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Visual and Postural Eye-Height Information Is Flexibly Coupled in the Perception of Virtual Environments

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We conducted two experiments to investigate how observers integrate postural and visual eye-height information when estimating the layout of interior space. In Experiment 1, we varied postural and visual eye-height information independently of each other in a virtual-reality setup. Observers estimated the width, depth, and height of simulated rooms. All dimensions were perceived as larger when the virtual visual eye-height corresponded to sitting on the floor as compared with standing upright. In contrast, the estimates remained widely unaffected by the observer's physical posture (likewise sitting vs. standing). In Experiment 2, we studied effects of the viewing condition (real vs. virtual rooms) and (in case of the virtual rooms) adaptation to congruence versus incongruence of visual and postural information. Both media yielded comparable results, which indicates that eye-height information is processed similarly in virtual and genuine reality. In addition, observers adapted to the (in)congruence of visual and postural cues. When we presented trials with congruent information first, both visual and postural cues had an effect on the estimates. However, when information was initially incongruent, observers mostly relied on visual cues, presumably relative to an internalized standard, and disregarded postural cues. Taken together, our results show that the integration of visual and postural eye-height information is situation-dependent.

Public Significance Statement

This study suggests a flexible, situation-dependent coupling of visual and postural cues in the extraction of eye-height information from a visual scene. In situations where visual and postural cues provide congruent information, humans can make use of both sources to fine-tune perceived eye-height; when, in contrast, visual and postural cues provide inconsistent information, postural information is disregarded in favor of visual information relative to an internalized, previously acquired standard. This flexible coupling of visual and postural cues is highly adaptive for dealing with unusual and ambiguous situations, such as virtual environments.

Keywords: eye-height, interior space, perceived size, posture, virtual reality

Eye-height relative to the ground plane is an important scaling variable when visually judging size and distance (Gibson, 1979; Purdy, 1958; Sedgwick, 1973, 1986; for an expert overview see Warren, 2020). In natural environments, visual cues and proprioceptive or vestibular cues usually provide the observer with consistent eye-height information. In virtual environments, however, the postural eye-height of the observer (i.e., the vertical distance of their eyes from the ground plane) often does not correspond to the visual eye-height (i.e., the simulated eye position relative to the ground plane of the virtual environment). For example, an observer could view a virtual scene on a head-mounted display (HMD) from varying simulated perspectives (e.g., standing, sitting) while remaining in a constant body position in the physical environment (e.g., sitting in a chair). Could this discrepancy change perceived spatial layout, or is perception robust across such liberties of virtual environments?

Sedgwick (1973) provided a formalization of how humans can make use of eye-height information to estimate the size and distance of distal objects. The extraction of eye-height seems to happen largely at a perceptual level and usually goes without the observer even noticing it (see Mark, 1987). In the simplified case of a flat and empty scene, the observer's eye-height (i.e., the vertical distance of their eyes from the ground plane) exactly corresponds to the horizon (dotted line in Figure 1A and 1B). In situations where the horizon is not directly visible (e.g., in an interior space; Figure 1C and 1D), one can "see" a "virtual horizon" maintaining one's line of gaze parallel to the flat ground or when moving forward. In the latter case, the focus of expansion of the optic flow is at the horizon. Note that for an object

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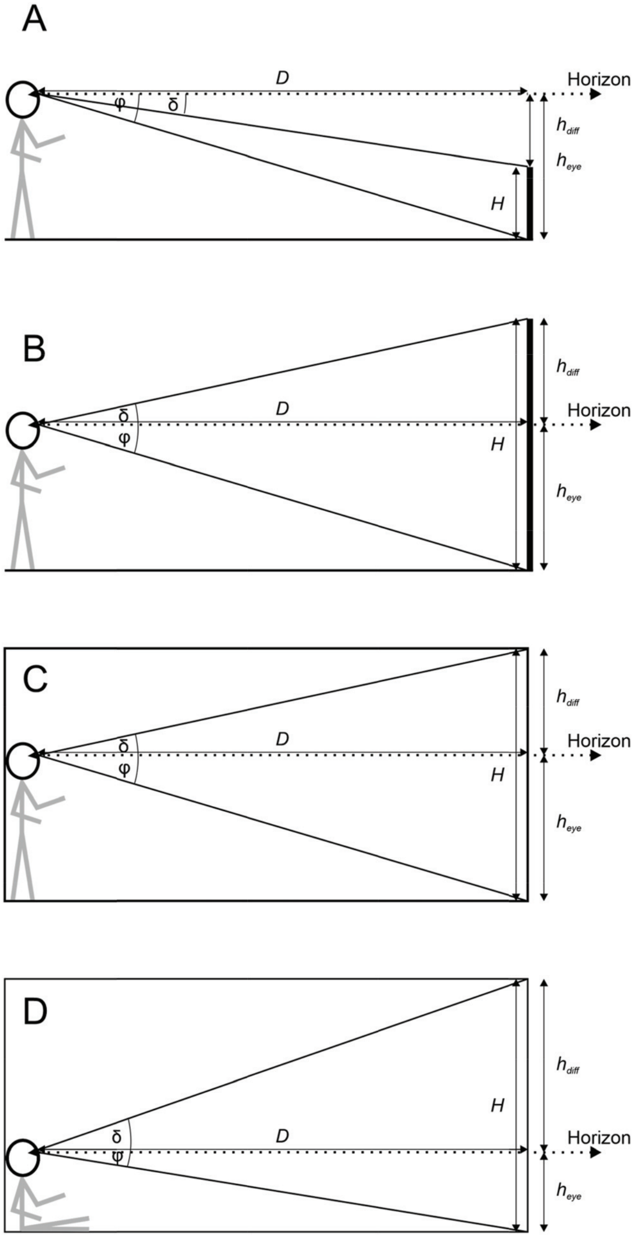
Figure 1

Perceived Distance D and Height H of an Object Shorter (A) or Taller (B) Than the Standing Observer; and Perceived Depth D and Height H of an Interior Space From a Standing Perspective (C) and a Sitting Perspective (D) as a Function of Perceived Eye-Height Above the Ground h_{eye}, Angle of Declination φ, and Angular Deviation of Object Height From Eye-Height δ



Note. The dotted line illustrates the eye-level/horizon, and h_{diff} is the difference between object height and eye-level. δ and h_{diff} are larger than zero for objects taller than the eye-level, equal to zero for objects at eye-level, and smaller than zero for objects smaller than the eye-level.

that is taller than the horizon, the horizon always divides it into equivalent portions regardless of the observer's distance from the object. The proportion of how much of the object is above versus below the visible or virtual horizon is distance-invariant, such that an observer can directly perceive the height of an object by comparing the vertical distance of the object's upper edge from the horizon to his or her eye-height. For example, an object that covers half the vertical distance between ground plane and horizon is half as tall as the observer's eye-height above the ground (Figure 1A). Sedgwick proposed that observers can use eye-height information for estimating the height of an object relative to their own eye-height. Note, that these estimations need not necessarily be accurate. The ground may not be level, or the observer may misperceive the interior horizon. Also, the perception of angular information may be subject to distortions (Durgin & Li, 2011; Li & Durgin, 2012; Li et al., 2011). According to Sedgwick's concept, the perceived height H of an object relative to the observer's perceived eye-height h_{eye} above the ground is given by

$$\frac{H}{h_{eye}} = \frac{\tan(\varphi) + \tan(\delta)}{\tan(\varphi)}, \tag{1}$$

where φ is the perceived angle of declination, and δ is the perceived angular deviation of the upper edge of the object from eye-height. When the object's upper edge is lower than eye-height, δ is negative; when the object is taller than eye-height, δ is positive. Thus, if one assumes that observers can use a reliable combination of the angular information provided in the visual scene (angles φ and δ), then they can scale the height of the object relative to their perceived eye-height. Note that the "perceived" here merely indicates that the visual system of the observer has to know or estimate his or her eye-height based on visual and/or postural cues, whereby the observer does not need to be aware of this process.

Moreover, eye-height provides distance information. An observer can estimate his or her distance to an object by taking into account the perceived eye-height h_{eye} and the perceived angle of declination φ:

$$D = \frac{h_{\text{eye}}}{\tan(\varphi)} . \tag{2}$$

It appears from the foregoing that the perception of h_{eye} is essential to scale the height and distance information included in the visual scene. Both visual (i.e., distance and slant of the ground plane) and postural cues (proprioceptive/vestibular; feedback regarding posture and body orientation relative to gravitational forces; see also Creem-Regehr et al., 2005; Stoper & Cohen, 1986) can inform h_{eye}.

In the examples shown in Figure 1, visual eye-height, as specified by optical cues, is identical to postural eye-height. This is very plausible for a natural viewing condition where a human views a visual scene with a level ground plane. Here, however, we are interested in situations where visual and postural eye-height are incongruent. An implication of the above equations is that at constant visual angles φ and δ, the perceived width, height, and distance of an object should increase as h_{eye} increases. Owing to the increase in perceived distance (Equation 2), the perceived width of an object should also be affected by a change in h_{eye} (given that the visual angles remain constant) because when subtending a constant vertical and horizontal visual angle, farther objects appear taller *and* wider (cf. Emmert, 1881). However, in natural environments, a change in postural eye-height almost invariably causes corresponding changes in visual eye-height and thus in the angles φ and δ. For instance, as shown in Figure 1, when observers inside a real room change their body posture from standing (panel C) to sitting (panel D), the visual eye-height becomes smaller and thus φ becomes smaller. At the same time it is plausible to assume that postural eye-height is updated accordingly. As a result, h_{eye} can be assumed to be precisely updated and, thus, according to Equation 2, the observer's estimate of the distance to the opposite wall should be unaffected by the change in body posture. In contrast, when visual eye-height changes independently of postural eye-height, so that h_{eye} possibly does not change in the same way as the angle φ changes because of the change in visual eye-height, this should affect the distance estimate according to Equation 2. Such a de-coupling of changes in postural eye-height and changes in visual eye-height could occur in virtual reality or in other artificial settings.

Previous studies have shown that manipulations of visual eye-height relative to postural eye-height affect perceived egocentric distance (Leyrer et al., 2011; Leyrer et al., 2015a, 2015b; Messing & Durgin, 2005; Ooi et al., 2001; Sinai et al., 1998) and size (Bertamini et al., 1998; Dixon et al., 2000; Twedt et al., 2012; Warren & Whang, 1987; Wraga, 1999a, 1999b; Wraga & Proffitt, 2000) of objects in action space (2 m up to 30 m distance from the observer; Cutting & Vishton, 1995). Compared with a condition where visual eye-height matches postural eye-height, perceived object distance increased when visual eye-height was lower than postural eye-height, whereas perceived distance decreased when visual eye-height was higher than postural eye-height. For example, using a VR setup, Leyrer et al. (2015b) varied postural cues between subjects (standing upright, sitting on a chair, or lying prone on a hospital bed) and presented the simulation of an open-field with a single target at 5 m average distance on an HMD. The visual eye-height (position of the virtual camera relative to the simulated ground plane) was varied within subjects. It either matched the postural eye-height (observer's physical eye-level relative to the ground plane of the laboratory) or was shifted by ±50 cm. Across all variations of posture, perceived target distance was highest for conditions of reduced visual eye-height (relative to postural eye-height), followed by the matched conditions, and lowest when visual eye-height was increased relative to postural eye-height.

With regard to perceived object size, Wraga (1999a, 1999b) reported a series of experiments using a partition wall with an aperture. Observers looked through the aperture at targets placed behind it on a height-adjustable floor. The aperture was constructed so that the observers could not see the ground plane directly in front of them. For this reason, the experimenter could change the height of the floor between trials unbeknownst to the observers. They reported that a 4.3- to 4.5-m distant target appeared taller when the floor was raised relative to the observer, which corresponds to a reduced visual eye-height relative to postural eye-height. In contrast, when body posture varied and visual eye-height matched postural eye-height, height estimates did not vary between a sitting and a standing observer position. Using a similar apparatus as Wraga and colleagues, Warren and Whang (1987) had already shown that observers judged a smaller passage between two adjustable partition walls to be passable when the floor behind the aperture was raised relative to the observer, as compared with when the floor was flat.

In sum, the existing research indicates that both visual and postural cues inform the perception of eye-height. When visual and postural eye-height change congruently, as is the case in the predominant number of everyday situations, the perceived size and distance of a target object remain constant. In contrast, for situations where visual and postural eye-height differ from each other, perceived target size and distance are distorted. Compared with conditions in which visual eye-height matches postural eye-height, objects appear farther away and larger when visual eye-height is lower than postural eye-height. In contrast, objects appear closer and smaller when visual eye-height exceeds postural eye-height.

Beyond this, it is an open question how to predict the distortions from the integration of postural and visual cues. Leyrer et al. (2015b) suggested a *posture updating* such that visual eye-height information is continuously processed relative to actual postural cues. In contrast, Sinai et al. (1998) formulated the idea that, particularly in unusual or ambiguous situations where visual eye-height and postural eye-height do not necessarily match, visual information might rather be scaled relative to an *internalized posture*. That is, observers have perceptually learned a typical eye-height tied to particular scenes, based on their body height and the posture they normally assume in that scene. In a given scene under conflicting eye-height information, visual information might be more likely processed relative to a higher/lower posture when such a scene is typically perceived in a standing posture/sitting posture. For example, suppose that the spatial layout of a room is typically perceived while standing. Then, in the case of conflicting visual and postural cues, visual eye-height should be scaled relative to a standing posture rather than a sitting posture, even if the observer is actually sitting. Thus, this model assumes that in situations with perceptual ambiguity, deviations of the visual information from an internalized eye-height lead to altered size and distance estimates, regardless of the actual posture of the observer.

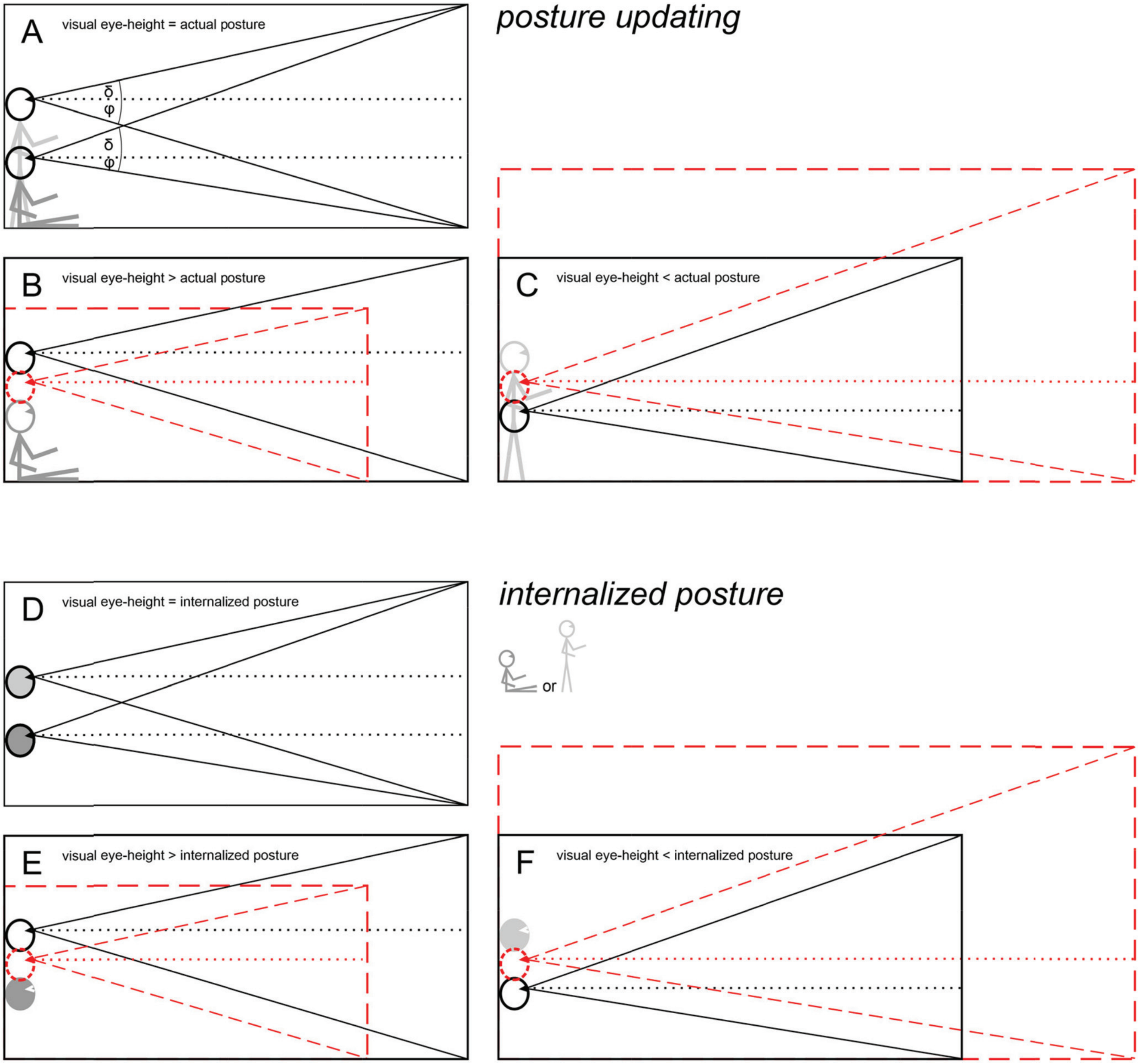
We take the notion of an *internalized posture* to have two interpretations, a strong and a weak one. The strong interpretation would claim that the visual eye-height and the internalized posture receive equal weight. Regarding our example of a standing internalized posture while estimating a room's spatial layout, this would mean an enormous increase in perceived room size when visual eye-height corresponds to a sitting posture compared with a standing posture (cf. Figure 2D and 2F). The weak interpretation, in contrast, merely predicts a bias in this direction. Given the power of visual specification (see General Discussion), we expect visual cues to dominate and thus predict biases rather than strong reliance on internalized posture.

In the following, we describe the two models in more detail. Figure 2 shows the changes in perceived eye-height and the resulting changes in the perceived spatial extent of a virtual interior space as a function of the used visual and postural information under the assumption of *posture updating* (Figure 2A–2C) and *internalized posture* (Figure 2D–2F). We now describe the predicted effects on perceived depth in detail. As outlined earlier in this article, the effects on perceived height and width can be expected to be uniform.

We first refer to the predictions derived from the *posture updating* model. In Figure 2A, the visual eye-height information in the simulated scene is identical to the actual posture of the subject in the laboratory. This situation is comparable with a natural viewing condition (see Figure 1), in which visual and postural eye-height provide congruent information. Thus, we can expect that h_{eye} and φ vary congruently as a function of actual posture. According to Equation 2, the observer's estimate of the room depth should be unaffected by a change in actual posture. Figure 2B shows a situation in which the visual eye-height exceeds the postural eye-height. For example, this would be the case when an observer is actually sitting on the floor of the real room while being presented with the simulation of an interior space from a standing

Figure 2

Predicted Perceived Eye-Height and Resulting Changes in the Perceived Extent of a Virtual Interior Space Depending on the Information Sources Used



Note. Panels A–C: Perceived eye-height as a function of visual eye-height and actual posture. Panels D–F: Perceived eye-height as a function of visual eye-height and internalized eye-height. The black solid heads indicate visual eye-height information, the stick figures indicate postural eye-height information (A–C; dark-gray = sitting, light-gray = standing), the gray filled heads (D–F) indicate internalized eye-height (dark-gray = sitting, light-gray = standing), and the red dashed heads (B, C, E, F) indicate the resulting perceived eye-height if deviant from visual eye-height. The solid rectangles show the virtual room seen from the side, and the red dashed rectangles (B, C, E, F) show predicted changes in the room's perceived layout depending on the deviation of resulting eye-height from visual eye-height. For illustration purposes, the specification of the resulting perceived eye-height (B, C, E, F) assumes that visual cues and actual or internalized posture information are equally weighted. An unequal weighting is of course conceivable. See the online article for the color version of this figure.

perspective. The integration of visual and postural eye-height information should result in a h_{eye} that is below visual eye-height information, as illustrated by the red dashed head. In this case, we can assume that h_{eye} decreases relative to the visual angle φ. According to Equation 2, the observer's estimate of the room depth should thus be smaller than in the situation with the same visual eye-height and matching visual and postural information, illustrated in Figure 2A. Conversely, when the visual eye-height is lower than the postural eye-height (Figure 2C; e.g., a standing observer views a room simulation filmed from a sitting perspective), we would expect that h_{eye} exceeds the visual eye-height, see again the red dashed head. We can thus assume that h_{eye} increases relative to φ, which, according to Equation 2, should result in a larger estimate of the room depth compared with situation with matching visual and postural eye-height information. In sum, according to the *posture updating* model, we would expect that, relative to a situation in which visual eye-height matches actual posture, the estimates of the spatial extent of a simulated interior space should increase when visual eye-height is lower than postural eye-height, and decrease when visual eye-height exceeds postural eye-height.

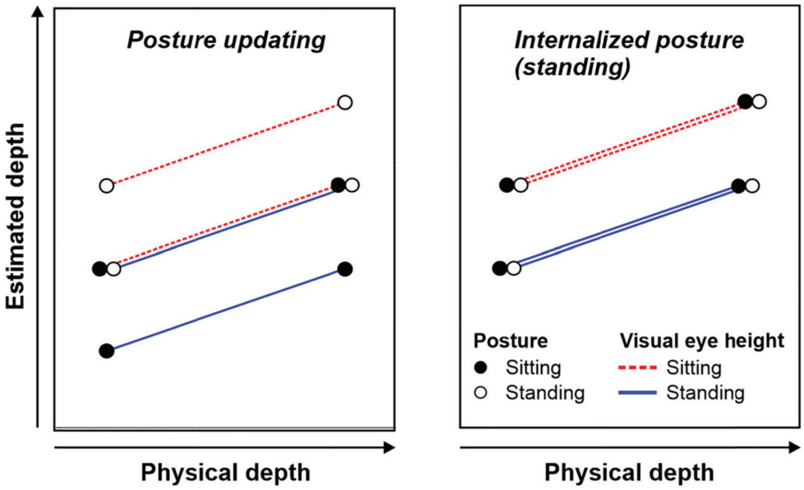
If we assume the *internalized posture* model instead (Figure 2D–2G), the predictions remain exactly the same when we substitute the actual posture with the internalized posture: If visual cues imply an eye-height above (Figure 2E)/below (Figure 2F) the internalized posture, respectively (see red dashed heads), this should lead to smaller/larger estimates compared with the estimates in a situation where visual cues correspond to the internalized posture (Figure 2D). In contrast to the predictions of the *posture updating* model, the *internalized posture* model does not include the actual body posture in the prediction of the perceived eye-height. Thus, the room size judgments should be unaffected by the postural position.

Be reminded that, under normal circumstances, posture and eye-height are tightly coupled. For such cases, where the point of observation is yoked to the head and the head to the body, the perceived layout of a visual scene should remain unaffected by changes in eye-height and both models make identical predictions. Only with special tools, such as a virtual-reality setup or a floor manipulation that goes unnoticed, can we create situations in which *posture updating* and *internalized posture* lead to different predictions.

Because none of the previous studies has independently varied visual eye-height and postural eye-height within subjects, it is currently unknown how observers integrate different sources of eye-height information depending on their availability or ambiguity. More precisely, previous studies have been limited to varying the visual eye-height information relative to a constant body posture. However, to answer the question to what extent the actual posture is taken into account in the perception of eye-height, or to what extent an internalized posture is taken as a reference instead, the actual postural eye-height and the visual eye-height must be varied independently. Only in this case do the predictions differ depending on whether we assume *posture updating* (Figure 3, left panel) or *internalized posture* (Figure 3, right panel). Figure 3 juxtaposes the predictions of the two models, for the example of perceived depth, as a function of visual eye-height and postural eye-height. Under the assumption of *posture updating*, for a given visual eye-height, we would expect larger estimates when the posture is standing (unfilled dots) compared with sitting (filled dots); for illustration refer back to Figure 2B and 2C. In addition, the estimates should remain unaffected by the manipulations of visual eye-height, provided postural eye-height matches visual eye-height. Under the assumption of an *internalized posture*, the estimates should be consistently larger for a sitting visual eye-height (red dashed lines) compared with a standing visual eye-height (blue solid lines) and largely uninfluenced by posture. When body posture is held constant, say sitting, and only visual eye-height is varied (corresponding to a consideration of only the filled dots in

Figure 3

Illustration of the Patterns Predicted by the Two Models (for Perceived Depth Only, Effects for Perceived Height and Width Are Analogous) as a Function of Posture and Visual Eye-Height, Provided the Two Are Dissociated



Note. The left panel shows the predicted pattern for posture updating, and the right panel shows the predicted pattern for internalized posture. Here we assume that a standing posture is internalized. For a sitting internalized posture, the order of the predicted values in the right panel would remain unchanged and the whole pattern would be shifted vertically such that the solid blue lines are at the level of the lower solid blue line in the left panel. See the online article for the color version of this figure.

Figure 3), as was the case in previous research, both models agree that a lower visual eye-height is associated with larger estimates.

To fill this gap, in the present study we conducted two experiments in which we varied visual and postural eye-height information independently of each other to examine in more detail how observers update and integrate visual and postural eye-height information in the perception of the layout of a scene under both matched and mismatched visual and postural eye-height information.

Experiment 1: Independent Variation of Visual and Postural Eye-Height Information

In Experiment 1, we used a VR setup to vary posture (sitting on the floor, standing upright) and visual eye-height (corresponding to a sitting or standing posture) independently of each other. Subjects estimated the width, depth, and height of virtual interior spaces under all of the four possible combinations of postural and visual eye-height. Based on Sedgwick's (1973) eye-height model, we derived different predictions depending on whether observers use *posture updating* or rely on *internalized posture*.

As depicted in Figure 2A, the *posture updating* model predicts no changes in the perceived size of the virtual rooms effected by changes in the observer's eye height in case visual and postural eye-height are identical. In contrast, the model predicts underestimation of spatial extent when visual eye-height is higher than postural eye-height (Figure 2B), and overestimation of spatial extent when visual eye-height is lower than postural eye-height (Figure 2C). Thus, in a given scene, the perceived spatial layout should not depend on visual eye-height per se but rather on the ratio of visual eye-height and postural eye-height (see also left panel of Figure 3).

The *internalized posture* model also predicts no changes in the perceived size of the virtual rooms effected by changes in the observer's visual eye-height when visual and internalized eye-height are matched (Figure 2D), but underestimation when visual eye-height exceeds internalized eye-height (Figure 2E), and overestimation of spatial extent when visual eye-height is below internalized eye-height (Figure 2F), largely independent of a variation of posture. Since *internalized posture* (e.g., sitting or standing; see Figure 2D) should be constant for a given scene, visual eye-height should uniformly influence the perceived spatial layout across all postures, in the sense that a lower visual eye-height should result in larger estimates than a higher visual eye-height (see also right panel of Figure 3).

Method

Ethics Statement

All experiments of this study were conducted in accordance with the Declaration of Helsinki. The study was approved by the Institutional Review Board of the Department of Psychology at the Johannes Gutenberg-Universität Mainz (approval number 2016-JGU-psychEK-012).

Participants

Thirty-one observers (24 women and 7 men), aged from 18 to 32 (*M* = 23.39 years, *SD* = 3.03 years), participated voluntarily in Experiment 1. All participants gave their written informed consent. They were uninformed about the objective of the experiment. Before the experiment, potential risks were explained to the participants. After the experiment, they were debriefed about the intention of the experiment.

All participants were familiar with the metric system and had normal or corrected-to-normal visual acuity and normal stereoscopic acuity. Note that eyeglass wearers were excluded from participation because of the limited space available inside the HMD. The visual acuity of all participants was 1.00 (Snellen fraction 6/6) or better, as confirmed by the Freiburg Visual Acuity test (FrACT; Bach, 1996). 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, at least six of the nine trials had to be answered correctly to qualify for participation.

A power analysis (power = 80%, α-level = 5%) with G*Power 3.1 (Faul et al., 2009) confirmed that the sample size was sufficient to detect a medium-sized effect, Cohen's (1988) $d_z = 0.5$, of visual and/or postural eye-height (see Figure 3). Owing to the substantial experimental variation, we expected at least medium effect sizes for visual and postural eye-height, if observers take these parameters into account in the perception of a room's spatial layout.

Stimuli and Apparatus

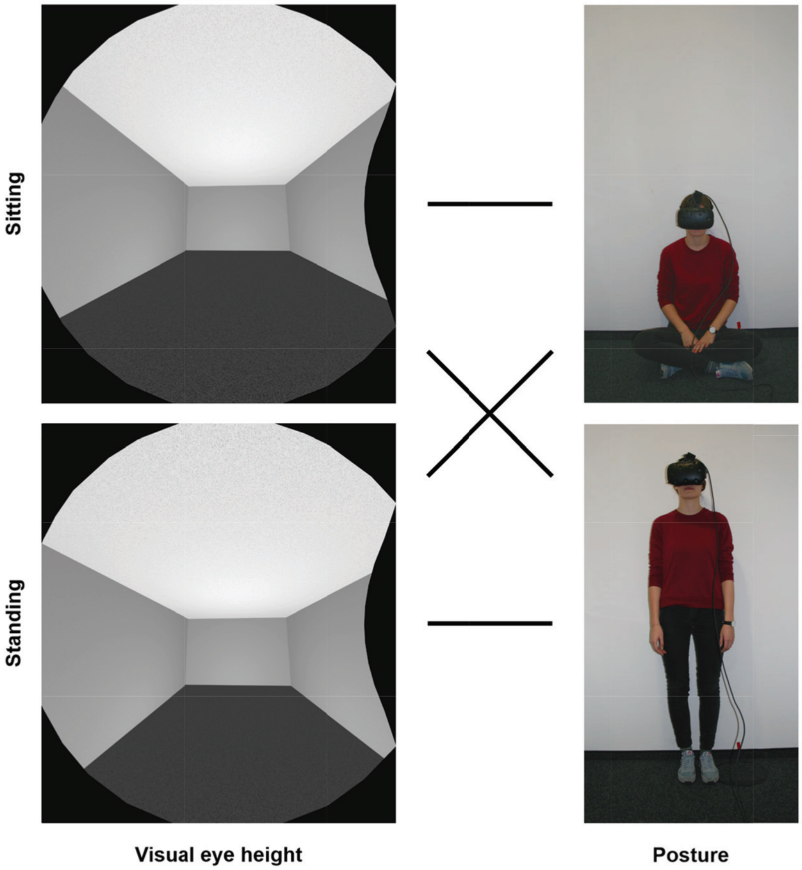
On each trial, we presented one rectangular room stereoscopically using an HMD (HTC Vive). We used the head-tracking of the HMD such that observers could dynamically explore the room by means of head movements. Between trials, we varied the visual eye-height of the observer such that the position of the virtual camera corresponded to the observer's physical eye-height when sitting on the floor or when standing upright. To this end, before the experiment, we measured each observer's physical eye-height in standing and sitting posture. In addition, the postural eye-height of the observer in the laboratory was varied between blocks. Observers were sitting on the floor in one half of the blocks and standing upright in the other half. Thus, visual eye-height and postural eye-height were either congruent (visual sitting – postural sitting, visual standing – postural standing) or incongruent (visual sitting – postural standing, visual standing – postural sitting). Figure 4 illustrates the variation of visual and postural eye-height.

We additionally varied the physical size of the room dimensions. In trials where the width was varied (width trials; 4.20, 4.50, and 4.80 m), depth and height were set constant at the medium values of 6.00 m and 2.90 m, respectively. When the depth was varied (depth trials; 5.70, 6.00, and 6.30 m), width and height were set constant at the medium values (4.50 m and 2.90 m, respectively). When the height was varied (height trials; 2.60, 2.90, and 3.20 m), width and depth were set constant at the medium values (4.50 m and 6.00 m, respectively; see Figure 5). All rooms had a light-gray ceiling, medium-gray walls, and a dark-gray floor. The surfaces were overlaid with a fine-grained texture and illuminated by means of an invisible light source positioned at the center of the room.

The observer's virtual position remained constant at 20 cm in front of the simulated room's front wall, horizontally centered between the left and the right side wall (see Figure 2). During the experiment, subjects were leaning with their back against a wall of the laboratory, either standing upright or sitting on the floor. The geometric field of view (gFOV; enclosed visual angle of the projection) was approximately 110° horizontally × 110° vertically.

Figure 4

Experiment 1: Independent Variation of Visual Eye-Height (Sitting, Top Left; Standing, Bottom Left) and Posture (Sitting, Top Right; Standing, Bottom Right)



Note. Congruent combinations of visual and postural eye-height are marked by horizontal lines, incongruent combinations are marked by diagonal lines. The screenshots on the left show example displays presented to the left eye. See the online article for the color version of this figure.

The virtual field of view (vFOV; visible area of the simulated room) corresponded to the gFOV.

The stimuli were generated using Vizard 5 (WorldViz, 2016) on an Intel Xeon E5 workstation with an NVIDIA QuadroM5000 graphics card and presented on an HTC Vive. The HMD had a resolution of 1,080 × 1,200 pixels per eye (horizontal × vertical), a color resolution of 8 bits per channel, and a refresh rate of 90 Hz. The individual interpupillary 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.

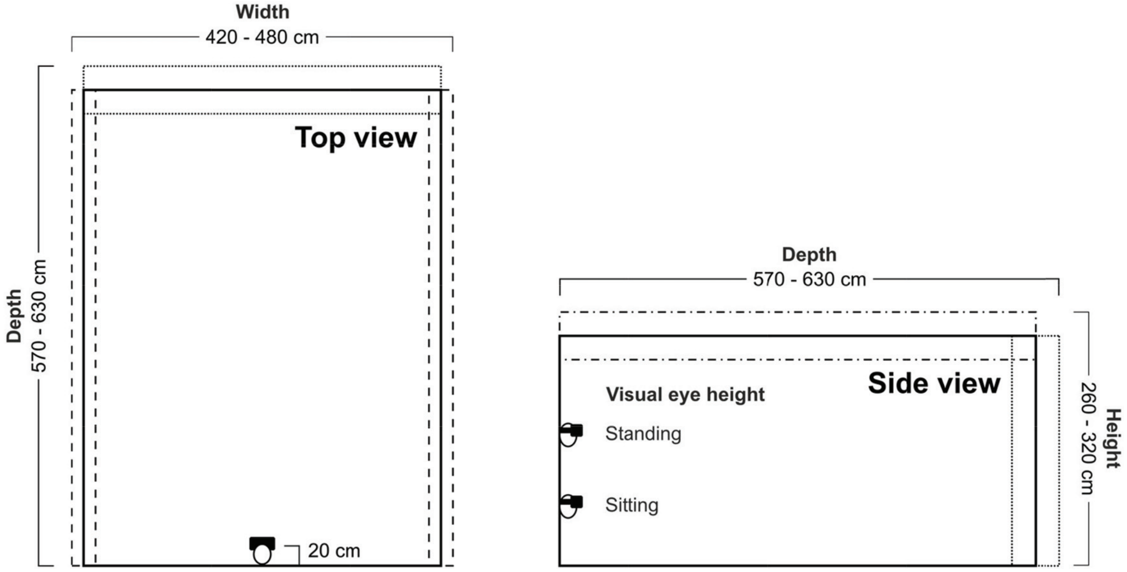
Design and Procedure

Subjects estimated the width (width trials), depth (depth trials), and the height (height trials) of the simulated rooms in each one third of the trials. On each trial, the room was first presented for 5 seconds and then a small text box asking for the estimated width/depth/height of the room was shown in the top center of the display. The simulated room was presented until the subject provided a verbal estimate in units of meters and centimeters. No time limit was given for the response. The experimenter entered the estimate using the computer keyboard and then advanced to the next trial. Note that we have validated this estimation procedure across several studies from our lab (Oberfeld & Hecht, 2011; Oberfeld et al., 2010; von Castell et al., 2014; von Castell et al., 2018a, 2018b, von Castell et al., 2020). A comparison with data from a visual matching task is provided in von Castell et al. (2017); for a more detailed discussion of the appropriateness of this procedure, see von Castell et al. (2020).

The initial block type (sitting vs. standing posture) was balanced between subjects and sessions. In session 1, half of the subjects started with sitting posture, the other half with standing posture. In session 2, this order was reversed. Subjects, who had started with sitting posture in session 1, started with standing posture in session 2, and vice versa. In each block, we presented trials for each of the three judged dimensions (width, depth, or height trials), each type combined with all of the three corresponding physical room sizes. Each of the resulting nine combinations of judged dimension and room

Figure 5

Experiment 1: Top View (Left-Hand Side) and Side View (Right-Hand Side) of the Observer's Virtual Position Relative to the Simulated Rooms



Note. The variation of the room's physical size is indicated by the dashed (width), dotted (depth), and dashed-dotted (height) lines.

size was presented with two different visual eye-heights (sitting, standing). Each of the resulting 18 conditions was presented three times per block. The experiment consisted of two sessions of two blocks each (one with sitting, the other with standing posture), such that each of the 36 experimental conditions (visual eye-height × posture × physical size × judged dimension) was presented six times to each participant.

In session 1, prior to the two test blocks, subjects completed nine training trials (three width, depth, and height trials each; drawn at random from the six combinations per judged dimension). The training trials were not taken into account in the data analyses. The time interval between sessions 1 and 2 was minimally 1 hr and maximally 1 week. In total, the experiment consisted of 216 trials and lasted approximately 100 min (60 min for session 1 and 40 min for session 2).

Subjects were tested individually in a dimly lit rectangular room with approximately 11.50 m^2 surface area and 2.64 m ceiling height. Because of the use of the HMD, the office room was not visible to the participants during the trials.

Results and Discussion

We analyzed the subjects' mean estimates in the 36 experimental conditions, averaged across the six repetitions per condition. Individual means were corrected for outliers using a Tukey criterion. Estimates more than three times the interquartile range lower than the first quartile or higher than the third quartile were classified as outliers and excluded from further analyses. This affected only 30 of the 6,696 estimates (.4%).

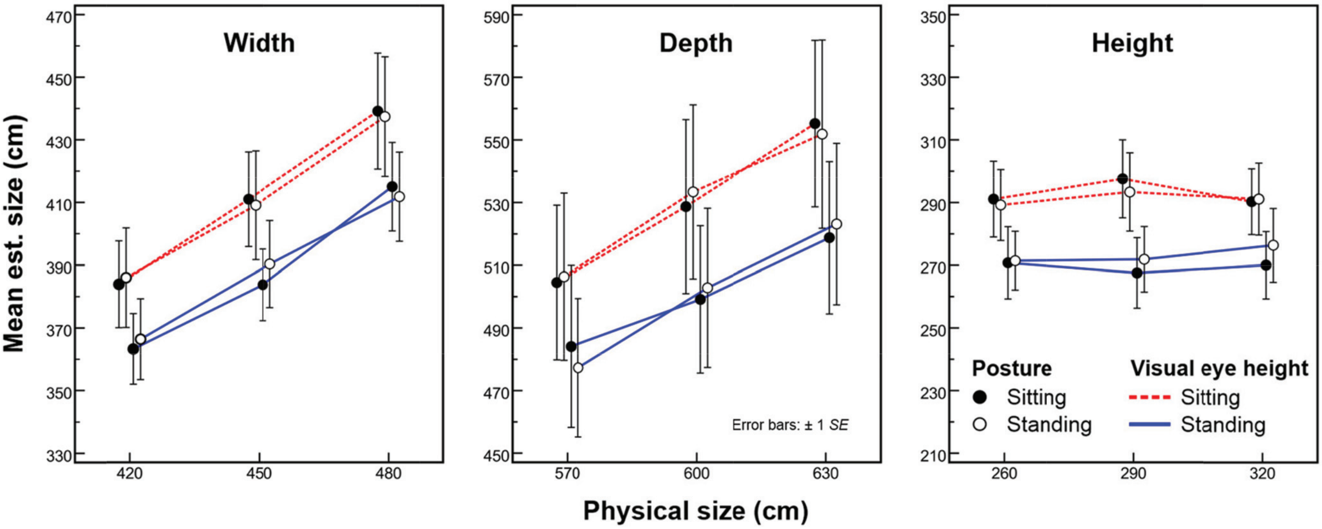
Figure 6 shows the mean width (left panel), depth (middle panel), and height (right panel) estimates as a function of visual eye-height, posture, and physical size. We computed a visual Eye-Height × Posture × Physical Size MANOVA (doubly multivariate repeated-measures analysis of variance) with the mean width, depth, 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 ε).

As can be seen in Figure 6, on average, all room dimensions were estimated larger in extent when the visual eye-height was sitting compared with standing. The MANOVA showed a significant effect of visual eye-height, $V = .39$, $F(3, 28) = 5.91$, $p = .003$. According to the post hoc rmANOVAs, visual eye-height had a significant influence on the width, depth, and height estimates, $F(1, 30) = 4.78$, $p = .001$, $\eta_p^2 = .32$, $F(1, 30) = 7.90$, $p < .001$, $\varepsilon = .38$, and $F(1, 30) = 4.01$, $p = .002$, $\eta_p^2 = .27$, respectively. To analyze the effect of visual eye-height in more detail, we calculated paired-samples t tests (two-tailed) for the comparisons of sitting visual eye-height with standing visual eye-height separately for each estimated dimension and physical size, averaged across the two levels of posture. We corrected for multiple testing on each dependent variable using the Hochberg (1988) procedure. All comparisons were significant, $t(30) \geq 2.62$, $p \leq .014$. The effect sizes were $.57 \leq$ Cohen's (1988) $d_z \leq .65$ for the width estimates, $.62 \leq d_z \leq .83$ for the depth estimates, and $.47 \leq d_z \leq .69$ for the height estimates, indicating a medium effect of visual eye-height on the perceived spatial extent of the virtual rooms.

In contrast, the multivariate effect of posture was clearly not significant, $V < .01$, $F(3, 28) = .02$, $p = .996$. The post hoc rmANOVAs confirmed the null effect of postural eye-height on the width, depth, and height estimates, $F(1, 30) = .05$, $p = .827$, $\eta_p^2 < .01$, $F(1, 30) = .02$, $p = .884$, $\eta_p^2 < .01$, and $F(1, 30) = .05$, $p = .828$, $\eta_p^2 < .01$, respectively. Parallel to the analysis of visual eye-

Figure 6

Experiment 1: Mean Width (Left), Depth (Middle), and Height (Right) Estimates as a Function of Visual Eye-Height, Posture, and Physical Size of the Judged Dimension



Note. Error bars show ±1 standard error of the mean (*SEM*) of the 31 individual estimates in each condition. See the online article for the color version of this figure.

height, we calculated paired-samples *t* tests (two-tailed) for the comparisons of sitting postural eye-height with standing postural eye-height, separately for each estimated dimension and physical size, averaged across the two levels of visual eye-height. None of these comparisons was significant, $t(30) \leq .59$, $p \geq .578$, $d_z \leq .11$. In the MANOVA, none of the interactions involving posture was significant, p values $\geq .363$. In particular, the effect of visual eye-height remained largely unaffected by the variation of posture, $V = .11$, $F(3, 28) = 1.11$, $p = .363$.

As shown in Figure 6, the perceived width increased with increasing physical width and the perceived depth increased with increasing physical depth, whereas the perceived height was largely unaffected by the manipulations of physical height. The MANOVA showed a significant main effect of physical size, $V = .82$, $F(6, 25) = 19.38$, $p < .001$. The post hoc rmANOVAs indicated a significant effect on perceived width, $F(2, 60) = 87.07$, $p < .001$, $\eta_p^2 = .74$, $\varepsilon = .67$, and perceived depth, $F(2, 60) = 54.28$, $p < .001$, $\eta_p^2 = .64$, $\varepsilon = .68$, but not on perceived height, $F(2, 60) = .77$, $p = .456$, $\eta_p^2 = .025$, $\varepsilon = .90$.

In the MANOVA, the visual Eye-Height × Physical Size interaction just missed significance, $V = .36$, $F(6, 25) = 2.38$, $p = .059$. According to the post hoc rmANOVAs, this interaction can be mainly attributed to perceived height, $F(2, 60) = 4.74$, $p = .024$, $\eta_p^2 = .14$, $\varepsilon = .69$. As can be seen in the right panel of Figure 6, the difference in perceived height attributable to the variation of visual eye-height was somewhat larger for the medium high ceiling compared with the low and high ceilings. Note that the direction of the effect of visual eye-height on estimated height did not change as a function of physical size. Rooms seen from the sitting perspective were consistently perceived higher compared with the standing perspective. The effect of visual eye-height on the width and depth estimates remained mostly consistent across the variations of physical size, $F(2, 60) = .59$, $p = .554$, $\eta_p^2 = .02$, $\varepsilon = .98$ and $F(2, 60) = 1.79$, $p = .177$, $\eta_p^2 = .06$, $\varepsilon = .96$, respectively. In the MANOVA, all remaining effects were not significant, p values $\geq .56$.

Taken together, our data show a consistent effect of visual eye-height on the perceived extent of interior space. When the displays showed the room from a sitting perspective, the rooms appeared wider, deeper, and higher compared with when the visual simulations corresponded to a standing perspective, largely unaffected by the variation of the posture of the observer and the physical size of the estimated dimension. In addition, we found that, contrary to the estimates for depth and width, the observers did not pick up the manipulation of room height. We did not expect this because it has been shown that observers are rather sensitive to changes in simulated room height when visual eye-height matches postural eye-height (von Castell et al., 2017). We assume that this finding is due to the independent variation of visual and postural cues. The manipulation of visual eye-height produced much larger changes in the visual angles φ and δ compared with the relatively moderate manipulation of ceiling height. Thus, we consider it likely that the manipulation of visual eye-height in a sense masked the manipulation of room height.

How do our findings relate to the two models for the integration of visual information and posture (consult Figures 2 and 3)? The pronounced effect of visual eye-height in combination with the near-zero effect of posture clearly favors the *internalized posture* model over the *posture updating* model. Be reminded that under the assumption of *posture updating* we would have expected posture to substantially moderate the effect of visual eye-height on perceived spatial extent (see Figure 3). Thus, in a scenario where visual eye-height and postural cues provide partly incongruent information (as was the case in 50% of the trials in Experiment 1), our results suggest that the observers relied primarily on visual information and largely ignored postural cues. However, because we presented rather artificial stimuli in Experiment 1, we conducted a second experiment to rule out that the pattern of results is specific to the artificial environment. If the nonconsideration of postural information is caused by the experimental decoupling of visual and postural information rather than by peculiarities of the presentation in visual virtual reality, a change of visual eye-height accompanied by congruent posture should produce an equally stable perceived layout in a natural and a virtual environment.

Experiment 2: Effects of Visual Eye-Height as a Function of Viewing Condition

Method

In Experiment 2, we compared the effect of visual eye-height (sitting, standing) on the perceived spatial configuration of rooms across three different viewing conditions. We contrasted a natural viewing condition with full consistency of visual eye-height and body posture in real interior spaces with two VR viewing conditions, one with congruent and one with incongruent posture. In contrast to Experiment 1, we used a between-subjects design such that each participant initially received only one level of congruence between visual and postural information. Based on previous findings (e.g., Wraga, 1999a, 1999b), we expected the experimental variation of visual eye-height to change the perceived spatial layout in the VR condition with incongruent posture first, but we expected no change in the perceived layout owing to the variation of visual eye-height for the real-room condition as well as the congruent-VR-first condition.

In both VR groups, we additionally presented the respective other condition after the initial condition. That is, in the second experimental block, subjects who had received the congruent condition in the first block now received trials where the simulated visual eye-height was incongruent with their body posture, and subjects who had started with the incongruent condition now received the congruent condition. This enabled us to study effects of the initial condition on the consideration of postural information. We sought to find out whether observers adapt to the congruence/incongruence of visual and postural information, which we call posture congruence. Following the idea that in Experiment 1 observers relied on *internalized posture* rather than on *posture updating* due to the ambiguity of the perceptual situation, we expected that in Experiment 2 observers who initially experienced an unambiguous situation with matching visual and postural eye-height information were more likely to relate the visual information to actual posture than observers who initially experienced an ambiguous perceptual situation with mismatching visual and postural cues. If so, actual postural cues should have a stronger effect when we initially presented the congruent trials compared with the incongruent trials.

Participants

A total of 144 observers volunteered for Experiment 2 and were assigned to three conditions of 48 participants each: the real-room condition (39 female, 9 male; mean age = 23.38 years, *SD* = 3.58), the congruent-VR-first condition (39 female, 8 male; mean age = 24.51 years, *SD* = 4.69), and the incongruent-VR-first condition (38 female, 10 male; mean age = 23.79 years, *SD* = 6.09). One further subject from the congruent-VR-first condition had to be excluded due to a recording error by the experimenter. All participants gave written consent and were briefed, debriefed, and tested for visual and stereoscopic (only participants in the VR conditions) acuity as in Experiment 1.

A power analysis conducted with G*Power (power = 80%, α-level = 5%) showed that the sample size was sufficient to detect medium-sized (d_z = 0.5) effects of visual eye-height and posture congruence. Given the pronounced variation of visual and postural eye-height, we expected at least medium effect sizes for these variables, if the manipulations of visual and postural eye-height influence the perceived spatial layout of the interior spaces (see also Experiment 1).

Stimuli and Apparatus

On each trial, we presented one rectangular room. In the real-room condition, we used two empty adjacent (left, right) office rooms (see left column of Figure 7) which were identical except for the position of the door and a small wall projection, which were mirrored on the depth axis. In the left room, the door was on the left side and the wall projection was on the right side of the room, while the right room had the mirrored layout. The rooms had a depth of 7.20 m (door to window), a width of 2.67 m, and a ceiling height of 3.23 m. Vertical blinds covered the west-facing windows. We tested in the morning hours to avoid direct sunlight through the windows. Six 60 × 60 cm ceiling-mounted floodlights additionally illuminated the rooms. The walls were coated with a white-painted fiberglass wallpaper. The floor covering was a blue-gray needle felt carpet and the ceiling consisted of 60 × 60 cm white ceiling panels. The VR rooms (right column of Figure 7) were replicas of the real rooms and were presented using the same experimental setup and laboratory room as in Experiment 1.

Across all viewing conditions, the observer's position inside the real or virtual room remained constant at 20 cm in front of the room's front wall, horizontally centered between the left and the right side wall (see Experiment 1). During the experiment, subjects were leaning with their back against the rear wall of the office room (real-room condition) or a wall of the laboratory (VR conditions), either standing upright or sitting on the floor, and could explore the real or virtual rooms by means of head movements.

Design and Procedure

On each trial, subjects successively estimated the width, depth, and height of the office rooms in meters and centimeters. The experiment consisted of two trials per subject in the real-room condition and of four trials per subject in the VR conditions. Subjects verbally estimated the spatial layout of the left room in one trial, and the spatial layout of the right room in the other trial. The experimenter recorded the estimates. No time limit was given for the responses. Each subject estimated one room in standing and the other in sitting posture. Within each group, the order of the dimensions to be estimated (width, depth, height), the initial posture (sitting, standing), the initial room (left, right), and all combinations thereof were balanced between subjects. Subjects were tested individually in one single session of approximately 15 min.

In the VR conditions, each simulated room was presented until subjects had provided the estimates. In the first block presented to the congruent-VR-first group, visual eye-height matched postural eye-height. The block consisted of two trials, one performed in standing and the other in sitting posture. In the first block (two trials) presented to the incongruent-VR-first group, visual eye-height was opposite to postural eye-height. That is, subjects saw the room from a sitting

Figure 7

Experiment 2: View of the Window Front (Upper Row) and the Door Side (Lower Row) of the Real Left Office Room (Left Column) and the Simulated Right Office Room (Right Column)

Note. See the online article for the color version of this figure.

perspective while standing upright in the laboratory and vice versa. In the second block, we additionally presented the other VR condition.

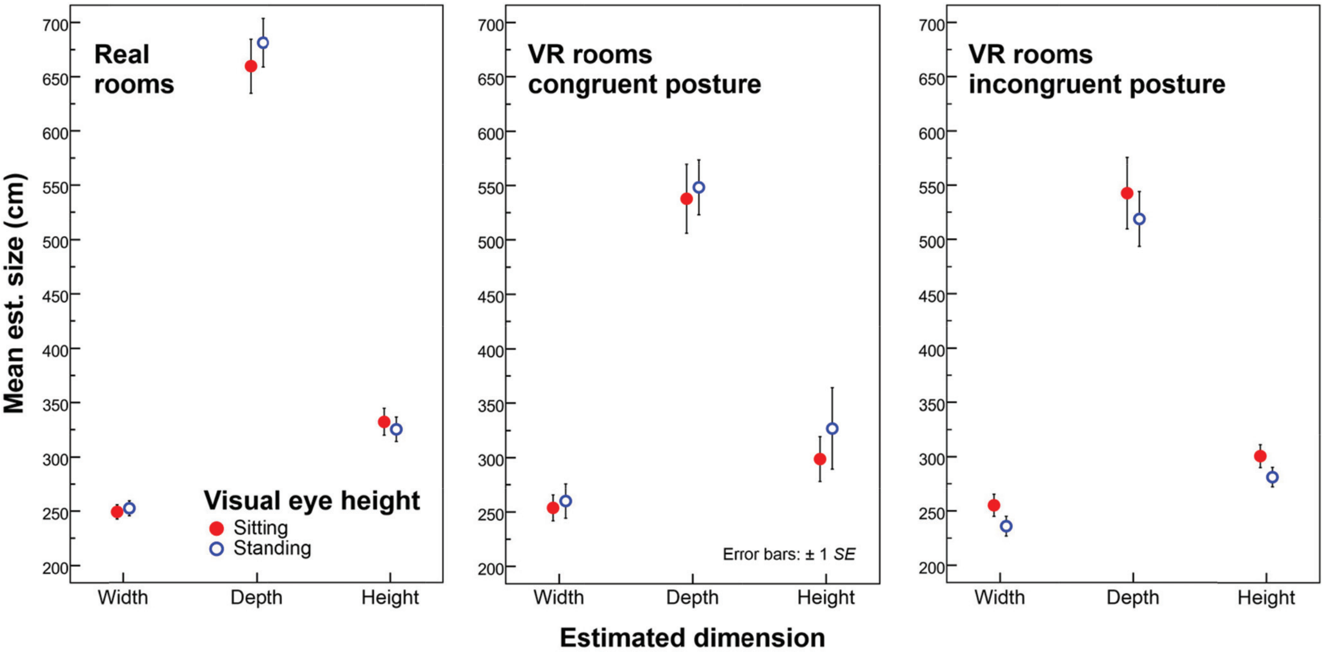
In the first trial of the real-room condition, subjects were blindfolded at the starting position outside the corridor near the two offices. The experimenter then guided them to one of the two rooms. After the desired observer position and posture had been adopted, the blindfold was removed, and the subject estimated the room's spatial layout. The blindfold was then put back on, and the subject was led back to the starting position and then guided to the second room. The blindfolding was used to ensure that the subjects could only see the room from the intended eye-height and observer position. In addition, we wanted to conceal that the two rooms were directly adjacent to each other because this could have suggested that the ceiling height was the same or very similar.

Results and Discussion

We first compared the size estimates for the real room with the estimates obtained in the initial block of the VR conditions with congruent and incongruent posture information first. Figure 8 shows the mean width, depth, and height estimates as a function of visual eye-height and viewing condition. Descriptively, the mean estimated depth in the real room and the estimated depth and room height in the congruent-VR-first condition were larger when visual eye-height (and also posture) was standing compared with sitting. In contrast, in the incongruent-VR-first condition, the mean estimates for all room dimensions were larger when visual eye-height corresponded to a sitting rather than a standing observer. We conducted a MANOVA with visual eye-height as within-subjects factor, viewing condition (real-room, congruent-VR-first, incongruent-

Figure 8

Experiment 2: Mean Width, Depth, and Height Estimates as a Function of Visual Eye-Height and Viewing Condition



Note. Error bars show ±1 standard error of the mean (*SEM*) of the 48 individual estimates in in the real-room condition and the incongruent-VR-first condition, respectively, and of the 47 individual estimates in the congruent-VR-first condition. For the VR conditions, only the data from the initial block are plotted. See the online article for the color version of this figure.

VR-first) as between-subjects factor, and the width, depth, and height estimates as dependent measures. The main effect of visual eye-height was not significant, $V = .01$, $F(3, 138) = .47$, $p = .703$, $\eta_p^2 = .01$. However, the MANOVA showed a significant visual eye-height × viewing condition interaction, $V = .11$, $F(6, 278) = 2.64$, $p = .017$, $\eta_p^2 = .05$. Separate post hoc rmANOVAs (univariate approach) for each dependent variable showed that this interaction was significant for the width estimates, $F(2, 140) = 4.27$, $p = .016$, $\eta_p^2 = .06$, and the height estimates, $F(2, 140) = 4.38$, $p = .014$, $\eta_p^2 = .06$, but not for the depth estimates $F(2, 140) = 1.69$, $p = .188$, $\eta_p^2 = .02$. To analyze this interaction in detail, we calculated paired-samples *t* tests (two-tailed) for the comparisons of sitting visual eye-height with standing visual eye-height, separately for each combination of viewing condition and estimated dimension. In the real-room condition, $t(47) \leq 1.16$, $p \geq .251$, $d_z \leq .17$, and the congruent-VR-first condition, $t(46) \leq 1.60$, $p \geq .116$, $d_z \leq .23$, none of the comparisons was significant. In contrast, in the incongruent-VR-first condition, the width estimates, $t(47) = 2.35$, $p = .023$, $\Delta_{\text{mean}} = 19.27$ cm, $d_z = .34$, and height estimates, $t(47) = 2.23$, $p = .030$, $\Delta_{\text{mean}} = 19.38$ cm, $d_z = .32$, were significantly larger when the visual eye-height corresponded to a sitting compared with a standing observer. Descriptively, the perceived depth was also larger when a sitting compared with a standing perspective was simulated, but this effect was not significant, $t(47) = 1.38$, $p = .174$, $\Delta_{\text{mean}} = 23.83$ cm, $d_z = .20$. Taken together, when visual eye-height was incongruent with posture, we found larger mean estimates for all room dimensions when visual eye-height was lower, albeit not significant for the depth estimates. In contrast, when visual cues did correspond to postural cues, we found a nonsignificant tendency toward larger size estimates when the visual eye-height corresponded to a standing compared with a sitting observer.

In the MANOVA, the effect of viewing condition was also significant, $V = .22$, $F(6, 278) = 5.60$, $p < .001$, $\eta_p^2 = .11$. The post hoc rmANOVAs showed that this effect can be mainly attributed to the depth estimates, $F(2, 140) = 9.03$, $p < .001$, $\eta_p^2 = .11$. Averaged across the manipulations of visual eye-height, the mean perceived depth was considerably larger in the real-room condition (670.46 cm) than in the congruent-VR-first condition (543.24 cm) and the incongruent-VR-first condition (530.67 cm; see Figure 8), $t(93) = 3.665$, $p < .001$, Cohen's (1988) $d = .75$, and. $t(94) = 3.980$, $p < .001$, $d = .81$, respectively. The congruent-VR-first and the incongruent-VR-first conditions did not differ significantly in perceived depth, $t(93) = .32$, $p = .751$, $d = .07$. According to the rmANOVAs, the width and height estimates remained largely stable across conditions, $F(2, 140) = .30$, $p = .740$, $\eta_p^2 < .01$, and $F(2, 140) = 1.05$, $p = .354$, $\eta_p^2 = .015$, respectively. Note that this pattern fits in well with results from previous studies comparing verbal estimates of spatial extent in virtual and real environments, according to which sagittal extent can be considerably underestimated in virtual environments, whereas perceived frontoparallel extent remains largely unaffected by the presentation condition (e.g., Geuss et al., 2012; Grechkin et al., 2010; Kelly et al., 2017; Kunz et al., 2009; but see Kelly et al., 2015). It has been shown that this underestimation of depth in VR can be efficiently counteracted when the observer is allowed to walk around in the virtual environment (Kelly et al., 2013; Siegel & Kelly, 2017; Siegel et al., 2017) when the rendering is very rich in detail (Loyola, 2018).

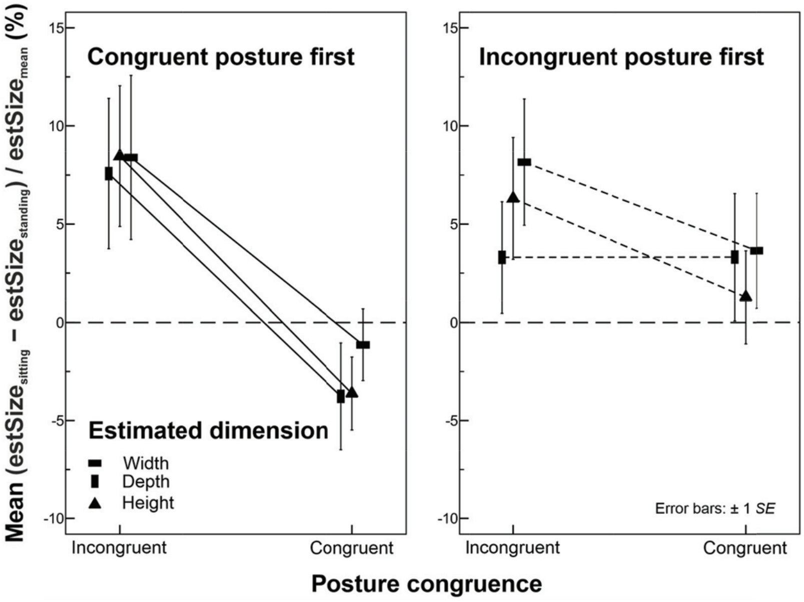
How do the results from Experiment 2 compare with those of Experiment1? In Experiment 1, the data indicated that observers did not integrate postural information when exposed to incongruent visual and postural eye-height information, resulting in a large effect of visual eye height. We had concluded that observers relied on *internalized posture* information rather than *posture updating*. In Experiment 2, we found higher estimates from the sitting perspective compared with the standing perspective in the incongruent-VR-first condition (Figure 8, right panel), which is compatible with both *posture updating* (Figure 2B and 2C) and *internalized posture* (Figure 2E and 2F). In contrast, in the congruent-VR-first condition, we found that the estimates were only weakly and nonsignificantly affected by visual eye-height, which favors *posture updating* (see Figure 2A). To answer the question of whether the larger estimates in the incongruent-VR-first condition in Experiment 2 were based on *internalized posture* or *posture updating*, we additionally considered the second block of trials that had been presented to each observer in the VR conditions subsequently to the initial condition. We assumed that observers who first saw the incongruent-VR-first condition recognized that posture information is not congruent with visual eye-height and, thus, relied on *internalized posture* rather than on *posture updating*, whereas observers who first saw the congruent-VR-first condition recognized that posture information is indicative of visual eye-height and therefore used *posture updating*. If so, the effect of visual eye-height should be largely independent of posture congruence in subjects who started with the incongruent-VR-first condition, but should be influenced by posture congruence in those who started with the congruent-VR-first condition.

As a measure of the effect of visual eye-height, we calculated the relative difference between the room size estimates obtained with the sitting visual eye-height and the estimates obtained with the standing visual eye-height. For each subject and combination of viewing condition (congruent-VR-first and incongruent-VR-first) and estimated room dimension, this is given by ($\text{estSize}_{\text{sitting}} - \text{estSize}_{\text{standing}}$)/$\text{estSize}_{\text{mean}}$, where $\text{estSize}_{\text{sitting}}$ is the estimated width/depth/height from the sitting perspective, $\text{estSize}_{\text{standing}}$ is the estimated width/depth/height from the standing perspective, and $\text{estSize}_{\text{mean}}$ is the mean estimated width/depth/height, averaged across both conditions and perspectives.

As can be seen in Figure 9, the effect of visual eye-height was less influenced by posture congruence when the incongruent-VR-first condition was presented first (right panel). For this order of blocks, all relative differences remained larger than zero across the levels of posture congruence, which indicates that the estimates from the sitting perspective remained larger than the estimates from the standing perspective. In contrast, when the congruent trials were presented first, the differences were only larger than zero when posture and visual eye-height were incongruent, but slightly smaller than zero when posture and visual eye-height were congruent. We calculated two separate rmANOVAs (univariate approach), one for each initial condition (congruent posture first, incongruent posture first), with posture congruence (congruent, incongruent) and the estimated dimensions (width, depth, and height) as the within-subjects factors, and the relative difference between sitting and standing perspective as the dependent measure. When observers first saw the congruent condition, the effect of posture congruence was

Figure 9

Experiment 2: Mean Relative Difference Between Sitting and Standing Visual Eye-Height in Perceived Width, Depth, and Height as a Function of Posture Congruence and Initial Condition



Note. Error bars show ±1 standard error of the mean (*SEM*) of the 47 individual estimates in the congruent-VR-first condition and the 48 estimates in the incongruent-VR-first condition.

significant, $F(1, 46) = 9.52$, $p = .003$, $\eta_p^2 = .17$, but not so when observers first saw the incongruent condition, $F(1, 47) = 1.24$, $p = .271$, $\eta_p^2 = .03$. To analyze the effect of posture congruence in detail, we calculated paired-samples *t* tests (two-tailed) for the comparisons of incongruent with congruent posture, separately for each combination of initial condition and estimated dimension. In the incongruent-posture-first condition, none of the comparisons was significant, $t(47) \leq 1.43$, $p \geq .159$, $d_z \leq .21$. In contrast, in the congruent-posture-first condition, all relative differences were significantly larger, when the posture was incongruent, $t(46) = 2.15$, $p = .036$, $\Delta_{\text{mean}} = 9.54\%$, $d_z = .31$ for the width estimates, $t(46) = 2.34$, $p = .024$, $\Delta_{\text{mean}} = 11.34\%$, $d_z = .31$ for the depth estimates, and $t(46) = 2.67$, $p = .011$, $\Delta_{\text{mean}} = 12.09\%$, $d_z = .39$ for the height estimates, respectively. In both rmANOVAs, all main and interaction effects regarding the estimated dimension were not significant (p values $\geq .398$), which indicates that the effect of posture congruence on the relative difference between sitting and standing perspective was rather similar across room dimensions.

In sum, the results of Experiment 2 show that in situations with congruent visual and postural information observers did largely compensate for changes in visual eye-height in both virtual (congruent-VR-first condition) and real environments (real-room condition). This finding is compatible with *posture updating*. When, however, visual information was incongruent with postural cues (incongruent-VR-first condition), observers estimated the room as larger when seen from the lower perspective. The additional analysis of order effects on the integration of postural cues suggests that observers indeed relied on *posture updating* in situations with initially congruent posture and visual eye-height information. However, when the posture was initially incongruent with visual eye-height, the pattern of results can be better explained by a reference to *internalized posture*.

General Discussion

Observers estimated the spatial dimensions of interior spaces from two different visual eye-heights and two different body postures. Other than in previous research, these conditions were fully crossed to compare the spatial updating hypothesis to that of an internalized posture. In Experiment 1, we presented virtual interior spaces and varied visual and postural eye-height information independently of each other. The observers estimated all room dimensions (width, depth, and height) larger when the virtual point of observation corresponded to their sitting eye-level above the ground. In contrast, body posture did not influence the perceived spatial layout of the rooms, neither did it interact with the effect of visual eye-height. We conclude from this that in an ambiguous situation where visual information varies independently of postural information, observers disregard their actual posture and rather rely on visual cues relative to an internalized standard eye-height, which they may have acquired previously. We have termed this the *internalized posture* model. The results from Experiment 1 speak for this model and are not compatible with the *posture updating* model, which assumes that proprioceptive posture information is permanently factored into spatial judgments.

In Experiment 2, we tested whether it was actually the mismatch between visual eye-height and body posture or, rather, the unfamiliar presentation in VR that caused the reliance on an internalized eye-height instead of an updating of postural eye-height. We therefore compared the width, depth, and height estimates from sitting and standing perspectives in real and virtual rooms with congruent visual eye-height and posture and added virtual rooms with incongruent visual eye-height and posture. In both real rooms and virtual rooms, when the congruent posture was presented first, the estimates were largely unaffected by the variation of visual eye-height, which speaks against the idea that VR per se caused the recourse to internalized representations of eye-height. The result speaks in favor of the idea that under otherwise identical conditions, observers are capable of *posture updating* to compensate for changes in visual eye-height in both virtual and a real environments. In the VR condition with incongruent posture first, in contrast, the rooms appeared consistently wider and higher, albeit nonsignificantly deeper, when the visual scene simulated a low (sitting) perspective. Experiment 2 also revealed that observers adapt to the congruence/incongruence of visual and postural eye-height information. This adaptation carried over to the subsequent trials. The results were in favor of *posture updating* when observers were initially presented with congruent posture, and in favor of *internalized posture* when observers were initially presented with incongruent posture. In sum, our results suggest that observers use both internalized posture and posture updating. And this is done flexibly based on the consistency of the prior information.

Integration of Visual and Postural Eye-Height Information

Simulations provide the opportunity to dissociate perceptual and postural information, which cannot easily be separated in real environments. With the help of this dissociation, we can understand which information is used and how it is integrated in the perceptual process. Previous results (Bertamini et al., 1998; Dixon et al., 2000; Leyrer et al., 2011; Leyrer et al., 2015a, 2015b; Ooi et al., 2001; Twedt et al., 2012; Wraga, 1999a, 1999b; Wraga & Proffitt, 2000) suggested that both visual and postural cues inform perceived eye-height, which in turn informs size and distance estimation. In the present study, we expanded on and qualified these findings by independently varying postural and visual eye-height information to investigate situational influences on the weighting and integration of these cues. Taken together, the results of Experiments 1 and 2 indicate that in situations with congruent visual and postural information, observers use *posture updating*, as suggested by Leyrer et al. (2015b), and therefore compensate for changes in visual eye-height in both virtual and real environments. For situations with incongruent visual and postural eye-height information, to the contrary, our results are compatible with the view that observers calibrate visual eye-height information with respect to internalized rather than flexibly updated posture. We suggest that this internalized parameter represents experience from past similar situations. Against this backdrop, we consider a flexible, situation-dependent coupling of visual and postural eye-height cues the most likely interpretation of our data. We deem such a strategy highly adaptive. In situations where visual and postural cues provide congruent information, humans can make use of both sources to fine-tune perceived eye-height and, thus, optimize the precision of the distance and size estimates of the elements in the surrounding scene. In situations where visual and postural cues provide inconsistent information, postural information is disregarded in favor of visual information relative to an internalized, previously acquired standard. This second mechanism enables the observer to access a meaningful interpretation of the arrangement of the ambient scene even under uncertain and/or contradictory perceptual conditions. Note that we do not assume that observers do explicitly process this discrepancy and then choose one of the two variants. We rather assume that this process is automatic.

A preference for visual information relative to an internalized standard, as opposed to postural information, in situations with incongruent visual and postural cues also seems plausible for another reason. Stoper and Cohen (1986) have shown a considerable increase in the accuracy and precision of eye-height judgments when observers can use visual cues in addition to postural cues. They conclude from their findings that visual cues stabilize or even dominate postural cues when judging eye-height. Note, however, that this cannot be verified because it is hardly possible to remove all postural cues and establish the baseline of pure eye-height judgments.

Implications for VR Simulations

From an application perspective, effects on the perceived layout of virtual environments attributable to incongruence of visual eye-height and posture are especially important for applications that rely on true-to-scale visualization (see also Rothe et al., 2019). This is, for instance, essential for architectural visualizations. An observer may remain seated in a chair in the physical environment while exploring a simulation of a house from different virtual perspectives. Based on our results, we derive the following recommendation for such applications: An incongruence of postural and visual eye-height is unlikely to compromise valid and reliable perception of the simulated architectural space, as long as the simulated visual eye-height remains constant and coincides with the internalized eye-height, which should be assessed before the presentation. If a person is used to view rooms from a standing perspective, the visual simulation of a standing perspective while the observer is physically seated should not lead to a distorted perception of the room or building size. However, we would like to point out that this statement refers only to presentations on an HMD with a static observation point. The latter allows for head movements but maintains a constant observer position within the simulated space, as implemented in our experiments. We can only speculate about the implications for simulations on an HMD, when the observer can freely navigate through the simulated structure. This should be less of a problem for simulations with full tracking of head and body movements, which are translated one-to-one into VR, because in such applications the simulated eye-height should correspond to the physical one anyway, comparable to the movement of an observer through a real environment. In contrast, the HMD-viewing with body movement might be problematic for applications where the observer remains physically stationary in a given posture (e.g., seated) but navigates through the virtual environment by means of an interface, such as a joy-stick or keyboard. Because observers usually move through rooms in an upright posture, the simulated movement through the virtual environment could also trigger expectations of a standing perspective. In this respect, a more valid perception of the simulated layout could be achieved if a standing visual eye-height is simulated independently of the physical posture. As mentioned, these considerations should be the subject of separate investigation.

Generalizability of Our Findings

We have conducted two experiments to investigate effects of visual and postural eye-height information on the perceived layout of simulated interior spaces. Depending on the experimental condition, we found that, on average, observers estimate the spatial dimensions of a room to be larger when the visual eye-height was below the internalized eye-height (Experiment 1 and incongruent-VR-first condition in Experiment 2) or below the actual postural eye-height (congruent-VR-first condition in Experiment 2). Thus, our results indicate that visual eye-height relative to internalized eye-height or postural cues is crucial to scale the perceived spatial layout of the scene. Having said this, it should be noted that the effect of visual eye-height was considerably stronger (in terms of effect size) in Experiment 1 than in the incongruent-VR-first condition of Experiment 2. How can this be explained? There were two main differences in the design of the experiments. First, in Experiment 1, we measured the effect of visual eye-height much more precisely than in Experiment 2. In Experiment 2, the effect of visual eye-height was investigated on the basis of maximally 4 trials per subject and dimension to be estimated. In Experiment 1, in contrast, we repeated each of the four combinations of visual eye-height and posture six times and additionally varied the size of each room dimension in three steps. The analysis of the eye-height effect in Experiment 1 was therefore based on a total of 72 trials per subject and dimension. Because the repeated-measures analysis we have chosen is based on deviations from the individual baseline due to experimental manipulations, we consider it plausible that the smaller effect size of the visual eye-height in Experiment 2 compared with Experiment 1 may be a consequence of the different designs and the resulting less precise estimation of the individual baseline in Experiment 2 (see also von Castell et al., 2018a). Second, Experiment 2 used high-fidelity renderings of real office rooms, whereas the simulated rooms in Experiment 1 were less detailed and rather minimalistic. It is conceivable that the observers used the additionally available visual cues in Experiment 2, such as the size and position of the window or the size and number of the ceiling panels, to partially compensate for the distortions in the perceived layout caused by the manipulation of visual eye-height. Beyond this, in both experiments, we used empty rooms devoid of object-based depth cues. The empty rooms mainly provided texture gradients and perspective, but no occlusion. With this in mind, it would be interesting to investigate how furniture may alter the effect of eye-height, as previous studies have shown that furniture can scale the perceived size of rooms (Imamoglu, 1973; von Castell et al., 2014). For example, when we stand upright, we typically see the upper side of a tabletop, but see its lower side when crouching on the floor. Be reminded that visual foreshortening of egocentric extent in VR mainly occurs in environments with reduced depth cues, as applicable to our experiments, whereas it is considerably reduced in rich simulations (Loyola, 2018) or when locomotion is possible (Kelly et al., 2013; Siegel & Kelly, 2017; Siegel et al., 2017). Durgin and colleagues (Durgin & Li, 2011; Li & Durgin, 2012; Li et al., 2011) suggested that foreshortening of the depth dimension can be attributed to a distorted perception of visual angles. Based on their findings in both natural environments and VR, they argue that observers generally tend to perceive the angle of declination steeper than it is, which then promotes a compressed perception of egocentric extent. The reduced foreshortening in environments with rich depth cues could be interpreted in the sense that the visual system uses the additionally available depth cues to compensate for such distortions. Against this backdrop, it seems conceivable that further depth cues may also reduce effects due to eye-height manipulations.

Overall, we assume that the somewhat weaker effect of visual eye-height in Experiment 2 does not speak against a transferability of our results to other simulations in VR. Having said this, it is an interesting remaining question to what extent other depth cues can compensate for incongruent eye-height information.

Conclusion

Consistent with previous results, our data suggest that both visual and postural cues inform perceived eye-height. In addition, our study shows for the first time that the integration of visual and postural information is situation-dependent. In particular, the weighting of postural cues turned out to be dependent on the context. In situations where visual cues and postural cues vary independently of each other, observers tend to disregard postural cues and mostly rely on visual cues relative to an internalized eye-height. In contrast, when visual and postural cues change in a congruent manner, observers consider postural cues in addition to the visual information. This flexible coupling of visual and postural cues is highly adaptive for dealing with unusual and ambiguous situations, such as virtual environments.

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