The Quarterly Journal of Experimental Psychology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t716100704

Surface lightness influences perceived room height

Daniel Oberfeld[a]; Heiko Hecht[a]; Matthias Gamer[b]
[a] Johannes Gutenberg-Universität, Mainz, Germany [b] Department of Systems Neuroscience, University Medical Center Hamburg-Eppendorf, Hamburg, Germany

First published on: 16 April 2010

To cite this Article Oberfeld, Daniel , Hecht, Heiko and Gamer, Matthias(2010) 'Surface lightness influences perceived room height', The Quarterly Journal of Experimental Psychology, 63: 10, 1999 — 2011, First published on: 16 April 2010 (iFirst)

To link to this Article: DOI: 10.1080/17470211003646161

URL: http://dx.doi.org/10.1080/17470211003646161

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
2010, 63 (10), 1999–2011

Psychology Press
Taylor & Francis Group

Surface lightness influences perceived room height

Daniel Oberfeld and Heiko Hecht
Johannes Gutenberg-Universität, Mainz, Germany

Matthias Gamer
Department of Systems Neuroscience, University Medical Center Hamburg-Eppendorf, Hamburg, Germany

Surprisingly little scientific research has been conducted on the effects of colour and lightness on the perception of spaciousness. Practitioners and architects typically suggest that a room's ceiling appears higher when it is painted lighter than the walls, while darker ceilings appear lower. Employing a virtual reality setting, we studied the effects of the lightness of different room surfaces on perceived height in two psychophysical experiments. Observers judged the height of rooms varying in physical height as well as in the lightness of ceiling, floor, and walls. Experiment 1 showed the expected increase of perceived height with increases in ceiling lightness. Unexpectedly, the perceived height additionally increased with wall lightness, and the effects of wall lightness and ceiling lightness were roughly additive, incompatible with a simple effect of the lightness contrast between the ceiling and the walls. Experiment 2 demonstrated that the floor lightness has no significant effect on perceived height, and that the total brightness of the room is not the critical factor influencing the perceived height. Neither can the results be explained by previously reported effects of brightness on apparent depth or perceived distance.

Keywords: Room perception; Architecture; Architectural psychology; Interior design; Colour; Brightness; Contrast; Depth; Psychophysics; Visual perception; Illumination; Interior space; Virtual reality.

In the fields of architecture, interior design, and home improvement, suggestions regarding effects of colour on the perceived dimensions of a room are ubiquitous. More specifically, effects of lightness or brightness (Gilchrist, 2007) of the walls, the ceiling, and the floor are common lore in the applied domain. Although the preference for a room does not necessarily increase monotonically with its height (Baird, Cassidy, & Kurr, 1978), a frequently asked question is how to select the colours of the different room surfaces in order to make the room appear higher. To illustrate this point, an internet search for "ceiling walls color height" returned several thousands of hits recommending solutions such as "If your ceilings are low, make sure you paint them a shade or two lighter than your walls to add height" (http://www.doityourself.com/stry/paintsteps

Correspondence should be addressed to Daniel Oberfeld, Department of Psychology, Johannes Gutenberg-Universität, 55099, Mainz, Germany. E-mail: oberfeld@uni-mainz.de

We thank two anonymous reviewers for helpful comments on an earlier version of this article. We are grateful to Agnes Münch for constructing the virtual rooms. The work was supported by the Interdisciplinary Centre for Neuroscience (IFSN) at the University of Mainz.

http://www.psypress.com/qjep
DOI:10.1080/17470211003646161

accessed on July 17, 2009). Textbooks on architecture and interior design also contain guidelines concerning the impact of room surface colour on the impression of width, height, and depth as well as on more global attributes such as the spaciousness of the room (Neufert & Kister, 2005). For example, Neufert and Kister (2005, p. 51) give several examples of how colour combinations of walls, ceiling, and floor should alter the perceived dimensions of interior space. They use the term "colour" but the visual examples they present suggest that it is the lightness rather than the hue of the different surfaces that causes the effects. Neufert and Kister propose that if the ceiling is lighter than the walls, then a room will appear higher than it would in cases where its walls are lighter than the ceiling, again assuming a crucial role of the lightness contrast between ceiling and walls. An additional important aspect related to the lightness of room surfaces is that light is continuously gaining importance as a means for creating and modifying architectural spaces (cf. Michel, 1996; Society of Light and Lighting, 2009).

To summarize, in the expert opinion in the field of architecture and interior design there is a strong consensus concerning the effects of surface lightness on the perceived dimensions of rooms. On the other hand, as is discussed below, sound experimental data are lacking, and the origin of the assumed effects is unclear. As an initial step towards a better understanding of the influence of surface lightness on the perception of interior space, psychophysical estimates of the height of rooms were obtained in the present study as a function of the lightness of the different room surfaces. Two experiments took advantage of virtual reality technology to simulate rooms whose actual height as well as ceiling, wall, and floor lightness could be systematically and quickly manipulated. The experimental conditions were selected to provide an answer to the question whether the ceiling lightness per se or the lightness contrast between ceiling and walls is responsible for the expected effects on perceived height. The results confirmed the proposed effect of ceiling lightness, but provided evidence against a role of the brightness contrast between the ceiling and the walls, instead demonstrating an additive effect of wall lightness. For this reason, we suggest an improved rule of thumb for making a room appear higher.

Despite the high importance of surface lightness for architecture and interior design, there appear to be only two empirical studies indirectly concerned with the effect of the lightness of the walls, the ceiling, and the floor on the perceived dimensions of a room. In an experiment by Matusiak (2006), observers judged the depth, width, height, and overall size of a full-scale real room on a rating scale. Only the wall opposite to the observer contained two elongated windows. If the two windows were oriented horizontally, then the room was judged higher if one window was placed next to the floor and the other next to the ceiling, than in a condition where both windows were positioned at the centre of the wall. Unfortunately, Matusiak reported only average ratings but no statistical tests. A similar effect was found for estimated width if the windows were oriented vertically and placed either at the centre of the wall or next to the sidewalls. Comparable results were obtained by Matusiak (2004).

A straightforward way to explain the effects of ceiling lightness on the perceived height of a room would be that an observer judges the height by estimating the distance of the ceiling from his or her eye height and perceives lighter ceilings to be farther away (cf. Matusiak, 2006). Puzzlingly, however, this idea is not compatible with the established effects of brightness or brightness contrast on depth perception and distance estimation. It has been known for a long time that a bright object subtending the same visual angle as a darker object appears closer (Coules, 1955; Helmholtz, 1867; Mount, Case, Sanderson, & Brenner, 1956) and that a brighter object also appears to be larger (Ashley, 1898; Gundlach & Macoubrey, 1931; Holway & Boring, 1940; Oyama & Nanri, 1960; Robinson, 1954; Wallis, 1935). Consistent with Emmert's law this object could also appear less distant (Emmert, 1881; for a critical discussion see Epstein, Park, & Casey, 1961). Early explanations for these effects of brightness on apparent distance were based on irradiation in the ocular media or on aerial perspective (Helmholtz, 1867).

Later experiments showed that the critical variable in this context is not brightness per se but rather brightness contrast (Dresp, Durand, & Grossberg, 2002; Egusa, 1983; Farnè, 1977; Ichihara, Kitagawa, & Akutsu, 2007; O'Shea, Blackburn, & Ono, 1994; Rohaly & Wilson, 1999). Against a dark background, a brighter object appears nearer, while against a bright background, a darker object appears nearer. In other words, an object with a higher brightness contrast to the background appears to be less distant. Again, aerial perspective is a viable explanation because it reduces both the area contrast and the texture contrast (Ichihara et al., 2007; Ross, 1967). Taken together, it is important to note that the present study concerned surfaces in the context of a larger object (i.e., a room), rather than small, isolated surface patches as in the experiments on depth perception mentioned above (see also General Discussion).

EXPERIMENT 1

Judgements of ceiling height of different real-world rooms suffer from the problem that unique aspects of a given room might prohibit comparisons with rooms of different size or proportion. Also, asking observers to make height judgements in a given room while changing only the lighting might appear as a nonsensical task. Thus, within-subjects comparisons are highly problematic, unless a way is found to vary the actual height of the ceiling. In virtual reality (VR) such manipulations can be easily accomplished from one trial to the next. We took advantage of this technology to manipulate actual ceiling height and surface lightness in a sequence of fully crossed random presentations.

Method

Participants

A total of 12 observers (6 women, 6 men) with normal or corrected-to-normal vision participated voluntarily in the experiment. Their mean age was 23.9 years ($SD = 3.2$ years) with a range of 19 to 31 years.

Apparatus

A rectangular virtual room with a constant depth of 6.0 m and a constant width of 4.5 m was designed for this experiment (see Figure 1). Ceiling height was varied between 2.9 and 3.1 m. The walls as well as the ceiling and the floor were covered with a fine-grained, grey-scale texture. The lightness of these textures was varied at three levels (dark, medium, light). The room was illuminated from the direction of the observer such that the luminosity of the rear wall appeared to be roughly uniform. Slight shading gradients in the corners of the room led to a natural appearance of the scene (see Figure 2, Panel A, for an example).

The virtual room was rendered using the animation software Vizard (WorldViz, 2004) on a Pentium IV computer (Dell Precision 650) equipped with an NVIDIA Quadro4 900 XGL graphics adaptor. It was displayed on a large rear projection screen (2.60 m horizontally, 1.93 m vertically). The projection allowed for stereoscopic viewing by use of two projectors with a resolution of 1,400 × 1,050 pixels each and a colour depth of 32 bits. The light of the two projectors was linearly polarized in orthogonal planes. Participants wore matching polarization filters such that each eye received a unique image. The refresh rate of

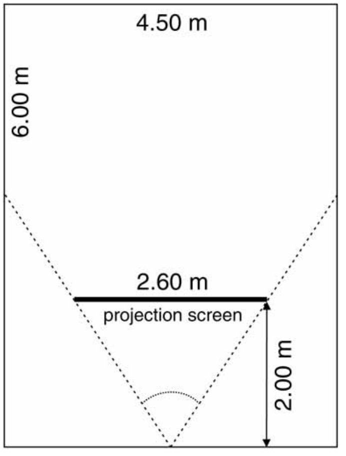

Figure 1. *Schematic top view of the virtual room used in Experiment 1. The observer was positioned at the (invisible) front wall and viewed the room through the projection screen (the viewing angle is depicted by dotted lines).*

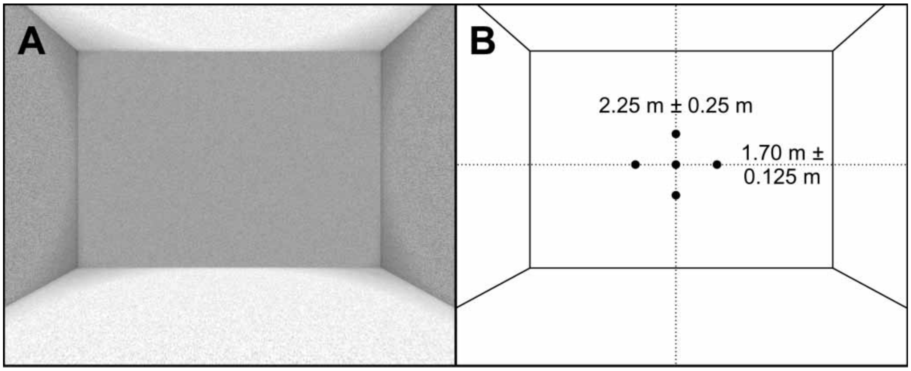

Figure 2. *A. Example stimulus used in Experiment 1 with medium-grey walls and light-grey ceiling and floor. The observer position corresponds to the central point in Panel B. B. Schematic illustration of the five observer positions (marked by black dots) that were used in Experiment 1. In addition to the central location, four positions were used by moving the virtual camera 0.25 m in the horizontal and/or 0.125 m in the vertical direction. The distance from the rear wall was fixed to 6.0 m.*

the display was 60 Hz for each eye, noninterlaced. Individual eye bases (interocular distances) were measured and taken into account to compute the stereoscopic disparity of the two images. We used stereoscopic viewing in order to make the scenes appear more realistic and more immersive, although recent studies by Glennerster, Tcheang, Gilson, Fitzgibbon, and Parker (2006) and Rauschecker, Solomon, and Glennerster (2006) showed that observers do not make strong use of stereo cues when judging the size of objects displayed in virtual reality. The simulated observer (i.e., the virtual camera) was placed at the invisible front wall of the virtual room with the gaze being oriented straight ahead. The camera's position in the frontoparallel plane was varied among a centred position and four displacements to the left, right, top, and bottom, respectively (see Figure 2, Panel B). These displacements of the observation point were introduced to prevent observers from using direct comparisons between successively presented rooms and thus circumvent the magnitude estimation task.

The participant was seated at a distance of 2.0 m from the projection screen. The viewing configuration was as if looking through a window sized 2.60 × 1.93 m (the dimension of the projection screen) into the virtual room (see Figure 1). The virtual position of the observer coincided with the invisible front wall of the room. A height-adjustable chair combined with a chin rest ensured that the observer's eye height was aligned with the centre of the projection screen. The horizontal and vertical viewing angles amounted to 66° and 51°, respectively.

Design and procedure

Four parameters were varied in a repeated measures design.

1. The physical height of the virtual room was varied on three levels (2.9, 3.0, or 3.1 m).
2. The room's ceiling and floor always had matching lightness: dark, medium, or light. We varied the lightness of ceiling and floor in parallel in the first experiment in order to achieve a maximum contrast between surface lightness in the "vertical" direction (ceiling and floor) and surface lightness in the "horizontal" direction (the walls).
3. The lightness of the walls was varied independently using the same factor levels of dark, medium, and light.
4. As described above, five different observer positions were used to prohibit direct comparisons between the virtual rooms across adjacent trials.

All factors were fully crossed, and the resulting 135 trials were presented in random order. On each trial, observers freely viewed the displayed room. No time limit was specified. After pressing the left mouse button, a vertically oriented judgement scale with a vertical slider appeared on the projection screen, showing estimated height in metres. Observers adjusted the slider to match the perceived height of the room within a range from 2.00 to 4.00 m in steps of 0.01 m. The slider's starting position was alternately set to either 2.00 or 4.00 m on each trial. After observers had adjusted the slider and confirmed the estimate, the next trial started. On a side note, we decided against using a forced-choice procedure because we anticipated that the direct comparison of two rooms presented on each trial might favour strategies like comparing the screen position of room edges between the two scenes (see above), rather than judging the height impression in a more holistic manner.

The experiment including three demonstration trials lasted about 40 minutes.

Results and discussion

The data were analysed via a repeated measures analysis of variance (ANOVA). The statistical results are displayed in Table 1. As shown in Figure 3, the estimated ceiling height increased with its physical height in an approximately linear manner. The effect of physical height was significant (Table 1). The effect of observer position was also significant. Inspection of the data showed that the translation of the position of the virtual observer in the vertical direction caused the effect. A lower position of the virtual observer corresponded to greater height estimates, consistent with a strategy of estimating the height of the room relative to one's eye height (Dixon, Wraga, Proffitt, & Williams, 2000; Franz, 2005; Marcilly & Luyat, 2008; Wraga, 1999). To gain further insight into the effects of physical height and observer position on the height estimates, multiple linear regression was used to predict the estimated height from physical height, the vertical position of the virtual observer, and the horizontal observer position.[1] The three independent variables (predictors) were entered simultaneously. The estimates of the regression coefficients for the fixed effects and their standard errors are displayed in Table 2. There was a significant positive relation between the height estimate and physical height and a significant negative relation between the estimate and the vertical position of the virtual observer. The intercept was not significantly different from 0, arguing against a systematic over- or underestimation of room height. Note that there was a large interindividual variation in the mean height estimates (see error bars in Figure 3). The regression coefficient for physical height (i.e., the slope of the regression line) did not differ significantly from the value of 1.0 corresponding to perfect accuracy. Taken together, these results show that the observers were indeed judging the height of the rooms and that they were capable of doing so rather consistently.

The question of primary interest in this study is of course, did ceiling/floor lightness and wall lightness also have an effect on estimated height? The effects of these two variables are displayed in Figure 4, averaged across physical height. As expected, rooms were judged as being higher if the ceiling and the floor were light rather than dark or medium-light. This effect of ceiling/floor lightness was significant (Table 1). With dark or medium-light walls, the height estimates obtained with dark ceiling/floor were virtually identical to the height estimates obtained with medium-light ceiling/floor. With light walls, however, observers judged the rooms as being higher if the ceiling and the floor were dark rather than medium light. However, the Ceiling/Floor Lightness × Wall Lightness interaction was not significant.

Unexpectedly, the height estimates showed a significant increase (Table 1) with wall lightness

[1] Due to the repeated measures structure of the data, a subject-specific, random-effects model approach was used (SAS PROC MIXED; cf. Burton, Gurrin, & Sly, 1998; Liang & Zeger, 1993). Subject-specific models assume regression parameters (i.e., intercept and slope) to vary from subject to subject. Random-effects models belong to the class of subject-specific models and model the correlation structure by treating the subjects as a random sample from a population of all such subjects. In the analysis, the variance–covariance matrix was specified as being of type "unstructured" (UN)—that is, the procedure placed no constraints on the correlations across observations within one subject.

Table 1. *Results of the repeated measures ANOVA conducted for the height estimates from Experiment 1*

Source	*df source*	*df error*	*F*	*p*	*Partial* η^2	$\tilde{\epsilon}$
Physical height (PH)	2	22	19.46**	**.001**	.64	.78
Ceiling/floor lightness (CFL)	2	22	8.80**	**.002**	.44	.97
Wall lightness (WL)	2	22	4.67*	**.024**	.29	1.0
Observer position (OP)	4	44	12.57**	**.001**	.53	.70
CFL × WL	4	44	0.43	.662		

Note: ANOVA = analysis of variance. A univariate approach (see Keselman, Algina, & Kowalchuk, 2001) with Huynh–Feldt correction for the degrees of freedom (*df*) was used (Huynh & Feldt, 1976), and the value of $\tilde{\epsilon}$ is reported. The within-subjects factors were physical height (PH; 2.9, 3.0, 3.1 m), ceiling/floor lightness (CFL; dark, medium, light), wall lightness (WL; dark, medium, light), and observer position (OP; five levels, see Method section). Partial η^2 is reported as a measure of association strength. Only effects discussed in the text are displayed. The remaining effects were not significant ($p > .05$). Bold *p*-values indicate significant effects.
$^*p < .05$. $^{**}p < .01$.

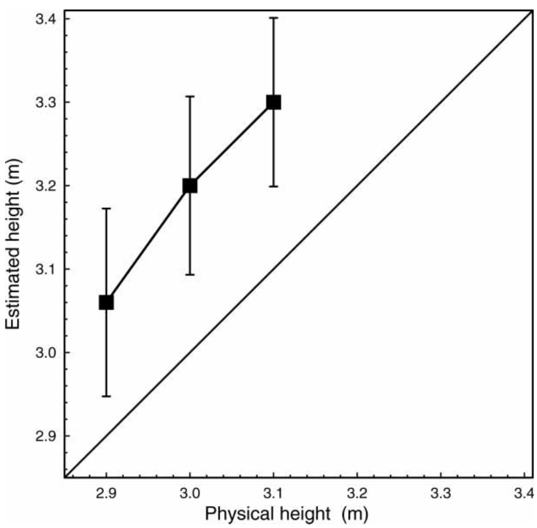

Figure 3. *Experiment 1. Mean estimated ceiling height as a function of physical height. Error bars show ±1 SEM of the 12 individual estimates.*

Table 2. *Experiment 1: Summary of the multiple regression analysis on estimated height*

Predictor	*B*	*SE*	*t(11)*	*p*
Intercept	−0.49	0.793	0.61	.55
Physical height	**1.22**	0.253	4.84**	<.001
Observer's horizontal position	0.001	0.044	0.03	.98
Observer's vertical position	**− 0.72**	0.158	4.57**	<.001

Note: Predictor variables: physical height, horizontal position of the virtual observer, and vertical position of the virtual observer. A random-effects model with an unstructured variance–covariance matrix was used. All predictors were entered simultaneously. Coefficients significantly different from zero are displayed in bold font.
$^*p < .05$. $^{**}p < .01$.

(see Figure 4). Do the data provide evidence for the presumed role of the lightness contrast between walls and ceiling (Neufert & Kister, 2005)? If the perceived height was indeed maximal for ceilings that are lighter than the walls, then a room with medium-light ceiling/floor and dark walls should have appeared higher than a room with the same ceiling/floor lightness combined with light walls. Our data are not consistent with this pattern but instead indicate a roughly additive effect of wall lightness and ceiling lightness.

Could the effect of wall lightness be due to a simultaneous lightness contrast (e.g., Helmholtz, 1867, p. 388–397) that made the ceiling appear lighter before a dark background as opposed to a light background?[2] Such a contrast effect is possible although unlikely due to large visual separation between ceiling and walls. However, it should produce the opposite pattern of results. If the perceived ceiling lightness was the critical variable determining perceived height, and if wall

[2] We are grateful to an anonymous reviewer for pointing out this possibility.

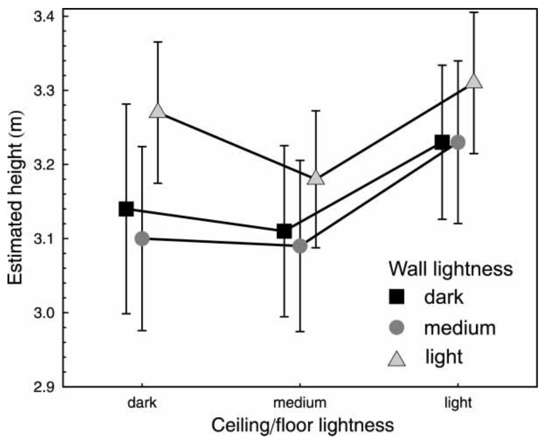

Figure 4. *Experiment 1. Mean estimated ceiling height as a function of ceiling/floor lightness and wall lightness. Black boxes: dark walls. Dark-grey circles: medium-light walls. Light-grey triangles: light walls. Error bars show* ± 1 SEM *of the 12 individual estimates.*

lightness were to exert an indirect effect via a lightness contrast, then the rooms should have appeared higher with dark rather than with light walls. The opposite was the case. Thus, a simultaneous lightness contrast between the ceiling and the walls cannot account for the observation that perceived height increased with wall lightness.

From trial to trial, the initial position of the slider used for obtaining the height estimates had alternated between 2.00 m and 4.00 m. The average estimated height was 3.17 m (standard deviation $SD = 0.34$ m) in the former and 3.20 m ($SD = 0.38$ m) in the latter condition, $t(11) = 1.29$, $p = .22$. Thus, no effect of initial slider position was found.

In sum, lighter ceilings do increase judged height as expected by the design experts. In addition, lighter walls also increase judged ceiling height. The latter effect has escaped the design experts.

EXPERIMENT 2: INDEPENDENT VARIATION OF FLOOR AND CEILING LIGHTNESS

Experiment 1 partly corroborated the assumed effects of surface lightness on apparent height by demonstrating that the perceived height increases with ceiling/floor lightness. However, the data from Experiment 1 do not allow a decision about whether the effects of ceiling/floor lightness on the height estimates were caused by ceiling lightness, floor lightness, or a combination of both because the two surfaces were always matched in lightness. Therefore, floor lightness and ceiling lightness were varied independently in Experiment 2. We expected the ceiling lightness to have a stronger effect on height estimates than the floor lightness, based on the assumption that the observers considered the distance of the ceiling from their eye height when making the height estimates. Note that the effect of the virtual position of the observation point in the regression analysis reported above provided evidence for such a strategy in Experiment 1. If observers reference perceived height with respect to their felt eye-height without looking at the floor, then floor lightness should be irrelevant. If on the other hand, perceptual floor position is used for this reference, then floor lightness should have an effect. Lighter floors should appear farther away, just as lighter ceilings do.

An additional question addressed in Experiment 2 is related to the observation of a roughly additive effect of ceiling/floor lightness and wall lightness on the height estimates in Experiment 1. One potential explanation would be that the perceived height increases with increases in the overall brightness of a room. Again, varying the lightness of ceiling and floor independently allowed us to test this hypothesis. If the overall brightness was the critical factor, then a light ceiling combined with a dark floor should result in the same perceived height as a dark ceiling combined with a light floor because the overall brightness is identical in these two situations.

Method

Participants

A total of 20 observers (14 women, 6 men) with normal or corrected-to-normal vision participated voluntarily in the experiment. Their mean age was 22.7 years ($SD = 3.53$ years) with a range of 17 to 33 years.

Apparatus
The same apparatus and basic configuration of the virtual rooms as those in Experiment 1 were used.

Design and procedure
The design involved three within-subjects factors:

1. The physical height of the virtual room was varied at three levels (2.9, 3.0, or 3.1 m).
2. The lightness of the ceiling had three levels (dark, medium, or light).
3. The lightness of the floor was varied independently using the same factor levels.

The lightness of the walls was fixed at a medium level. The three factors were fully crossed, and each of the 27 factorial combinations (Height × Ceiling Lightness × Floor Lightness) was presented three times. The order of presentation was randomized. Essentially the same procedure as that in Experiment 1 was used. The observers made their height estimates using the same vertical slider presented on the screen. The starting position (2.00 m or 4.00 m) of the slider alternated from trial to trial. The position of the virtual observer was varied randomly from trial to trial, within a range of ±19 cm in the horizontal and of ±13 cm in the vertical direction, in 0.5-cm steps.

The experiment including four demonstration trials lasted approximately 40 minutes.

Results and discussion

The individual data obtained in each experimental condition were aggregated across trial repetitions, and the resulting data were analysed via a repeated measures ANOVA using a multivariate approach. The within-subjects factors were physical height, ceiling lightness, and floor lightness. The ANOVA results are displayed in Table 3.

As can be seen in Figure 5, the significant effect of physical height again indicated that observers were indeed judging the height of the room (Table 3).

As expected, the rooms appeared higher when the ceiling was light rather than medium light (Figure 6), confirming the results from Experiment 1. This effect of ceiling lightness was significant (Table 3). Descriptively, the dark floor resulted in higher estimates than the lighter floors (Figure 7), but the effect of floor lightness was not significant. Thus, ceiling lightness, but not floor lightness, influenced the perceived room height.

There was a significant Height × Floor Lightness interaction (Table 3). This effect might be traceable to the stronger effect of floor lightness at low physical height (Figure 7).

Table 3. *Results of the repeated measures ANOVA conducted for the height estimates from Experiment 2*

Source	*df source*	*df error*	*F*	*p*	*Partial* η^2
Physical height (PH)	2	18	18.61**	**.001**	.67
Ceiling lightness (CL)	2	18	4.46*	**.027**	.33
Floor lightness (FL)	2	18	0.44	.651	.05
PH × FL	4	16	3.51*	**.031**	.47

Note: ANOVA = analysis of variance. A multivariate approach was used. The remaining effects were not significant ($p >$ .18). Bold p-values indicate significant effects.
$^*p < .05$. $^{**}p < .01$.

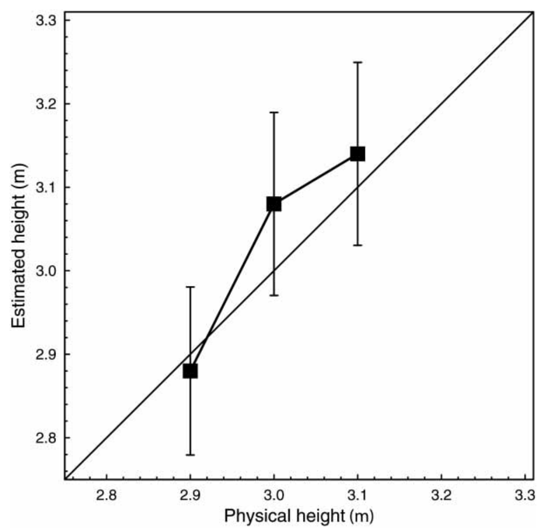

Figure 5. *Experiment 2. Mean estimated height as a function of physical height. Error bars show* ±*1* SEM *of the 20 individual estimates.*

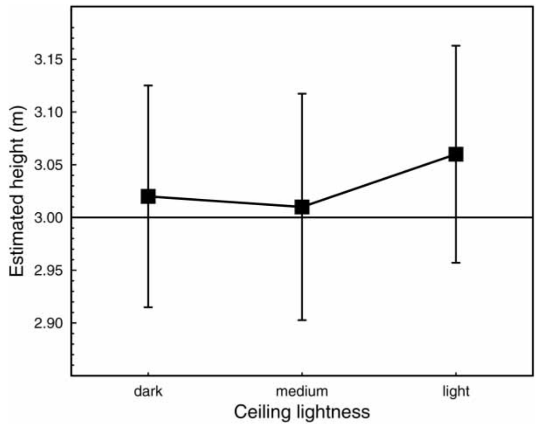

Figure 6. *Experiment 2. Mean estimated height as a function of ceiling lightness. Error bars show* ± 1 SEM *of the 20 individual estimates.*

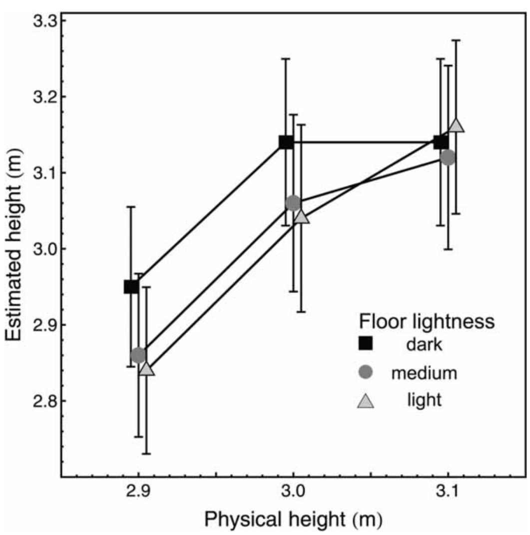

Figure 7. *Experiment 2. Mean estimated height as a function of floor lightness and physical height. Black boxes: dark floor. Dark-grey circles: medium-light floor. Light-grey triangles: light floor. Error bars show* ± 1 SEM *of the 20 individual estimates. (Symbols are slightly shifted on the horizontal axis in order to avoid overlapping error bars.)*

However, we have no convincing explanation for this effect. The remaining effects were not significant ($p > .18$).

Can the results be explained in terms of the total brightness hypothesis? Recall that according to this hypothesis, rooms with the same combination of ceiling and floor lightness (e.g., one dark and one light surface) should appear identical in height, regardless of whether it is the ceiling or the floor that is lighter. Figure 8, Panel A, shows mean height estimates for all conditions where the floor and the ceiling differed in lightness. Descriptively, the results speak against the total brightness hypothesis, as on average the estimated height was greater when the ceiling (discs with lighter upper half) rather than the floor (discs with lighter lower half) was the lighter surface, while the surface lightness combination had essentially no effect. A repeated measures ANOVA (multivariate approach) with the within-subjects factors physical height, surface lightness combination, and position of the lighter surface (floor or ceiling) did not reveal a statistically significant effect of lightness combination, $F(2, 18) = 0.29$, $p = .75$, providing evidence against the total brightness hypothesis. On the other hand, the effect of the position of the lighter surface failed to reach significance, $F(1, 19) = 2.75$, $p = .114$. Note, however, that we were testing an equivalence hypothesis, because the total brightness hypothesis assumes no effect of the position of the lighter surface. Commonly, only p-values exceeding .2 are regarded as clear evidence against an equivalence hypothesis (Klemmert, 2004). A potential reason for the nonsignificant effect of position of the lighter surface is a significant Physical Height × Position of the Lighter Surface interaction, $F(2, 18) = 5.31$, $p = .015$, $\eta^2 = .37$. As shown in Figure 8, Panel B, this interaction can be attributed to the fact that the estimated height differed depending on whether the floor or the ceiling were lighter at the two lower physical heights, but not at a physical height of 3.1 m. Three ANOVAs with the within-subjects factors surface lightness combination and position of the lighter surface conducted for each physical height separately showed a significant effect of position of the lighter surface at the lowest physical height, $F(1, 19) = 5.33$, $p = .032$, $\eta^2 = .22$, a marginally significant effect at the intermediate physical height, $F(1, 19) = 4.00$, $p = .060$, $\eta^2 = .17$, but no effect at the largest physical height ($p = .78$).

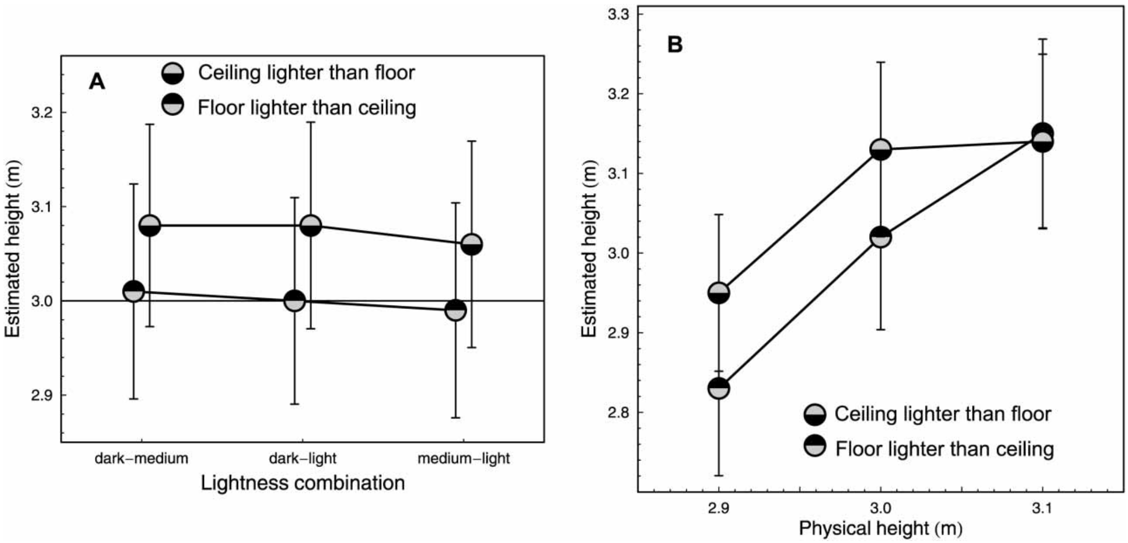

Figure 8. *Experiment 2. Panel A: Mean estimated height as a function of the combination of ceiling and floor lightness and the position of the lighter surface. Discs with lighter upper half: ceiling lighter. Disks with lighter lower half: floor lighter. Panel B: Mean estimated height as a function of physical height and the position of the lighter surface. Error bars show* ±*1* SEM *of the 20 individual estimates.*

Taken together, these results speak against the idea that the overall brightness is the critical factor determining perceived room height.

GENERAL DISCUSSION

In a recent review of research on colour in architecture and environmental design, Caivano (2006) concluded that there is a lack of communication between designers and scientists on this topic. The experiments reported here are first steps towards a better understanding of common guidelines regarding the effects of surface lightness on the perceived dimensions of rooms proposed for many decades in the applied field.

One of the basic expert assumptions was confirmed by our results: Both experiments showed an increase in the perceived height with increases in ceiling lightness. On the other hand, there were two findings not directly consistent with the predictions voiced from the field of architecture. First, the rooms also appeared higher when the lightness of the walls was increased. Second, the effects of ceiling lightness and wall lightness were roughly additive. This pattern contradicts the common assumption that the lightness contrast between the ceiling and the walls is the critical variable. Experiment 2 additionally showed that the floor lightness has essentially no effect on perceived height, and that the effects on apparent height cannot be explained by the overall brightness of a room. It remains for future experiments to test whether the brightness of the upper visual field is the main factor influencing height estimates (see Footnote 2). It would also be interesting to run a study where overall luminance is increased while all contrasts remain unchanged.

How may distance perception be involved when judging ceiling height?

As discussed in the introduction, the observation that a lighter ceiling appears higher cannot be explained in a straightforward manner with the effects of brightness on the perceived distance of small objects (e.g., Coules, 1955). Bright objects appear closer. There are several potential explanations for the diverging findings. First, it is not fully clear whether observers do indeed base their height estimates on the perceived distance between their eye height and the ceiling (Wraga, 1999), as assumed by Matusiak (2006) and as would be compatible with the effects of shifts of the observer position in the vertical direction found in Experiment 1. We discuss some alternative cues to ceiling height below.

Secondly, and more importantly, the experiments studying perceived distance or depth as a function of the brightness or the brightness contrast typically presented small objects in front of a uniform background. In our stimuli, however, the ceiling subtended a large viewing angle and was not presented on a uniform background. Thus, one could argue that the ceiling was presented before the background of the walls. Still, according to the principle that objects appear more distant if the contrast to the background is higher (e.g., Farnè, 1977), for a medium lightness of the walls, the perceived distance of the ceiling from the eye height of the observer should have been larger with a dark or light than with a medium-light ceiling. This prediction is incompatible with the roughly monotonic relation between ceiling lightness and perceived height found in Experiments 1 and 2. Thus, the effects of lightness on perceived ceiling height cannot be explained within the common framework of brightness leading to an underestimation of distance. It appears that the impression of interior space follows different laws.

Could observers have used alternative geometrical cues to judge ceiling height?

An example for an alternative cue to ceiling height might be the length of the vertical edges separating the sidewalls from the back wall. If observers had been able to isolate this cue and evaluate it in a pictorial manner, performance should have been unaffected by lightness. It is thus unclear how increases in the lightness of the ceiling and/or the walls would increase the perceived length of the vertical edge.

In a theoretically more interesting way, geometrical relations may be the basis for height estimation, and surface lightness may have modified the interpretation of spatial geometry. For instance, the perceived angles formed by the intersections of the walls in the top corners of the room might be modified by the lightness of the involved surfaces. Assuming that this angle is perceived as too obtuse on the side of the lighter surface, the height judgement might be increased as a consequence of the angle overestimation. Regardless of how convincing one may find Gregory's interpretation of the Müller-Lyer illusion (Gregory, 2005; Metzger, 1936; Ward, Porac, Coren, & Girgus, 1977), the three-dimensional position of an edge is tied to its two-dimensional shape. Unfortunately, the problem with such an explanation is that increasing ceiling lightness and wall lightness should have opposite effects. The hypothesis that lightness modifies the processing of geometric cues predicts that a light ceiling should increase its perceived height whereas a light wall should decrease perceived height. The additive positive effects of ceiling and wall lightness on perceived height are not compatible with such a hypothesis.

Also, and probably most importantly, the classical experiments relating to geometrical aspects of distance illusions typically compared the perceived distance of two small objects or object parts located on the frontoparallel plane, while we studied the perceived dimensions of a three-dimensional room. With some notable exceptions, the classical geometric illusions appear to elicit three-dimensional space rather weakly (Pike & Stacey, 1968). Thus, it appears unlikely that the lightness effects we have observed can be reduced to the intermediary action of geometric illusions.

The ability of lightness to modulate perceived height should be regarded as a phenomenon in its own right. It remains to be investigated whether the other dimension of colour, most notably the hue of the room surfaces, have an additional effect on perceived height. This should be done while controlling for lightness and saturation. These factors are typically confounded in the applied context or in popular books on colour (e.g., Heller, 2008). In studies that did control for lightness and saturation, hue by itself has been found to affect distance estimates for small objects (e.g., Egusa, 1983; Guibal & Dresp, 2004; Mount et al., 1956; Oyama & Yamamura, 1960; Taylor & Sumner, 1945; Troscianko, Montagnon, Leclerc, Malbert, & Chanteau, 1991). Red lights appear closer than green or blue lights of comparable luminance. However, hue had a smaller effect on apparent distance than lightness. If our finding that bright ceilings are judged to be higher although bright objects appear closer can be attributed to hue, we would predict that a red ceiling should appear higher as well. We are currently testing this hypothesis.

As a final note, our results suggest that the practical guidelines currently provided for choosing the colours of the walls, the ceiling, and the floor in order to make a room appear higher should be modified. A rule of thumb consistent with our data would be: "If you intend to make the room appear higher, paint both the ceiling and the walls in a light colour. You are free to choose the colour of the floor because it has no effect on the perceived height".

Original manuscript received 20 July 2009
Accepted revision received 18 January 2010
First published online 16 April 2010

REFERENCES

Ashley, M. (1898). Concerning the significance of intensity of light in visual estimates of depth. *Psychological Review*, *5*(6), 595–615.

Baird, J. C., Cassidy, B., & Kurr, J. (1978). Room preference as a function of architectural features and user activities. *Journal of Applied Psychology*, *63*(6), 719–727.

Burton, P., Gurrin, L., & Sly, P. (1998). Extending the simple linear regression model to account for correlated responses: An introduction to generalized estimating equations and multi-level mixed modelling. *Statistics in Medicine*, *17*(11), 1261–1291.

Caivano, J. L. (2006). Research on color in architecture and environmental design: Brief history, current developments, and possible future. *Color Research and Application*, *31*(4), 350–363.

Coules, J. (1955). Effect of photometric brightness on judgments of distance. *Journal of Experimental Psychology*, *50*(1), 19–25.

Dixon, M. W., Wraga, M., Proffitt, D. R., & Williams, G. C. (2000). Eye height scaling of absolute size in immersive and nonimmersive displays. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(2), 582–593.

Dresp, B., Durand, S., & Grossberg, S. (2002). Depth perception from pairs of overlapping cues in pictorial displays. *Spatial Vision*, *15*(3), 255–276.

Egusa, H. (1983). Effects of brightness, hue, and saturation on perceived depth between adjacent regions in the visual field. *Perception*, *12*(2), 167–175.

Emmert, E. (1881). Grössenverhältnisse der Nachbilder [Size ratios of afterimages]. *Klinische Monatsblätter für Augenheilkunde*, *19*, 443–450.

Epstein, W., Park, J., & Casey, A. (1961). The current status of the size−distance hypotheses. *Psychological Bulletin*, *58*(6), 491–514.

Farnè, M. (1977). Brightness as an indicator to distance: Relative brightness per se or contrast with the background? *Perception*, *6*(3), 287–293.

Franz, G. (2005). *An empirical approach to the experience of architectural space*. Dissertation, Max Planck Institute for Biological Cybernetics, Tübingen, Germany, and Bauhaus University, Weimar, Germany.

Gilchrist, A. L. (2007). Lightness and brightness. *Current Biology*, *17*(8), R267–R269.

Glennerster, A., Tcheang, L., Gilson, S. J., Fitzgibbon, A. W., & Parker, A. J. (2006). Humans ignore motion and stereo cues in favor of a fictional stable world. *Current Biology*, *16*(4), 428–432.

Gregory, R. L. (2005). The Medawar Lecture 2001: Knowledge for vision: Vision for knowledge. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1458), 1231–1251.

Guibal, C. R., & Dresp, B. (2004). Interaction of color and geometric cues in depth perception: When does "red" mean "near"? *Psychological Research*, *69*(1−2), 30–40.

Gundlach, C., & Macoubrey, C. (1931). The effect of color on apparent size. *American Journal of Psychology*, *43*, 109–111.

Heller, E. (2008). *Wie Farben wirken: Farbpsychologie, Farbsymbolik, kreative Farbgestaltung* [Effects of colours: Colour psychology, colour symbolism, and creative colour design] (4th ed.). Reinbek, Germany: Rowohlt Taschenbuch Vlg.

Helmholtz, H. (1867). *Allgemeine Encyklopädie der Physik: Vol. 9. Handbuch der physiologischen Optik* [General encyclopaedia of physics: Vol. 9. Handbook of physiological optics]. Leipzig, Germany: Voss.

Holway, A., & Boring, E. (1940). The dependence of apparent visual size upon illumination. *American Journal of Psychology*, *53,* 587–589.

Huynh, H., & Feldt, L. S. (1976). Estimation of the Box correction for degrees of freedom from sample data in randomized block and split-plot designs. *Journal of Educational Statistics*, *1*(1), 69–82.

Ichihara, S., Kitagawa, N., & Akutsu, H. (2007). Contrast and depth perception: Effects of texture contrast and area contrast. *Perception*, *36*(5), 686–695.

Keselman, H. J., Algina, J., & Kowalchuk, R. K. (2001). The analysis of repeated measures designs: A review. *British Journal of Mathematical and Statistical Psychology*, *54,* 1–20.

Klemmert, H. (2004). *Äquivalenz- und Effekttests in der psychologischen Forschung* [Tests for equivalence and effects in psychological research]. Frankfurt am Main, Germany: Lang.

Liang, K. Y., & Zeger, S. L. (1993). Regression analysis for correlated data. *Annual Review of Public Health*, *14,* 43–68.

Marcilly, R., & Luyat, M. (2008). The role of eye height in judgment of an affordance of passage under a barrier. *Current Psychology Letters*, *24*(1), 12–24.

Matusiak, B. (2004). The impact of lighting/daylighting and reflectances on the size impression of the room. Full-scale studies. *Architectural Science Review*, *47*(2), 115–119.

Matusiak, B. (2006). The impact of window form on the size impression of the room—full-scale studies. *Architectural Science Review*, *49*(1), 43–51.

Metzger, W. (1936). *Gesetze des Sehens* [Laws of vision]. Frankfurt am Main, Germany: Kramer.

Michel, L. (1996). *Light: The shape of space. Designing with space and light*. New York: Wiley.

Mount, G. E., Case, H. W., Sanderson, J. W., & Brenner, R. (1956). Distance judgment of colored objects. *Journal of General Psychology*, *55*(2), 207–214.

Neufert, E., & Kister, J. (2005). *Bauentwurfslehre* [Building design] (38th ed.). Wiesbaden: Vieweg.

O'Shea, R. P., Blackburn, S. G., & Ono, H. (1994). Contrast as a depth cue. *Vision Research*, *34*(12), 1595–1604.

Oyama, T., & Nanri, R. (1960). The effects of hue and brightness on the size perception. *Japanese Psychological Research*, *2*(1), 13–20.

Oyama, T., & Yamamura, T. (1960). The effect of hue and brightness on the depth perception in normal and color-blind subjects. *Psychologia*, *3,* 191–194.

Pike, A., & Stacey, B. (1968). The perception of luminous Muller-Lyer figures and its implications for the misapplied constancy theory. *Life Sciences*, *7*(8), 355–362.

Rauschecker, A. M., Solomon, S. G., & Glennerster, A. (2006). Stereo and motion parallax cues in human 3D vision: Can they vanish without a trace? *Journal of Vision*, *6*(12), 1471–1485.

Robinson, E. J. (1954). The influence of photometric brightness on judgments of size. *American Journal of Psychology*, *67*(3), 464–474.

Rohaly, A. M., & Wilson, H. R. (1999). The effects of contrast on perceived depth and depth discrimination. *Vision Research*, *39*(1), 9–18.

Ross, H. E. (1967). Water, fog and the size-distance invariance hypothesis. *British Journal of Psychology*, *58,* 301–313.

Society of Light and Lighting (2009). *The SLL lighting handbook*. London: Author.

Taylor, I., & Sumner, F. (1945). Actual brightness and distance of individual colors when their apparent distance is held constant. *Journal of Psychology: Interdisciplinary and Applied*, *19,* 79–85.

Troscianko, T., Montagnon, R., Leclerc, J., Malbert, E., & Chanteau, P. L. (1991). The role of color as a monocular depth cue. *Vision Research*, *31*(11), 1923–1929.

WorldViz. (2004). Vizard [Computer Software]. Santa Barbara, CA: WorldViz.

Wallis, W. (1935). The influence of color on apparent size. *Journal of General Psychology*, *13,* 193–199.

Ward, L. M., Porac, C., Coren, S., & Girgus, J. S. (1977). The case for misapplied constancy scaling: Depth associations elicited by illusion configurations. *American Journal of Psychology*, *90*(4), 609–620.

Wraga, M. (1999). The role of eye height in perceiving affordances and object dimensions. *Perception and Psychophysics*, *61*(3), 490–507.