov et al. (1997), and within 2.10 – 7.00 c/deg (1.5 – 5° visual angle, 10.5 full cycles) in a study by Rentschler et al. (1981). In the present study, the perceived spatial extent consistently increased with the wall patterns' density. The most pronounced overestimation in comparison to the plain wall was observed for pattern densities of 3.24 – 4.85 c/deg. Since we have not presented pattern densities above 4.85 c/deg, the question of whether even higher densities would lead to a decline in the width and height judgments, remains open. In addition, note that we observed an increase in the perceived spatial extent not only in the direction perpendicular to pattern orientation, as in the OKI, but also in the direction parallel to pattern orientation. We are not

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aware of studies on the OKI reporting estimates for the latter direction, and to our knowledge all studies on the OKI presented vertical bars.

Giora and Gori (2010) varied the number of segmenting elements and the visual angle of small checkerboard-like patterned squares independently of each other and reported that the perceived area of the squares did not increase linearly with the number of segmenting elements, but rather with density (elements per degree of visual angle). Thus, number and density of elements are two distinct features of segmentation. For small two-dimensional objects, the distinction between pattern density and number of segmenting elements can be easily maintained through the manipulation of the object's retinal size. The variation of the object's retinal size changes the pattern's density (in terms of spatial frequency) independently of the number of segmenting elements (see also Robinson, 1998; Spiegel, 1937). However, with respect to the perceived layout of interior spaces, the distinction between pattern density and number of segmenting elements, i.e. stripes, is more difficult to maintain because the patterned surface is an integral part of the interior space (cf. Thiel, 1970). A variation of the patterned surface's retinal size is only possible through the variation of either the spatial layout or the variation of the observer's position. In the present study, in order to reduce the complexity of the presented stimuli, the observer's position relative to the patterned rear wall remained constant in all experiments (5.80 m viewing distance). A change in the number of stripes thus inevitably led to a change in pattern density and vice versa. For both theoretical and practical reasons, it would be important to know whether a room's perceived spatial extent is mainly affected by the number of stripes or by the density of the stripe pattern. Thus, a further study with independent variation of number of stripes and pattern density would be interesting. In such a study, it would make sense to define pattern density not in terms of full cycles per degree viewing angle but in terms of full cycles per unit of length (e.g., meter).

Experiment 4 showed that the effect of pattern density is surprisingly robust across variations of spatial context. However, the display condition shifted the estimates for the

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stripe patterns relative to the plain baseline condition (see Figure 12). More precisely, the perceived decrease of width and height due to low-density patterns was maximal when spatial information was fully available (3D room), whereas the perceived increase in width and height due to high-density patterns was maximal when spatial information was reduced to a minimum (2D rear wall). Interestingly, previous studies on the OKI have shown that the exact shape of the function that links the number of dividing lines to the perceived size of the filled extent depends on the figure's retinal size (e.g., Kreiner, 2014; Long & Murtagh, 1984; Spiegel, 1937). For example, Long and Murtagh (1984) varied the horizontal viewing angle of vertically striped objects across a range between 0.68° and 11.69° (observer distance set constant at 2.1 m). They reported that, relative to the unfilled extent, a large number of dividing lines led to a more pronounced increase in the perceived extent in the small stimuli compared to the large stimuli, and a small number of dividing lines led to a more pronounced decrease in the perceived extent in the large stimuli compared to the small stimuli. This is in agreement with our results. Using much larger stimuli with a visual angle of about 40° horizontally and 30° vertically (see Experiment 4), we found a considerable underestimation of the perceived extent of the lowest-density pattern relative to the plain baseline condition.

With respect to *pattern orientation*, von Helmholtz (1867) assumed the principle of the Helmholtz-square to be also applicable to larger surfaces in three-dimensional contexts. However, in Experiment 3 we found that subjects judged stereoscopically presented interior spaces with vertical stripes to be higher but narrower than rooms with horizontal stripes, which is in line with the interior-design experts suggestions but the opposite of the well-established effects observed for the Helmholtz-square. In Experiment 4, when no spatial context was provided (2D rear wall), subjects perceived the vertical patterns to be wider than horizontal patterns with the same density (as suggested by von Helmholtz), whereas, when spatial context was provided (2D room and 3D room), subjects perceived the horizontal patterns to be wider than vertical patterns with the same density (as observed in Experiment 3

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and suggested by interior-design experts). Thus, at least for the width estimates, the results of Experiment 4 indicate that the seemingly incompatible suggestions concerning effects of pattern orientation on the perceived extent of stripe patterns might be due to different perceptual contexts.

However, neither previous results on the Helmholtz-square nor the architectural guidelines are in line with our finding that both width and height estimates increased with the density of stripe patterns, irrespective of pattern orientation. The Helmholtz-square as well as the architectural guidelines follow the rationale that the visual enlargement of one dimension of a given rectangular surface is inevitably accompanied by the visual reduction of the other dimension. In contrast, our results show that high-density wall patterns can enhance the perceived size of *both* dimensions at the same time. We have been suspicious of this baffling finding. In Experiment 4, display condition 2D rear wall, we therefore considerably increased the luminance contrast of the stripe patterns in order to make the orientation more salient. We also varied the available spatial context between display conditions (2D rear wall, 2D room, 3D room). However, it turned out that this pattern remained stable across all experimental manipulations. With this in mind, our data also indicate that, in order to improve a room's perceived spatial extent, pattern density is more important than pattern orientation.

How can the pattern-density effect be explained?

In the present study, we found that stripe patterns with higher densities made rooms appear both wider *and* higher than stripe patterns with lower densities and plain walls, only weakly modulated by pattern orientation. A first possible explanation for this dual effect of pattern density could be that the density changes the *perceived distance to the rear wall,* such that rear walls with high-density patterns appear more distant than rear walls with low-density patterns and plain rear walls. Since in our experiments the retinal size of the rear wall did not change with pattern density, this could explain why subjects overestimated both width and

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height of high-density patterns in comparison to the low-density patterns (cf. Emmert, 1881). But how could high-density patterns have made rear walls appear more distant?

First, according to Gibson (1950; 1979, pp. 66-68), the texture density of the rear wall might have served as a cue to the observer's viewing distance such that rear walls with higher texture densities were perceived as more distant than walls with lower densities. Following this consideration, the high-density stripe patterns might have made the rear wall appear more distant than did low-density patterns. This could explain the differences between high- and low-density stripe patterns. If the effects on perceived spatial extent were indeed due to texture density, an interesting prediction is that the effects we observed for stripe patterns should also be observed for other textures such as random dot patterns. With this in mind, it is an interesting question whether patterned side walls may also influence the perceived spatial layout of interior spaces. One could expect that patterned side walls amplify the texture gradient (Gibson, 1979, p. 160) and therefore increase the perceived depth of a given room (see also Gärling, 1970). In addition, it has been shown that distances on the sagittal plane appear larger when they are segmented as compared to empty (Luria, Kinney, & Weissman, 1967). However, it is difficult to explain the observed differences between the plain wall and the textured walls by changes in perceived depth due to differences in texture density. Although highly speculative, the plain wall could be considered as having an extremely high pattern density (beyond the spatial resolution of the visual system), so that it should be perceived as more distant than any striped walls. However, we did not observe the largest perceived width and height for rooms with plain rear walls, but for rooms with high-density stripe patterns.

Second, the 2D rear-wall patterns might have induced the perception of a 3D arrangement.[2] It has long been known from Gestalt psychology that a luminance contrast between adjacent regions in the visual field is one of the principal cues for figure-ground-

[2] The authors are grateful to reviewer Birgitta Dresp-Langley for pointing out this potential explanation of our findings.

organization (e.g., Gelb & Granit, 1923 [for an expert translation see Kinateder & Nelson, 2017]; Rubin, 1921), which in turn has the power to induce the perception of pictorial depth (e.g., Dresp-Langley & Reeves, 2014; Dresp, Durand, & Grossberg, 2002; Guibal & Dresp, 2004). Even if speculative, the dark stripes (or the bright stripes) could have been perceived as an alignment of figures, e.g., pillars in the case of vertical stripes or bars in the case of horizontal stripes, in front of a uniform background. Based on the familiar size of the respective figure (e.g., the typical diameter of a pillar), the thickness of the stripes might have served as a cue for the perceived distance to the observer, whereby a small number of thick stripes should have made the figure arrangement appear closer to the observer than a large number of thin stripes. In contrast, in the unpatterned plain condition, no such mechanism should have come into effect, such that the perceived distance of the rear wall remained unchanged. With this in mind, compared to the plain baseline condition, high-density patterns could have pushed the perceived position of the rear wall farther away from the observer and low-density patterns could have pulled the perceived position of the rear wall closer to the observer. Due to the constant visual angle of the rear wall across the manipulations of pattern density (see above), a small number of thick stripes should then have reduced the rear wall's perceived width and height below baseline level, whereas a large number of thin stripes should have increased perceived extent beyond baseline level. Note that these predictions are perfectly in line with our findings. However, further research is needed before such considerations can be substantiated.

Could the effect of pattern frequency be explained by changes in perceived brightness? In our stimuli, the mean luminance of the stripe patterns (i.e. the mean of the luminance values of the light-gray and the dark-gray stripes) was matched to the luminance of the medium-gray plain walls (cf. Giora & Gori, 2010). However, since we did not test whether this indeed resulted in patterned and plain surfaces being perceived as equally bright, we cannot rule out that the perceived brightness of the rear-wall surface changed depending

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on pattern density. For example, it might have been the case that the stripe patterns were perceived as darker than the plain gray wall. As outlined in the Introduction, previous studies (Oberfeld & Hecht, 2011; Oberfeld et al., 2010; von Castell et al., 2017, 2018a, 2018b) have reported that changes in surface luminance affect the perceived layout of interior space, in the sense that dark surfaces appear nearer than bright surfaces. Thus, brightness-related changes in perceived depth would be compatible with our observations for low pattern density, but not for high pattern density.

In addition, also the brightness contrast between the rear wall and the adjacent surfaces may have changed as a function of pattern density. For example, in the low density patterns, the brightness contrast between the bright thick stripes at the edges of the rear wall (see Figure 6) and the adjacent surfaces (side walls in the case of vertical stripes or ceiling and floor in the case of horizontal stripes) may have been more pronounced compared to the high-density patterns with very small edge stripes. However, pattern-density related changes in perceived luminance contrast are unlikely to have caused changes in perceived depth because the perceived layout of interior spaces has proven largely independent of the luminance contrast between adjacent surfaces (Oberfeld et al., 2010; von Castell et al., 2018a). For example, perceived depth remained largely unaffected by the luminance contrast between the rear wall and the ceiling or the side walls (for an overview see von Castell et al., 2018a). In contrast, data on depth perception of relatively small objects viewed before a uniform background indeed show that the luminance contrast between object and background affects the perceived distance to the object, in the sense that objects with higher contrast to the background are perceived as nearer than objects with lower contrast (e.g., Dresp-Langley & Reeves, 2014; Dresp et al., 2002; Farnè, 1977; Guibal & Dresp, 2004; O'Shea, Blackburn, & Ono, 1994). Thus, here again, it appears that findings concerning the perceived distance of relatively small objects cannot necessarily be transferred to the perceived layout of interior space.

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Comparing our stimuli to the original Helmholtz-square with regard to their basic geometric properties, it is obvious that they differ considerably with regard to retinal size and aspect ratio. More precisely, our stimuli covered a visual angle equal or greater than 41.54° horizontally and 28.07° vertically and an aspect ratio of approximately 4:3 (horizontal:vertical). The Helmholtz-square, in contrast, typically covers a few degrees of visual angle and has, by definition, an aspect ratio of 1:1. As outlined above, previous studies have reported that the OKI is not immune to changes in stimulus size. However, even though Robinson (1998, p. 51) stated that "*...the Helmholtz-square illusion, like the Oppel-Kundt illusion, varies with the number of lines, width of lines and size of figure or distance from the observer*", we are not aware of any study that has investigated effects of stimulus size (or any other of the listed variables) on the Helmholtz-square. It therefore cannot be ruled out that changes in visual angle interfere with the effects originally observed for the Helmholtz-square. However, even if this were true, it would not reconcile our findings with the interior designers' suggestions, which clearly refer to large surfaces and aspect ratios unequal 1:1, because walls in interior spaces are typically wider than high (as was the case in our study). The other relevant aspect is that for the Helmholtz-square, the task is a paired comparison between the perceived height and the perceived width of the stimulus. It is likely that this task is more sensitive to detect small changes in the perceived ratio between height and width, as compared to the separate estimates for height and width collected in our experiments. This could partly explain why the effect of pattern orientation was weak and sometimes non-significant in our study. However, it does clearly not explain why in some conditions we found an effect of pattern orientation in a direction opposite to the Helmholtz-square.

Moreover, the stripe patterns used in the present study mostly had a lower pattern contrast compared to the original Helmholtz-square. Could this have caused the weak effect of pattern orientation? Be reminded that we tested potential effects of pattern contrast in Experiment 4, display condition 2D rear wall, where we presented only the rear wall (without

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stereoscopic depth cues and spatial context). Even though the variation of pattern contrast was quite substantial with Weber contrasts of 55% for the low-contrast condition (as in all remaining experiments) and 96% for the high contrast condition, the effect of pattern contrast as well as all interaction effects involving pattern contrast were clearly not significant for the width and height estimates. Because we did not test potential effects of pattern contrast in the two conditions with spatial context (Experiment 4, display conditions 2D room and 3D room), we cannot completely rule out effects of pattern contrast when spatial context and stereoscopic depth are available. However, based on the approximate null effect of pattern contrast in Experiment, 4 display condition 2D rear wall, and previous findings regarding effects of pattern contrast on orientation sensitivity in small stimuli (up to a few degrees of visual angle; e.g., Bowne, 1990; Mareschal & Shapley, 2004; Skottun, Bradley, Sclar, Ohzawa, & Freeman, 1987), we consider this unlikely. For example, Bowne (1990) presented slightly rotated small gratings and varied the luminance contrast between the gratings and the uniform background. He reported an increase in orientation sensitivity with increasing contrast, which levelled off between 32% and 50% luminance contrast. Furthermore, already in such very small stimuli, the effect of pattern contrast on orientation sensitivity appears to decrease when stimulus size increases (cf. Mareschal & Shapley, 2004). With that in mind, considering the contrasts (55% and 96%) and the large visual angles (at least 41.54° horizontally by 28.07° vertically) of the stripe patterns in the present study, the variation of pattern orientation should have been comparably noticeable in both contrast conditions. Be also reminded that observers were directly facing the rear wall such that the rear wall covered a large visual angle approximately in the center of the visual field. Thus, any supra-threshold variation of the rear-wall pattern should have been highly salient across all display conditions. Taken together, reduced pattern contrast compared to the original Helmholtz-square seems hardly responsible for the weak effect of pattern orientation.

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In sum, we do not have a convincing explanation for the weak and unexpected effects of pattern orientation. In contrast, pattern density consistently influences the perceived extent of spatial dimensions and should be considered as an important means to improve the perceived spatial layout of interior rooms, even though the perceptual mechanisms underlying this effect are not yet fully understood. Since the stimuli we presented in the present study were somewhat artificial, additional studies using real interior spaces or higher fidelity simulations of interior spaces would be desirable.

Applicability to real-world scenes

We presented static stereoscopic room simulations on a large projection screen. This approach enabled a high level of experimental control and variation of the independent variables. However, stereoscopically simulated scenes provide less precise depth cues than genuine three-dimensional real-world scenes. According to Hoffman, Girshick, Akeley, and Banks (2008), such stereoscopic simulations suffer from a distorted retinal blur gradient (see also Vishwanath & Blaser, 2010; Zannoli, Love, Narain, & Banks, 2016) due to the flat (two-dimensional) screen of the presentation medium, reduced vergence accuracy due to impaired coupling of accommodation and vergence, and constant accommodation due to fixed screen-to-eye distance. Apart from that, observer distance to any point of both the projection screen and the virtual scene was at least 2 m in our experimental setup (see Figure 3). Depth information from retinal blur, vergence, and accommodation should thus have played a subordinate role (cf. Cutting & Vishton, 1995; Watt, Akeley, Ernst, & Banks, 2005). Furthermore, the static stereoscopic images provided no depth information through motion parallax. Thus, the impression of depth was mainly driven by binocular disparity and static pictorial depth cues, such as linear perspective, texture gradient, and relative height. The consistent overall underestimation of the simulated rooms' *absolute* width and height, which we found across all reported experiments, might be in part due to the limited depth cues as

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compared to real-world scenes. However, because we were interested in the perceived size of rooms with patterned walls *relative* to equally sized rooms with plain walls, the direction and slope of the reported effects is unaffected by the absolute level of estimates. Thus, not denying the additional benefit of a validation in real-world scenes with full availability of visual depth cues, we argue that the overall underestimation of spatial extent is not at odds with the applicability of our results to real-world scenes.

Appropriateness of the applied magnitude-estimation procedure

In the present study, we used size estimates on a centimeter scale to measure the perceived size of the virtual rooms. We decided against forced-choice or adjustment procedures and in favor of magnitude estimation for several reasons. First, magnitude estimation is a well-established method in psychophysics, and we have data confirming that the latter is appropriate for our purposes: In a recent study from our lab regarding effects of ceiling luminance on the perceived height of interior spaces (von Castell et al., 2017), we compared height estimates on a centimeter scale with the results from a two-interval height-matching task. In the latter, observers had to match the perceived ceiling height with a height-adjustable pillar. This task allows for a direct visual match and does not require any metric judgment. When varying ceiling luminance, the height matches showed that bright ceilings appeared higher than dark ceilings, that is, the pillar had to be higher in order to be perceived as high as the ceiling when the ceiling color was bright, as compared to dark. The results from the height estimates on the centimeter scale (the same procedure as in the present manuscript) showed essentially the same effect of ceiling luminance on perceived ceiling height. Second, we have replicated the above described effect of surface luminance across a series of five publications (Oberfeld & Hecht, 2011; Oberfeld et al., 2010; von Castell et al., 2017, 2018a, 2018b) using magnitude estimation (estimates on a centimeter scale). This high amount of consistency across experiments with different participants additionally endorsed the utility

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and accuracy of estimates on a centimeter scale. Third, in all studies cited above, we found that perceived spatial extent consistently increased with physical spatial extent. Note that we have also observed this tight and reliable connection between physical stimulus size and perceived stimulus size in the present study: across all experiments, perceived width increased as a function of physical width and perceived height increased with physical height. Fourth, as this is the first systematic study of effects of stripe patterns on the perceived layout of interior spaces, we decided for a design that economizes on the number of trials per condition in favor of a larger gamut of stimulus features and the ability to directly replicate potential findings within one study. Forced-choice or adjustment procedures would have required considerably more trials to assess effects of stripe patterns on the perceived layout of interior spaces. Fifth, forced-choice or adjustment procedures would have involved a sequential presentation of the two stimuli per trial. A parallel presentation would not have been possible due to the large visual angle of the stimulus. In the case of an adjustment procedure, this would have made the PSE (point of subjective equality) estimates prone to memory effects. Also, in two-interval tasks, time-order errors play a role (Fechner, 1860; Hellström, 1985; for an example see von Castell et al., 2017), which can introduce an additional bias on the PSE estimates.

For these reasons, we believe that the magnitude estimation procedure applied in the present study is appropriate for measuring the perceived spatial extent of interior spaces. Notwithstanding, the replication of our findings with alternative psychophysical scaling procedures would of course be desirable.

Conclusion

In the present study, effects of stripe surface patterns that alter the perceived size or distance of relatively small 2D-objects did not generalize to simulated interior spaces. It seems that interior space perception has its own set of rules.

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We propose an anisotropy of object perception and interior space perception. A stripe pattern on an object biases its perceived spatial extent differently in the direction perpendicular to the stripe orientation compared to the direction parallel to the stripe orientation. A gain in the direction perpendicular to the stripe orientation is accompanied by a loss in the direction parallel to the stripe pattern, and vice versa. A similar pattern on a wall of an interior space produces a qualitatively different bias. Space is biased to extend uniformly in parallel *and* perpendicular to the stripes' orientation, as a function pattern density. Thus, stripes could be said to have object-defining properties in the former case and space-creating properties in the latter case. The nature of this anisotropy deserves to be studied further.

Practically speaking, if one would like to maximize the perceived extent of a room by means of stripe patterns on the walls, our results suggest to use stripe patterns with high pattern density.

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Figure Captions

Figure 1: *Top row: Illustration of the Oppel-Kundt-illusion. The distance between A and B appears larger than the distance between B and C. Bottom row: Illustration of the Helmholtz-square. The horizontally striped square (H) appears taller than wide, the vertically striped square (V) appears wider than tall.*

Figure 2: *Experiment 1. Selected two-dimensional screenshots of the stimuli. From top left to bottom right: Rear-wall patterns with 0, 4, 12, and 36 vertical stripes. The resulting pattern densities were 0.05, 0.14, and 0.41 cycles per degree (c/deg). In all screenshots, the simulated room width and ceiling height were 4.50 and 2.90 m, respectively.*

Figure 3: *Experiment 1. The observer's (O) position relative to the projection screen (S) and the variable-width room simulations (rectangular frames). The gray shaded area of the rooms was not visible to observers. Virtual dimensions are printed in gray, real dimensions are printed in black.*

Figure 4: *Experiment 1. Top row: mean width estimates as a function of pattern density (c/deg, plotted on a log scale; panel A) and as a function of room width and ceiling height (panel B). Bottom row: mean height estimates as a function of pattern density (c/deg; panel C) and as a function of ceiling height and room width (panel D). In panels A and C, significant differences from the plain condition are marked by an asterisk; the dashed lines indicate the average veridical spatial extent. Error bars show ± 1 standard error of the mean (SEM) of the 20 individual estimates in each condition.*

Figure 5: *Experiment 2. Top row: mean width estimates as a function of pattern density (c/deg, plotted on a log scale; panel A) and as a function of room width and ceiling height (panel B). Bottom row: mean height estimates as a function of pattern density (c/deg;*

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panel C) and as a function of ceiling height and room width (panel D). In panels A and C, significant differences from the plain condition are marked by an asterisk (for details see Experiment 1); the dashed lines indicate the average veridical spatial extent. Error bars show ± 1 SEM of the 20 individual estimates in each condition.

Figure 6: *Experiment 3. Selected two-dimensional screenshots of the presented stimuli. Top row from left to right: Vertical rear-wall patterns with 4, 6, and 36 stripes. The resulting pattern densities are 0.05, 0.07, and 0.41 c/deg. Bottom row from left to right: Horizontal rear-wall patterns with 4, 24, and 36 stripes. The resulting pattern densities are 0.07, 0.41, and 0.61 c/deg. In all screenshots, the simulated room width and ceiling height are 4.40 and 2.90 m, respectively.*

Figure 7: *Experiment 3. Top row: mean width estimates as a function of the vertical patterns' density (c/deg, plotted on a log scale; panel A) and as a function of room width and ceiling height (panel B). Bottom row: mean height estimates as a function of the vertical patterns' density (c/deg; panel C) and as a function of ceiling height and room width (panel D). In panels A and C, significant differences from the plain condition are marked by an asterisk (for details see Experiment 1); the dashed lines indicate the average veridical spatial extent. Error bars show ± 1 SEM of the 20 individual estimates in each condition.*

Figure 8: *Experiment 3. Top row: mean width estimates as a function of the horizontal patterns' density (c/deg, plotted on a log scale; panel A) and as a function of room width and ceiling height (panel B). Bottom row: mean height estimates as a function of the horizontal patterns' density (c/deg; panel C) and as a function of ceiling height and room width (panel D). In panels A and C, significant differences from the plain condition are marked by an asterisk (for details see Experiment 1); the dashed lines indicate the mean veridical spatial extent. Error bars show ± 1 SEM of the 20 individual estimates in each condition.*

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Figure 9: *Experiment 3. Mean relative differences to the plain baseline condition (indicated by the dashed lines) for the width estimates (panel A) and the height estimates (panel B) as a function of pattern density (c/deg, plotted on a log scale) and pattern orientation, averaged across room width and ceiling height. Error bars show ± 1 SEM of the 20 individual estimates in each condition.*

Figure 10: *Experiment 4, display condition 2D rear wall. Selected two-dimensional screenshots of the presented stimuli. Rows 1 and 2 show high-contrast rear-wall patterns, and rows 3 and 4 show low-contrast rear-wall patterns, each presented in vertical (rows 1 and 3) and horizontal (rows 2 and 4) pattern orientation. The pattern densities are 0.41 (column 2) and 3.24 c/deg (column 3). In all screenshots, the simulated room width and ceiling height are 4.40 and 2.90 m, respectively.*

Figure 11: *Experiment 4, display condition 2D rear wall. Mean relative differences to the plain baseline condition (indicated by the dashed lines) for the width estimates (panels HC_W and LC_W) and the height estimates (panels HC_W and LC_H) as a function of pattern density (c/deg, plotted on a log scale), pattern orientation, and pattern contrast (high: panels HC_W and HC_H, low: panels LC_W and LC_H), averaged across room width and ceiling height. Error bars show ± 1 SEM of the 20 individual estimates in each condition.*

Figure 12: *Experiment 4, display conditions 2D rear wall, 2D room, and 3D room. Mean relative differences to the plain baseline condition (indicated by the dashed lines) for the width estimates (left column) and the height estimates (right column) as a function of pattern density (c/deg, plotted on a log scale), pattern orientation and display condition (2D rear wall: top row, 2D room: middle row, 3D room: bottom row), averaged across room width and ceiling height. Error bars show ± 1 SEM of the 20 individual estimates in each condition.*

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Figure 13: *Experiment 4, display conditions 2D rear wall, 2D room, and 3D room. Top row: mean relative differences to the plain baseline condition (indicated by the dashed lines) for the width estimates (panel DC_W) and the height estimates (panel DC_H) as a function of display condition and pattern orientation, averaged across room width, ceiling height, and pattern density. Bottom row: mean relative differences to the plain baseline condition (indicated by the dashed lines) for the width estimates (panel PD_W) and the height estimates (panel PD_H) as a function of pattern density (c/deg, plotted on a log scale) and pattern orientation, averaged across room width, ceiling height, and display condition. Error bars show ± 1 SEM of the 20 individual estimates in each condition.*

Figure 14: *Experiments 1 – 3 and 4, display condition 3D room. Mean relative differences to the plain baseline condition for the width estimates (panel W) and the height estimates (panel H) as a function of pattern density (c/deg, plotted on a log scale) and experimental condition (solid lines = vertical orientation, dashed lines = horizontal orientation), averaged across room width and ceiling height.*

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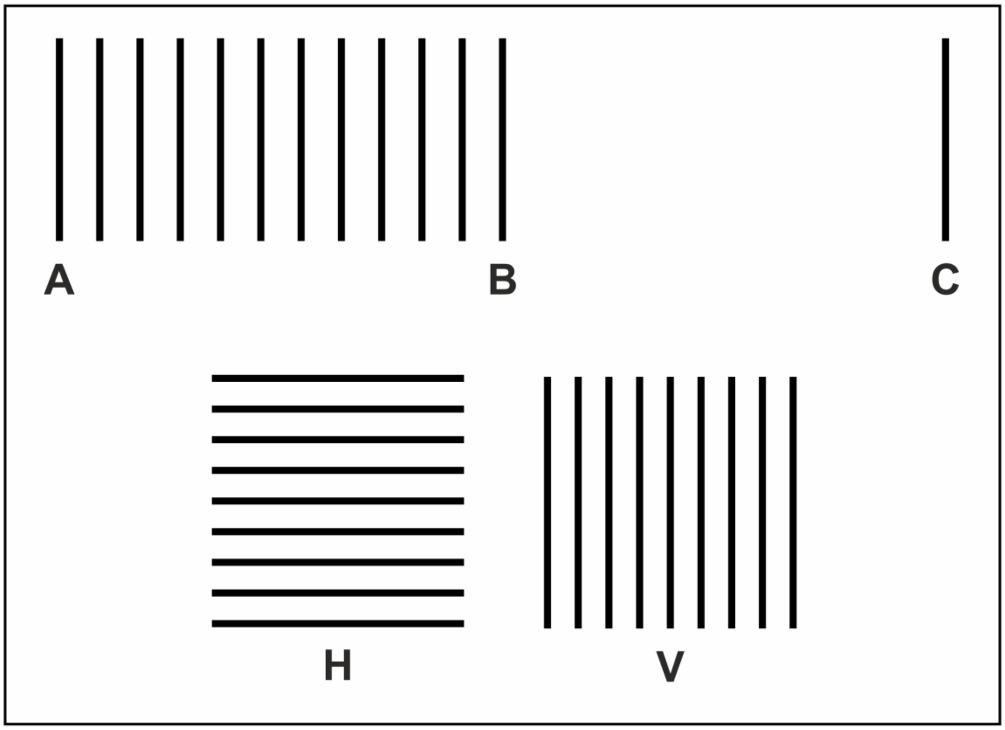

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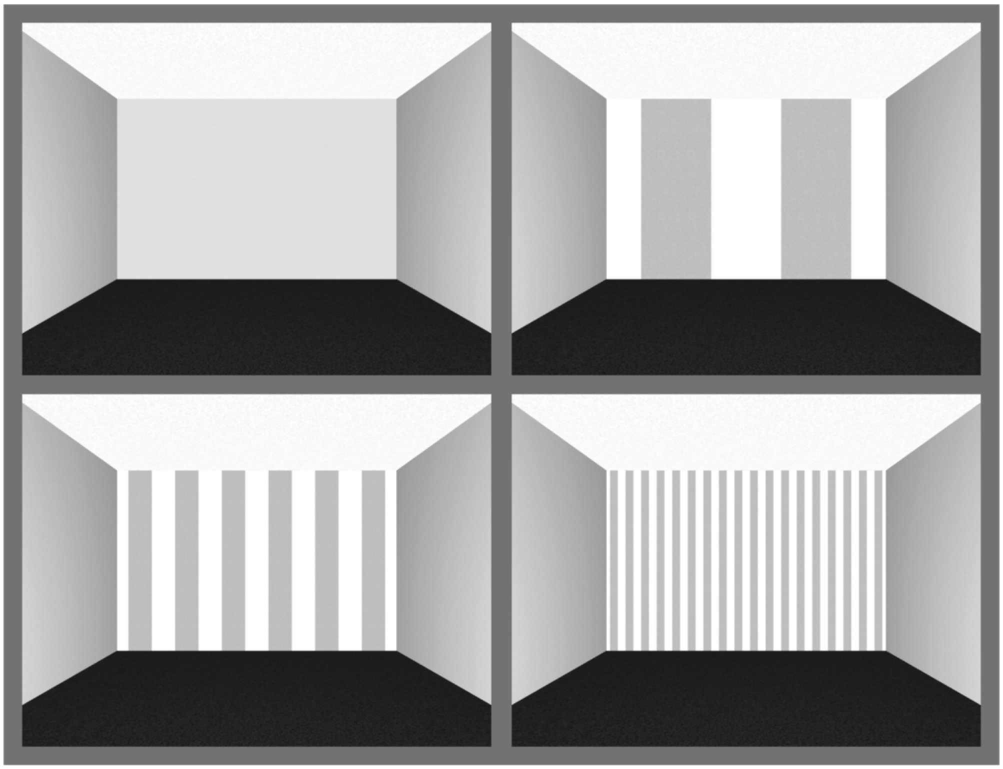
DOI: 10.1177/1747021819876637



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143x109mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637

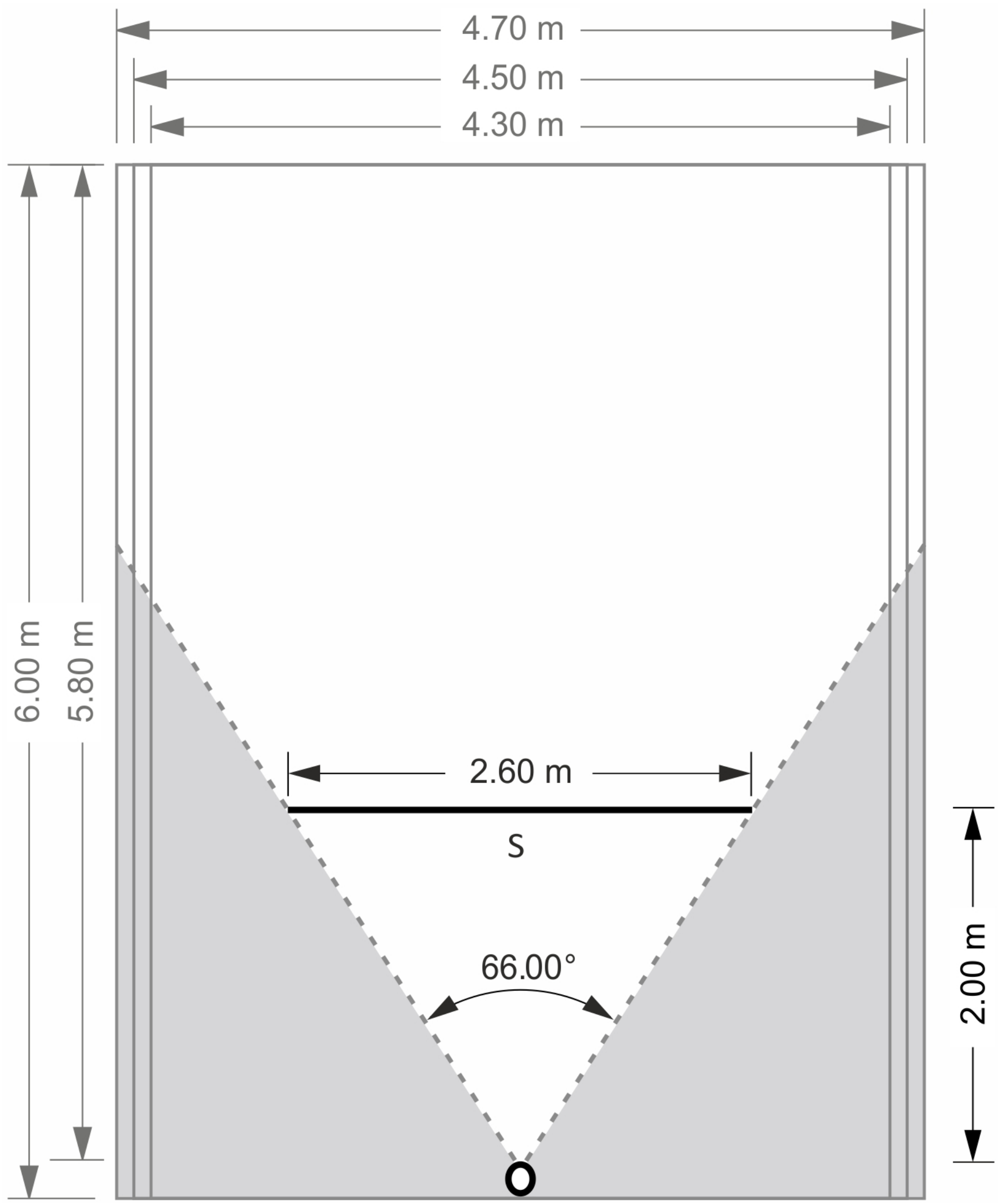
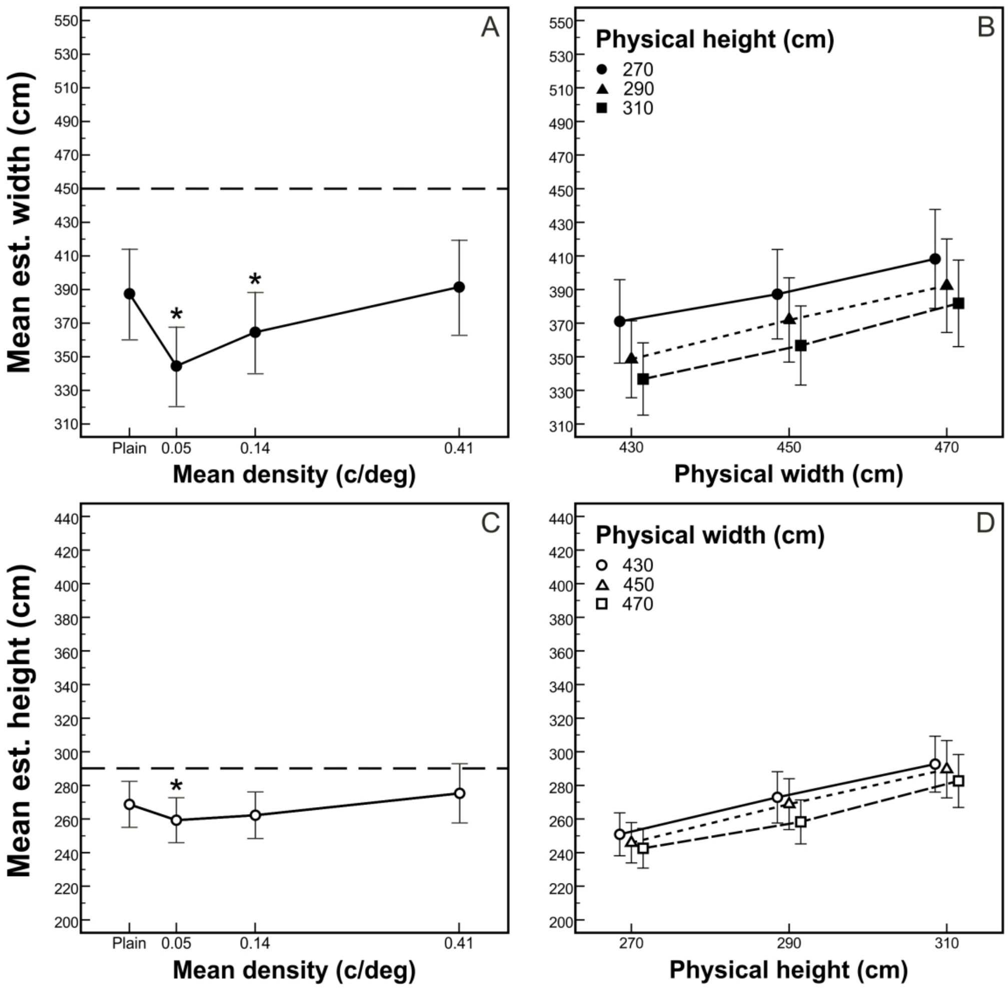


Figure 3: Experiment 1. The observer's (O) position relative to the projection screen (S) and the variable-width room simulations (rectangular frames). The gray shaded area of the rooms was not visible to observers. Virtual dimensions are printed in gray, real dimensions are printed in black.

116x139mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637



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229x224mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637

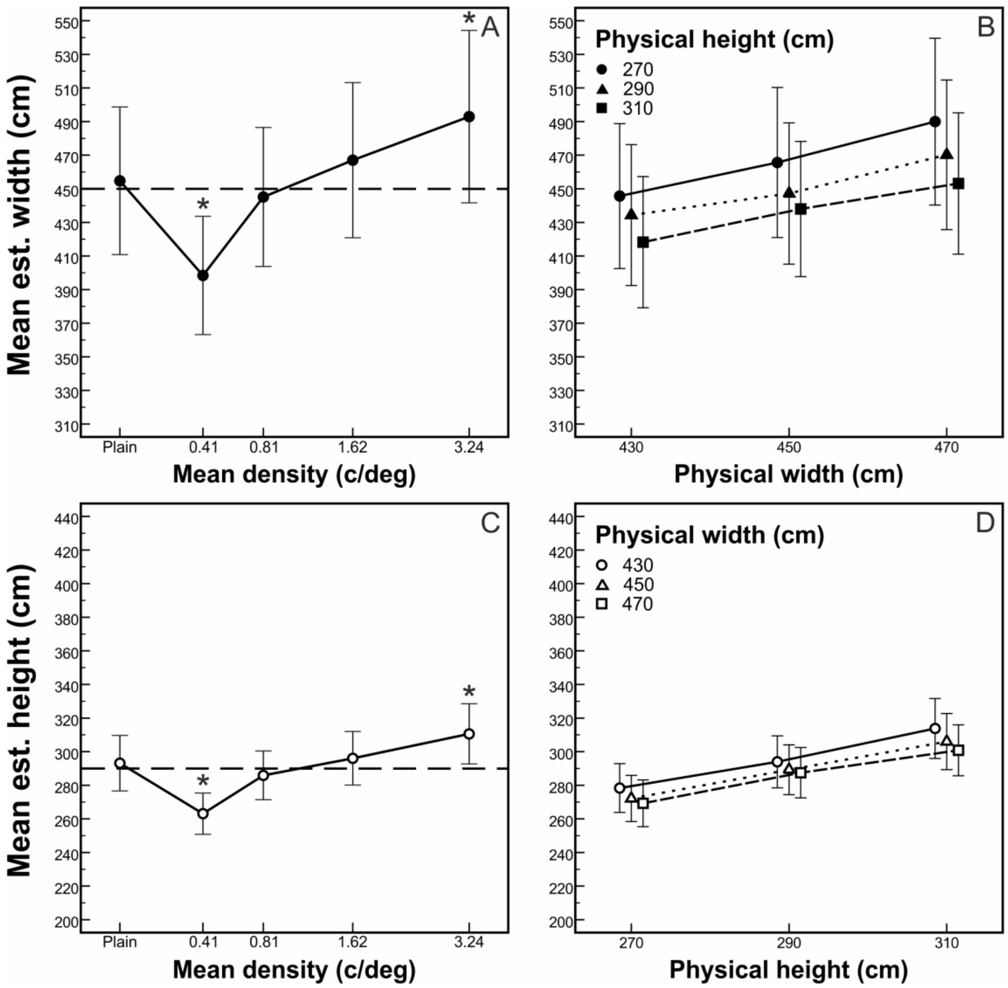
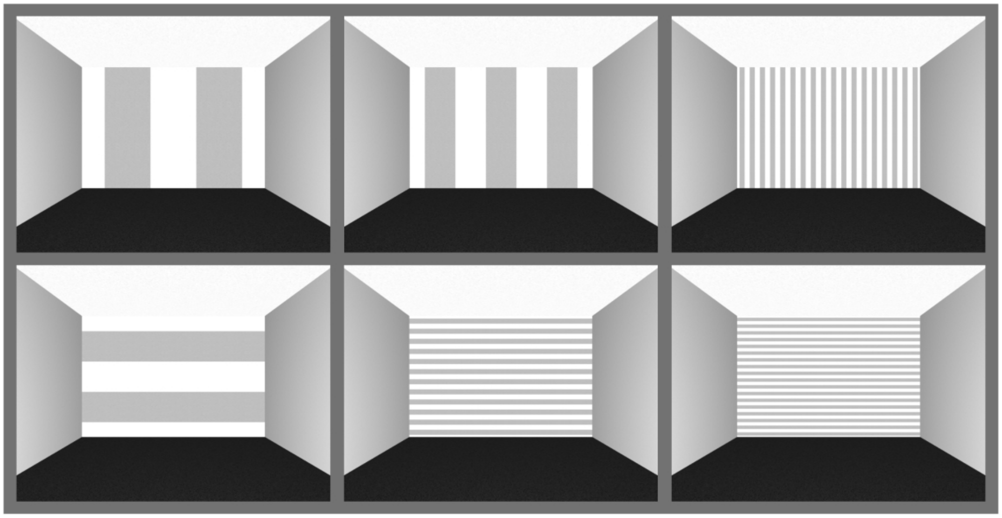


Figure 5: Experiment 2. Top row: mean width estimates as a function of pattern density (c/deg, plotted on a log scale; panel A) and as a function of room width and ceiling height (panel B). Bottom row: mean height estimates as a function of pattern density (c/deg; panel C) and as a function of ceiling height and room width (panel D). In panels A and C, significant differences from the plain condition are marked by an asterisk (for details see Experiment 1); the dashed lines indicate the average veridical spatial extent. Error bars show ± 1 SEM of the 20 individual estimates in each condition.

229x224mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637



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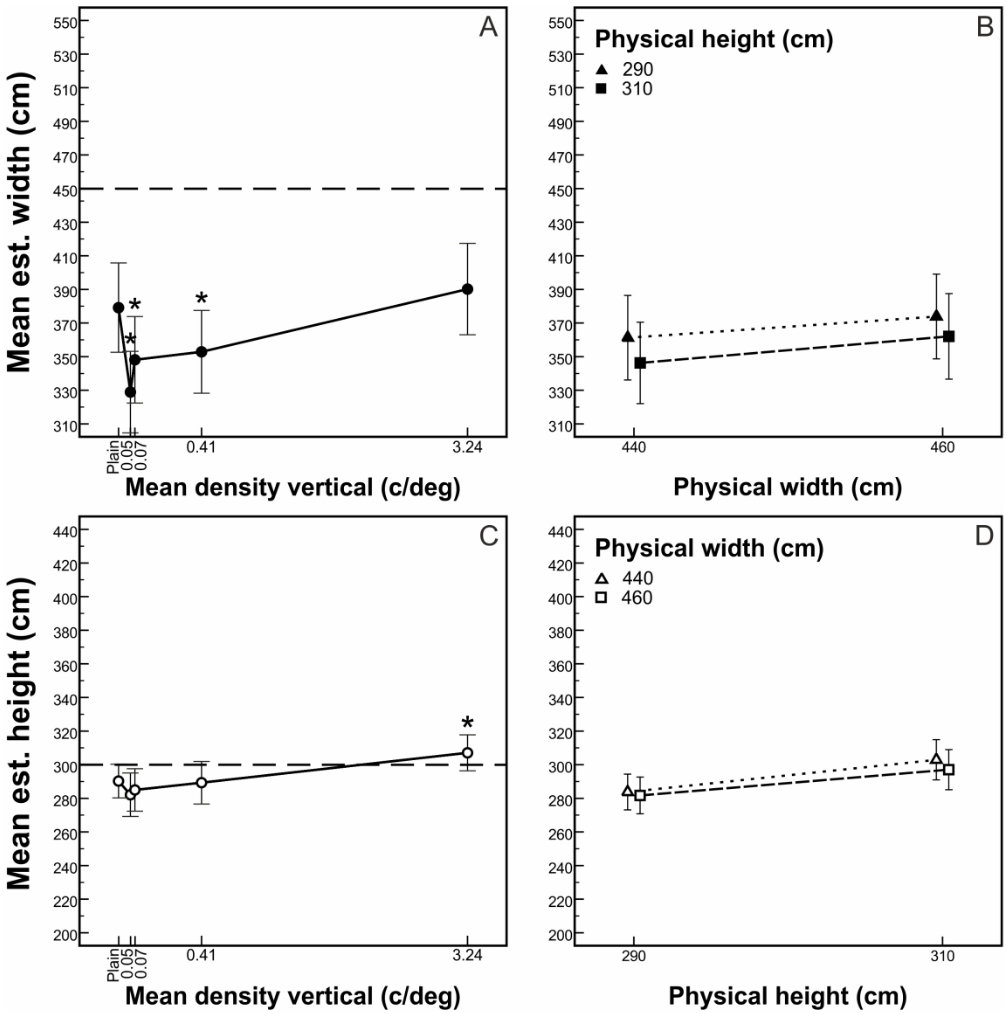
214x110mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637



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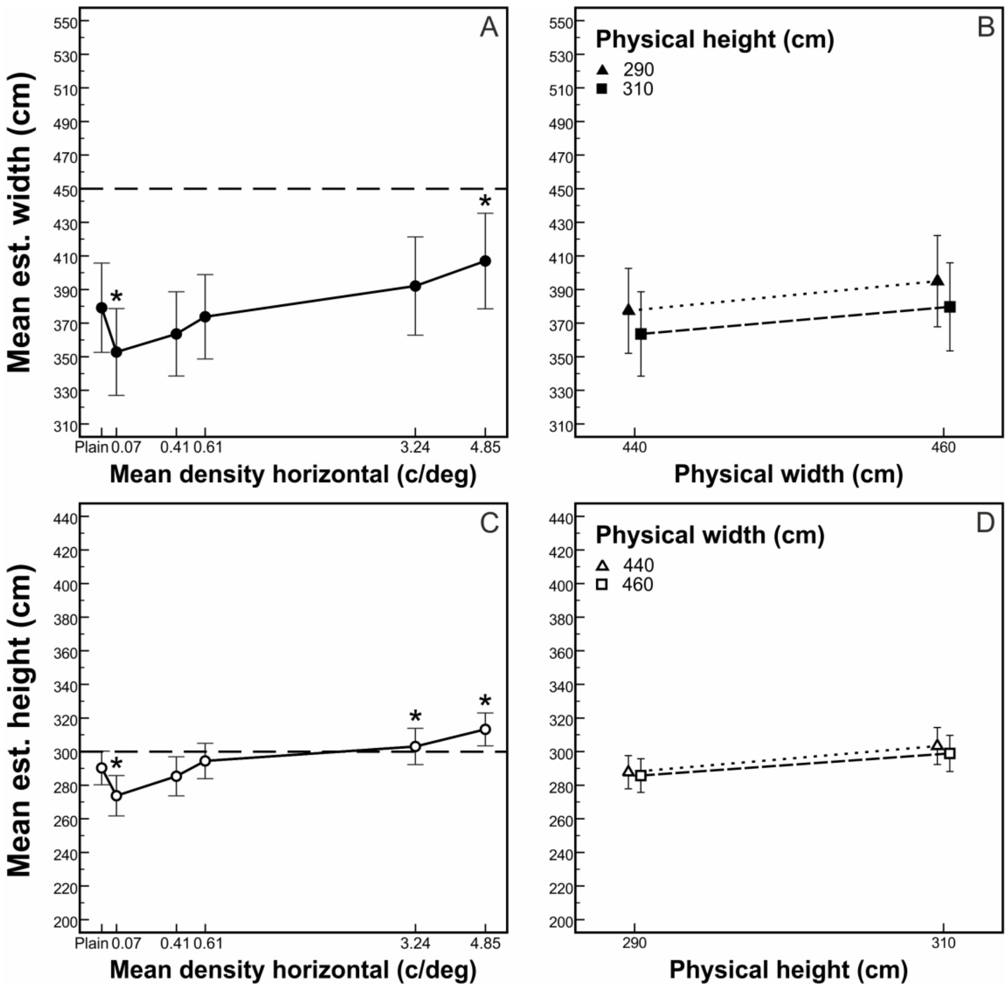
229x230mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637



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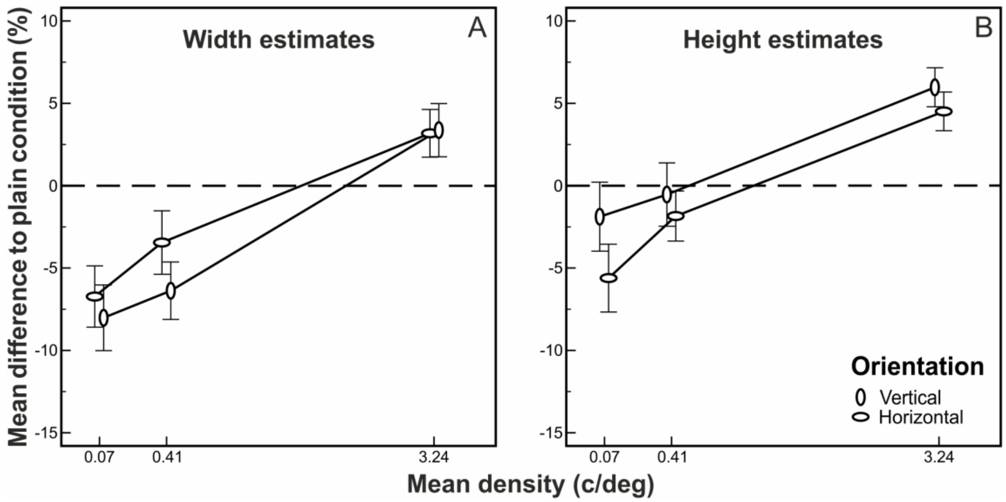
229x224mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637



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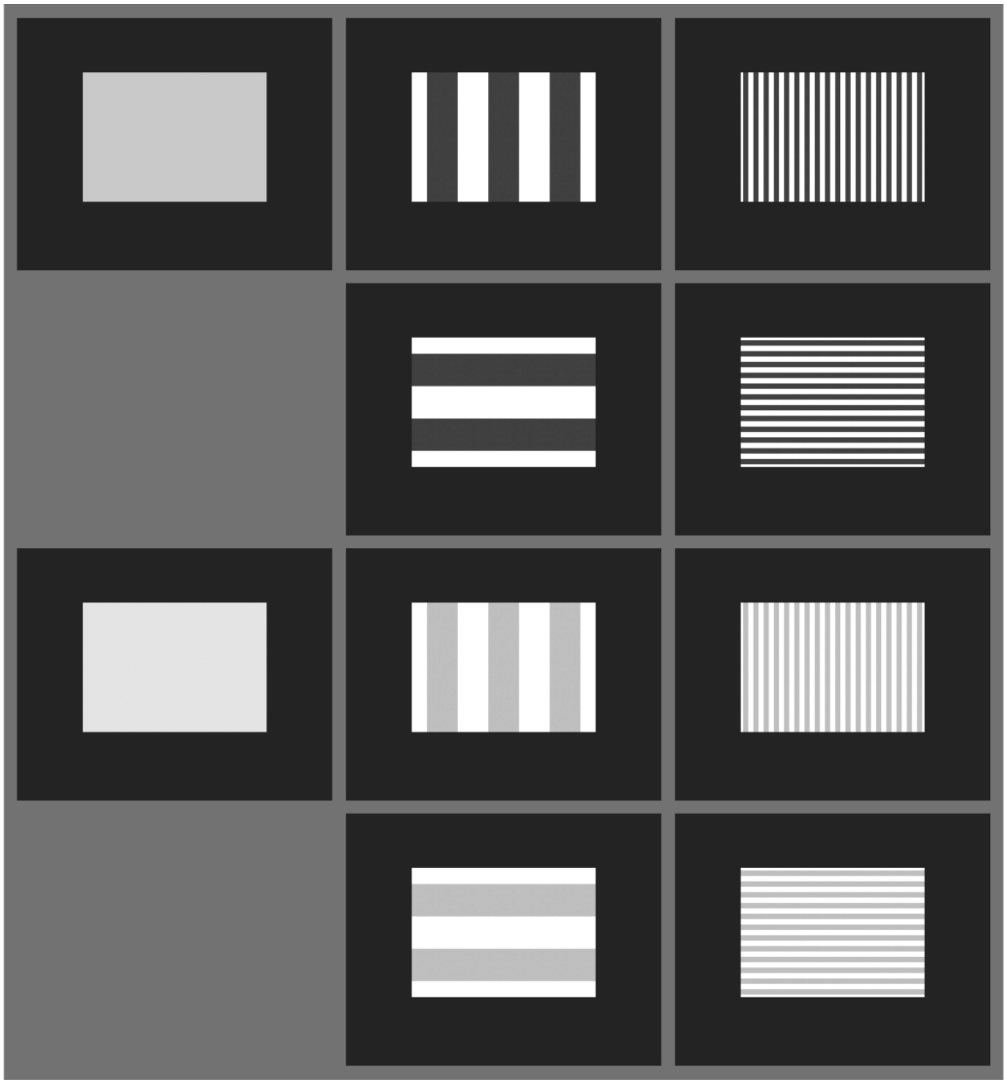
224x111mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637



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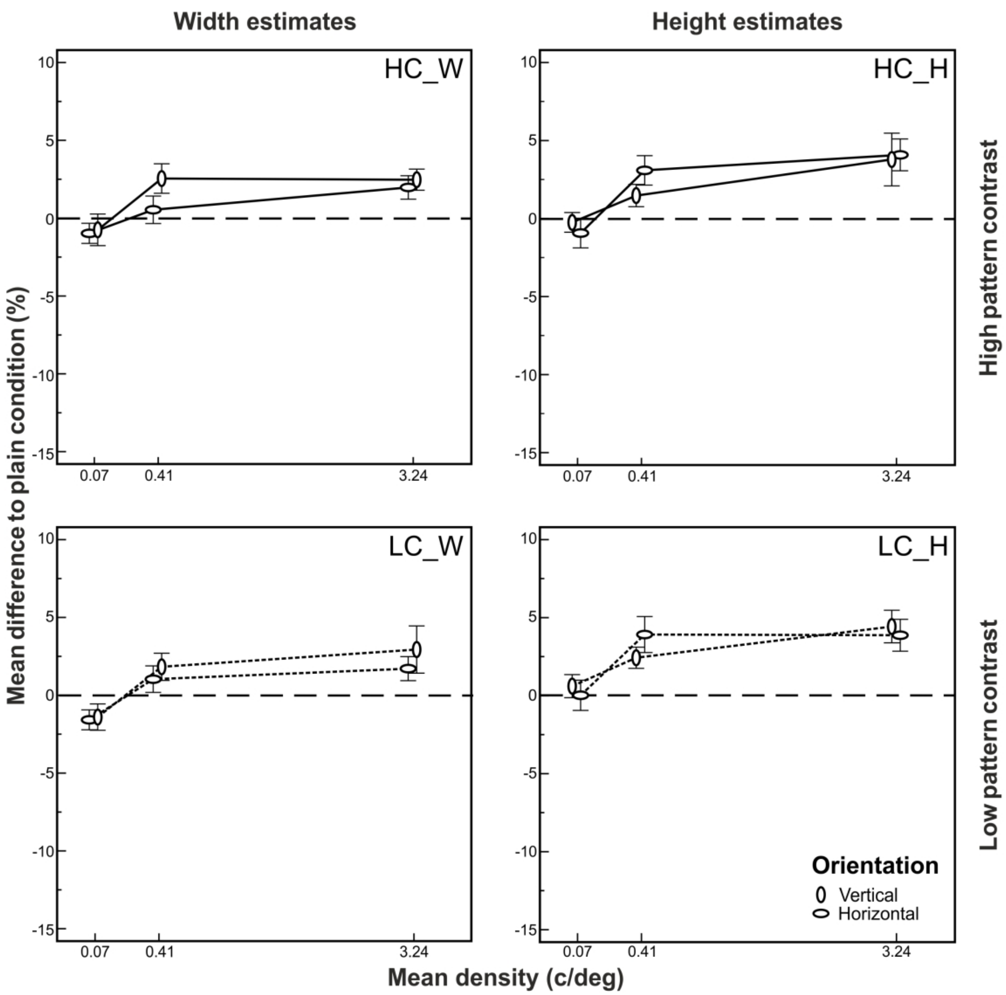
213x229mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637



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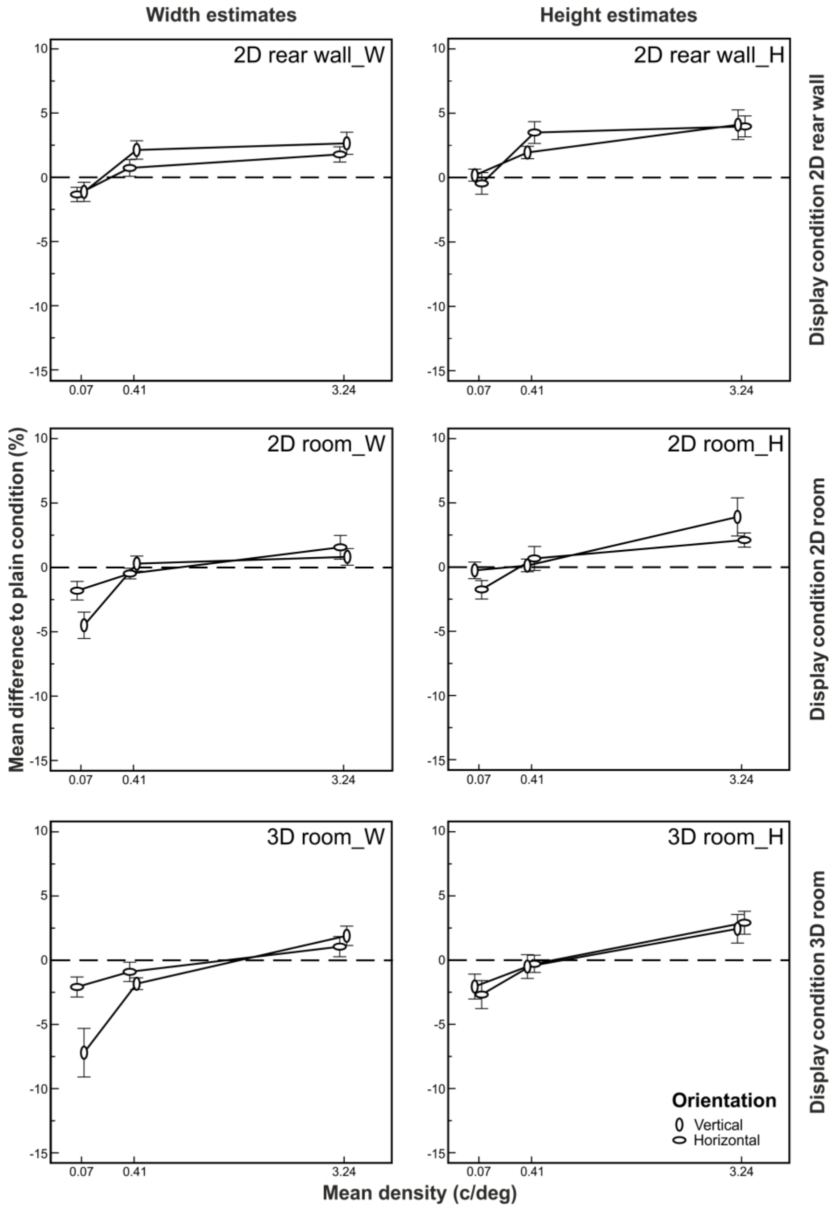
236x232mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637



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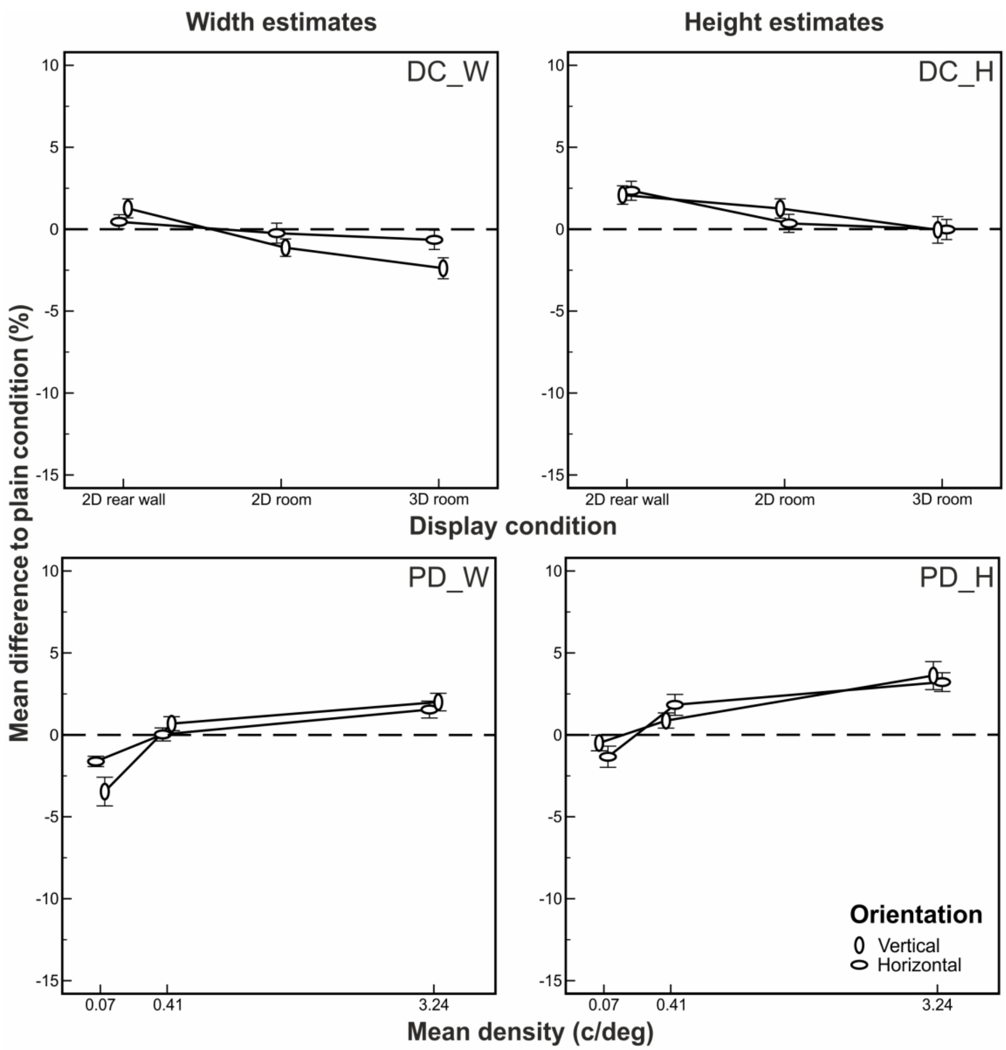
235x343mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637



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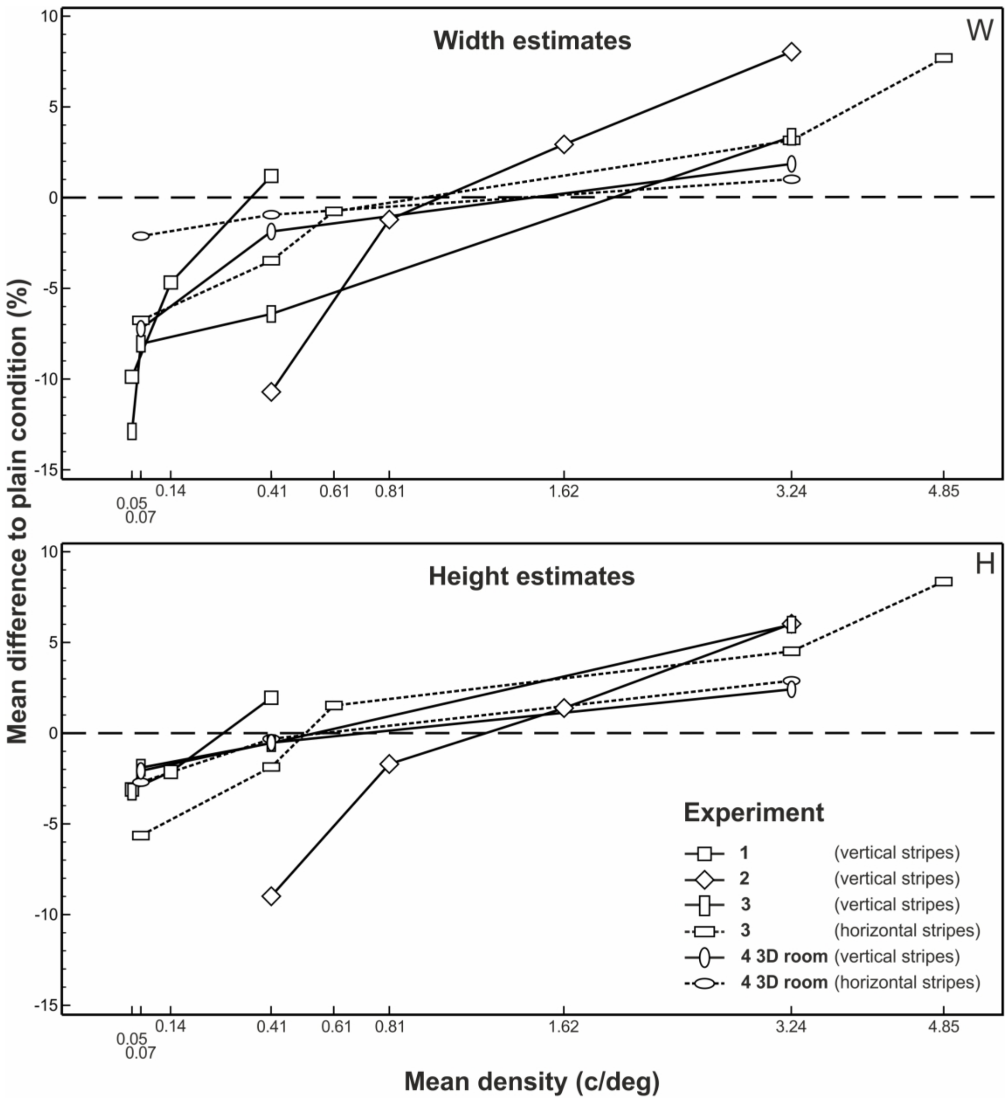
225x235mm (300 x 300 DPI)

DOI: 10.1177/1747021819876637



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218x238mm (300 x 300 DPI)

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Table 1: *Experiment 3. Presented number of stripes mean densities (averaged across room width and height), as a function of pattern orientation*

Pattern orientation			
Vertical		Horizontal	
Number of stripes	Density (c/deg)	Number of stripes	Density (c/deg)
4	0.05	*4*	**0.07**
6	**0.07**		
		24	**0.41**
36	**0.41**	*36*	0.61
		192	**3.24**
288	**3.24**	*288*	4.85

Note: Pairs with matching numbers of stripes are printed in italics; pairs with matching density are printed in bold font.

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