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The Effect of Blur on the Perception of Up

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ABSTRACT

Purpose. Knowing one's orientation relative to the environment is important for many aspects of vision including object recognition, action planning, and balance. Here we assess how inadequate optical correction for typical refractive errors might influence this. We measured the effect of blur on the perception of orientation as measured by the subjective visual vertical (SVV) and the perceptual upright (PU).

Methods. The SVV and the PU were determined using a tilted line (was the line tilted left or right of vertical?) and the Oriented CHAracter Recognition Test (OCHART; was a character a "p" or a "d"?), respectively, in the presence of tilted visual backgrounds that were blurred using Gaussian blur with a radius of from 0 to 91 arc min. This is approximately equivalent to between 0 and 13 diopters of refractive error.

Results. Blur reduced the influence of vision on both the SVV and PU by one just noticeable difference (84%) when vision was blurred by 11 to 13 arc min. That is, visual cues to self-orientation remain effective until vision is degraded to about 20/240 – roughly equivalent of taking off a pair of 2 diopter prescription glasses.

Conclusions. This reduction in the effectiveness of vision for determining orientation has important implications for the visually impaired and the elderly. Attempting tasks that require balance in the presence of uncorrected refractive errors may be more hazardous than expected. The effect of not optically correcting peripheral vision may also be consequential owing to the role of the far periphery in balance control.

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Key Words: blur, spatial frequency, perceptual upright, subjective visual vertical, aging, balance, orientation perception

The perception of the relative orientation of oneself and the world is fundamental to many aspects of perception including recognizing faces and objects,[1] reading,[2] the perception of shape,[3] balance,[4–7] and predicting how objects are going to behave when dropped or thrown.[8] Misinterpreting the upright direction can lead to errors in all these[9] and hence potentially threaten balance.[10] Many people have refractive errors in their vision. This article assesses the consequences of refractive error on the contribution of vision in providing information about orientation.

Establishing an "up" direction is a multimodal cue integration process that relies on visual, gravity, and idiotropic cues.[11] This multimodal cue integration process has been evaluated using a range of different methodologies including the subjective visual vertical (SVV)[11–13] and the perceptual upright (PU).[14] These probes measure different aspects of "up" and are influenced to a different extent by the various cues. Measuring the SVV involves aligning a line with the perceived gravitational vertical and may correspond to the perceived direction of up critical for balance. The PU is a more perceptual measure, assessing the effect of the up direction on the recognition of letters and objects. Both these measures are influenced by vision, although the SVV is generally influenced less than the PU. Vision typically contributes about 15% to the SVV and 25% to the PU, with the remainder coming from the orientation of the body and the direction of gravity.[14] This means that if the visual cue is orthogonal to the upright body, it evokes tilts of 10° and 18° of the SVV and PU, respectively. When multisensory cues are combined to give a single estimate of a perceptual parameter, such as the size of a block that is both seen and felt, or the direction of vertical, the cues are typically combined in inverse proportion to their reliability.[14,15] This produces the mathematically most reliable (least variability) estimate and is known as the maximum likelihood estimate (MLE).[16] Both the PU and the SVV follow the MLE combination rule.[14] The MLE predicts that, as vision becomes less reliable as a result of blurring, less emphasis will be placed on it in determining upright and that all estimates of up (including SVV and PU) will be affected similarly by degraded vision.

There are several visual cues to the direction of up contained in typical scenes. These include the structure of the environment, the

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orientation of the horizon, and the arrangement of objects that have a clear top and bottom such as lamps, trees, and people. The PU is particularly strongly influenced by the arrangement of such objects, whereas the SVV is more influenced by the structure of the environment.[17,18] This division is compatible with their relative importance to perception and self-orientation, respectively.[14,19] Since the orientation of objects with a clear right way up is likely conveyed more by their details (high spatial frequency content) and the structure of the environment is conveyed more by lower spatial frequencies, it might be expected that the SVV would be affected less than the PU by blur since blur selectively removes higher spatial frequencies from the image.

The best-corrected visual acuity in healthy eyes declines with age from middle age onward.[20,21] Although the effect of reduced visual acuity (blur) on visual tasks such as detection, recognition, and localization has been extensively investigated,[22–25] and despite the acknowledged importance of vision for maintaining balance, there have been few studies on the effect of reduced visual acuity on the perception of orientation and upright although Ebenholtz[26] showed that blur did have an effect on the effect of a tilted frame on the perceived orientation of a rod. This lacuna has perhaps occurred because it was previously thought that proprioceptive visual functions such as orientation in space and the control of self-motion were largely a function of peripheral vision[27] where acuity is poor anyway.[28–31] Indeed, even as much as 18 diopters of blur have little effect on the induction of circularvection,[32] apparently confirming the "insensitivity of the ego-stabilization system to retinal image blur." However, this conclusion cannot be generalized to the effect of blur on static cues since circularvection is driven by movement signals rather than by spatial structure. Furthermore, the dominant role of the periphery in proprioceptive vision may have been exaggerated by studies that did not equate retinal area.[33] In fact, image blur has been shown to significantly increase postural sway in adults[34,35] and in the elderly,[36] implying an important role in ego-stabilization.

To quantify the effect of blur on the visual contribution to the perception of up, we simulated decreased visual acuity by Gaussian blurring of the visual image[37,38] and measured the effect of the resulting degraded image on the influence of visual cues on the SVV and PU. The effect of vision was measured by misaligning visual cues to "up" relative to the orientation of the body and gravity. This enabled us to assess the relative influence of vision by measuring the amount that the PU and the SVV were pulled toward the visually defined up direction and then determining how much blur was needed to reduce this visual effect to a percentage of its maximum value. For both measures, we wanted to know if degrading vision within the range typically found in uncorrected vision (up to about 5 diopters) might have a significant influence on vision's role in perceiving orientation.

METHODS

Participants

Ten participants (6 men and 4 women aged between 23 and 45 years) took part in the experiment. All participants had normal or corrected-to-normal vision and reported no history of vestibular dysfunction. Each participant completed an informed consent agreement that conformed to the ethical guidelines of York University and the Declaration of Helsinki.

Apparatus

Visual stimuli were presented on an Apple iBook laptop computer with a resolution of 48 pixels/cm (21 pixels/degree). The computer screen was masked to a circular aperture subtending 42° and was viewed at 25 cm through a black circular shroud that obscured peripheral vision. The shroud also acted as a semirigid padded head restraint to control both the viewing distance and the orientation of the observer's head relative to the screen. The laptop was mounted in an aluminum frame to maintain the screen at a fixed angle and to hold the shroud in place. Participants responded by pressing one of two keys on a handheld Gamepad (Gravis Gamepad Pro) input device.

Procedure

Observations were collected in two separate sessions: one for the SVV and the other for the PU. The order in which an individual subject did the two conditions was randomized. Stimuli consisted of a probe superimposed on a background. Two different probes were used: a line segment to identify the SVV and a character (the Oriented CHAracter Recognition Test [OCHART][14]) to identify the PU. For the SVV, observers were presented with a line at various orientations superimposed on a stationary visual background with various amounts of blur (see below) and were asked whether the line was tilted counterclockwise or clockwise from the gravitational vertical. For the PU, they were presented with the character ("p") at various orientations superimposed on a stationary visual background with various amounts of blur and asked whether the character was a "p" or a "d." Neither the line nor the character was blurred. Stimuli were presented for 500 ms, after which a gray screen of the same mean luminance appeared with a 0.45°-diameter central fixation spot. Observers responded using two buttons on the game pad. For the SVV, the buttons corresponded to tilted "left" or "right." For the PU, the buttons corresponded to "p" or "d." The observers' responses were blocked by the controlling software until stimulus offset and the appearance of the fixation point. Once the response was made, the next trial was initiated after an approximately 150-ms delay.

Stimulus: SVV

The SVV was measure by a line stimulus that subtended $3.1° \times 0.45°$. The line probe extended out from the fixation point nd was presented between ±15° from gravitational vertical in 3° steps (11 orientations) where 0° was vertical. The probe was superimposed on one of eight backgrounds: an image with clear clues as to gravitational up and down positioned upright with respect to gravity or tilted by 22° to the right. The background was chosen as one that has been used extensively before.[14] Other backgrounds have been shown to have comparable effects.[39,40] This tilt was chosen because the SVV has been shown to be maximally shifted by a background tilted by this amount.[14] Five different blurred versions of the tilted background were used. Blurred versions were created by filtering the original image using Adobe Photoshop Version 4 with a radius of Gaussian blur (σ) of

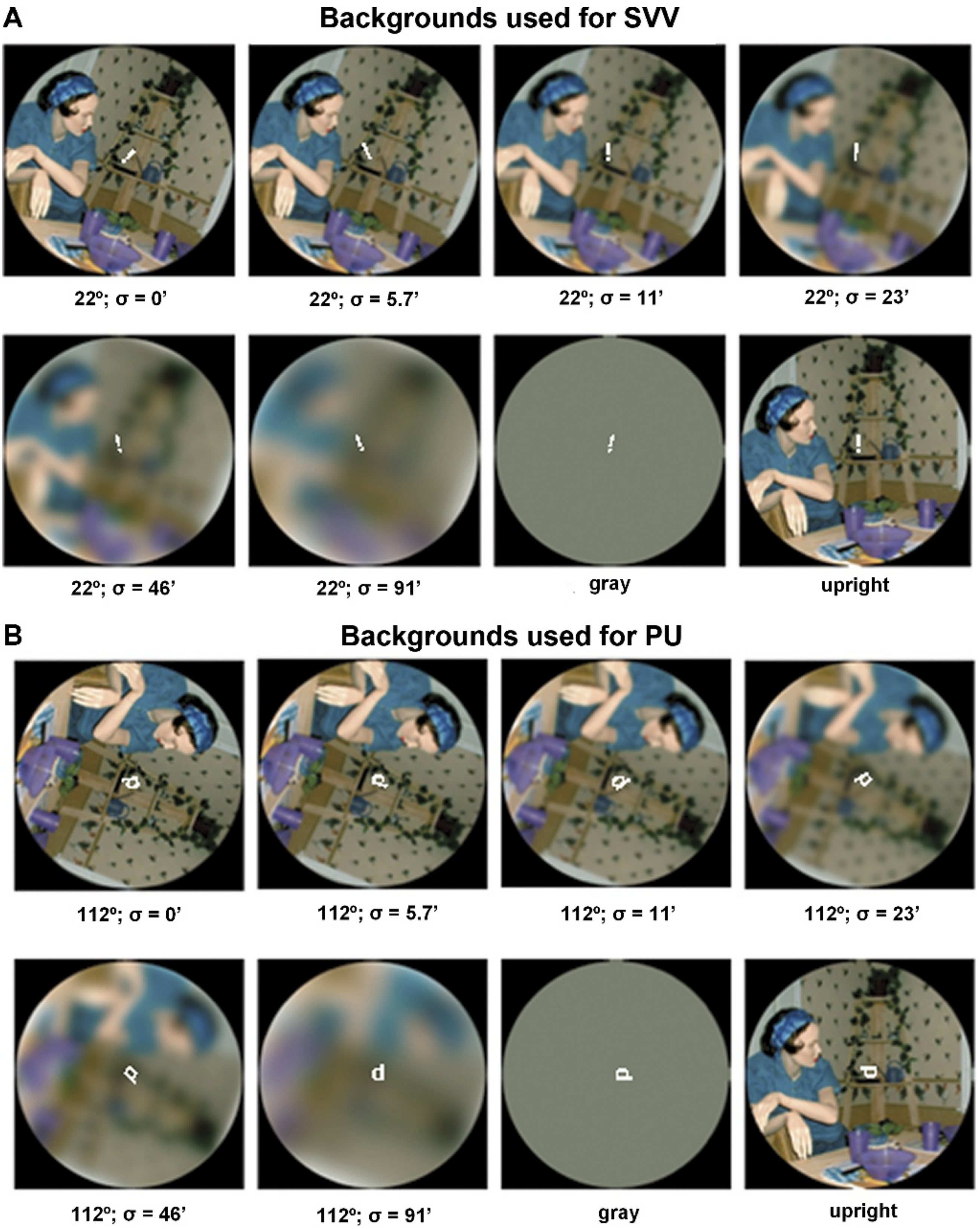


FIGURE 1.

The visual backgrounds used to influence the SVV (A) and the PU (B). The backgrounds were tilted by the amount known to produce the largest effects (22° for the SVV and 112° for the PU) and blurred by a Gaussian blur with radius (σ) between 0 and 91′. The test probes are shown superimposed on these backgrounds. PU indicates perceptual upright; SVV, subjective visual vertical.

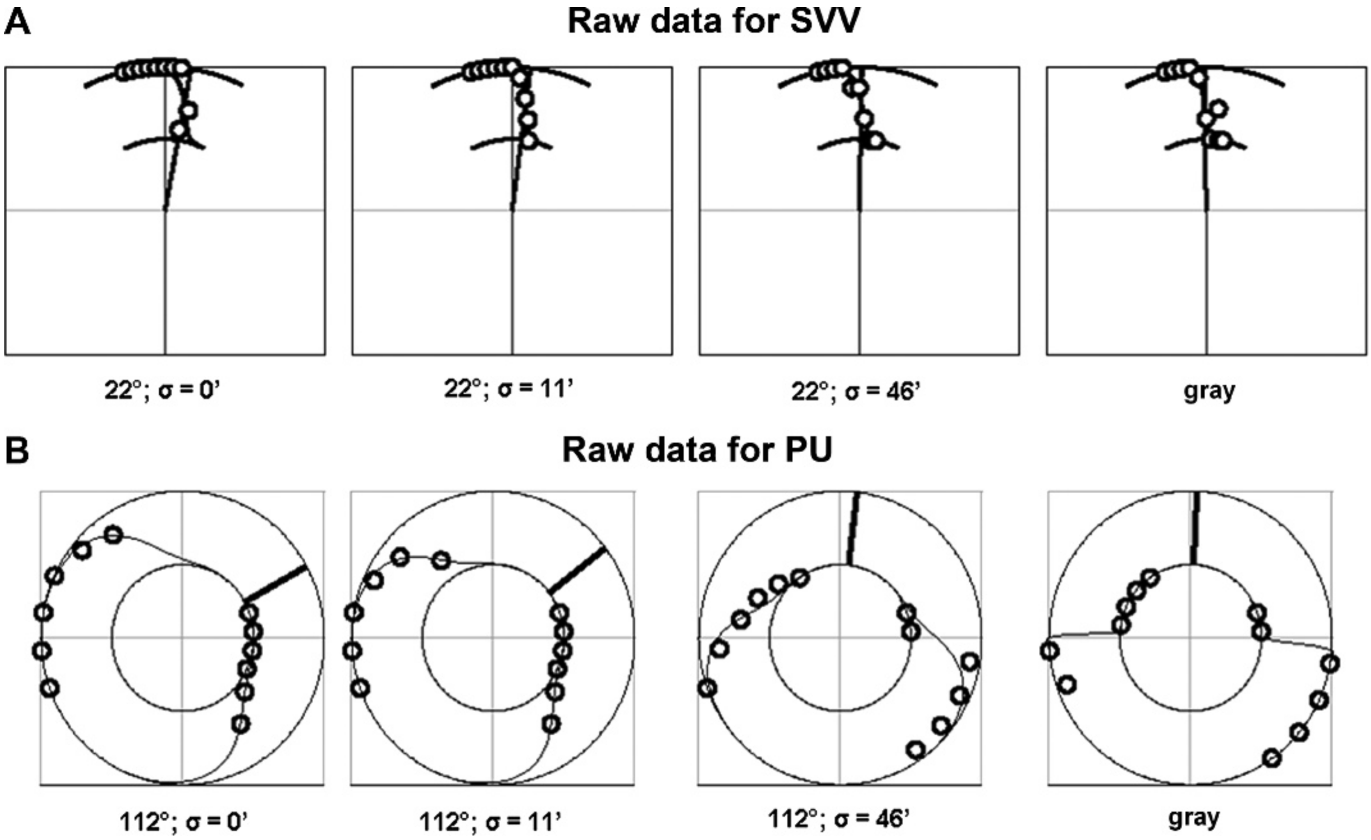


FIGURE 2.

Data from a typical subject for some of the conditions tested in this experiment identified by the tilt of the background image and the amount of Gaussian blur specified under each example. Responses are plotted in polar form, with the angle corresponding to the tilt of the probe and 12-o'clock position corresponding to gravitational upright. A, Typical SVV data. The radial distance corresponds to the probability of the line segment being seen as tilted to the left where a radius of 1 corresponds to 100% "right" and 2 corresponds to 100% "left." A psychometric function is fitted through the data (see text) and the solid bar radiating from the center corresponds to the SVV. B, Typical PU data. The radial distance corresponds to the probability of the character being identified as a "p" where a radius of 1 corresponds to 100% "d" and a radius of 2 corresponds to 100% "p." A double psychometric function (see Methods) is fitted through the data, and the mean of the two 50% points gives the orientation of the PU which is shown as a solid line. PU indicates perceptual upright; SVV, subjective visual vertical.

2, 4, 8, 16, and 32 pixels corresponding to 5.7, 11.4, 22.9, 45.7, and 91.4 arc min, respectively (Fig. 1A). These figures can be converted into acuity (in arc min) by multiplying by root 2 assuming normal 20/20 vision.[37] A gray background of equal mean luminance was also used. Each probe/background combination was presented six times. There were thus 11 probe orientations × 8 backgrounds with 6 repetitions resulting in 528 trials that were presented in random order.

Stimulus: PU

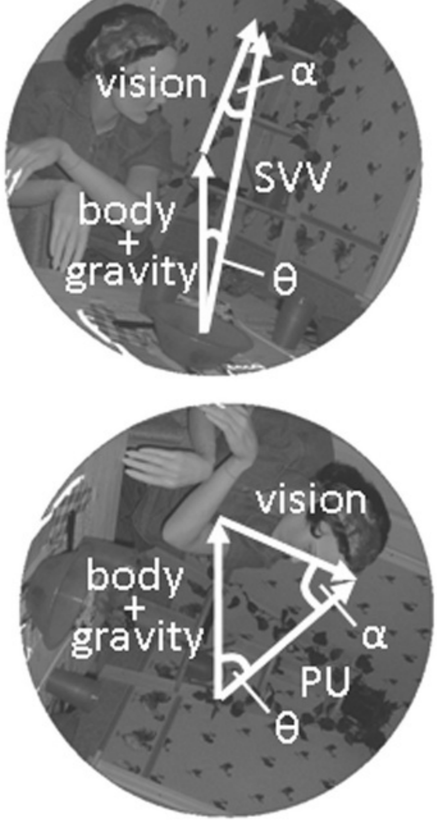
The PU was measured by the character "p" that subtended 3.1° × 1.9°. The probe character was presented at orientations from 70° to 145° and from 250° to 325° in 15° steps (12 orientations), where 0° corresponds to an upright "p" with the stem aligned with gravity and +ve is a clockwise displacement from upright. The probe was superimposed on the same visual background that was used for the SVV (Fig. 1) presented either upright (with respect to gravity and the observer) or tilted by 112° to the right. This background tilt was chosen because the PU has been shown to be maximally shifted by a visual tilt of this amount.[14] As for the SVV, five blurred versions of the tilted background were used. Blurred versions were created by filtering the original image using Adobe Photoshop Version 4 with radius of the Gaussian blur given by σ = 2, 4, 8, 16, and 32 pixels corresponding to 5.7, 11.4, 22.9, 45.7, and 91.4 arc min, respectively (Fig. 1B). A gray background of equal mean luminance was also used. Each probe/background combination was presented seven times. There were thus 12 probe orientations × 8 backgrounds × 7 repetitions resulting in 672 trials that were presented in random order.

Data Analysis: SVV

For each combination of probe orientation and visual background, the fraction of times the SVV probe was identified as rotated counterclockwise with respect to gravity was plotted as a function of the orientation of the line. A hyperbolic tangent was fit to each data set using:

$$x = 0.5 \times \left(1 + \tanh\left((\Theta - \Theta_1)/z\right)\right) \tag{1}$$

where x is the percentage of times the probe was identified as rotated counterclockwise relative to gravity, Θ is the orientation of the line, Θ_1 is the SVV, and z is a parameter representing



$$\frac{\text{vision}}{\text{vision + body + gravity}} = \frac{\sin(\theta)}{\sin(\theta) + \sin(\alpha)} \times 100\%$$

FIGURE 3.

A simple vector model of the relative contribution of visual and nonvisual cues to the SVV and PU. The visual and nonvisual cues to upright are represented as vectors in their veridical directions. The angles of the SVV and PU (Θ), with the visual background tilted by 22° and 112°, respectively, were measured experimentally. Solving the geometry allows us to calculate the percentage contribution of the visual component. PU indicates perceptual upright; SVV, subjective visual vertical.

the sensitivity of the probe. The hyperbolic tangent is a standard sigmoidal psychometric function (like the cumulative Gaussian) but has the advantage that it can be easily adapted to allow multiple transitions.[41] It is thus most suitable for the PU (where there are there are two transitions). The function was used for the SVV for compatibility. Fig. 2A shows typical responses of a single subject plotted on a polar plot where the distance from the center corresponds to x (a radius of 1 corresponds to 100% "right" and a radius of 2 corresponds to 100% "left") and the polar angle corresponds to the orientation of the probe line. The psychometric function (Eq. [1]) is fitted through the data obtained from a typical subject for some sample experimental conditions (see legend). The SVV is shown as a thick radial line.

Data Analysis: PU

For each combination of probe orientation and visual background, the percentage of times the OCHART probe was identified as a "p" was plotted as a function of the orientation of the character. The product of two hyperbolic tangents (equivalent to two sigmoidal functions) was fit to each data set using:

$$x = 0.5 \times \left(1 - \tanh\left((\Theta - \Theta_1)/z\right)\right) \times \tanh\left((\Theta - \Theta_2)/z\right) \quad (2)$$

where x is the percentage of times the probe was identified as a "p," Θ is the orientation of the character ("d" at Θ = 0°), Θ_1 and Θ_2 are the two orientations or points of subjective equality (PSE), and z is a parameter representing the sensitivity of the probe. The mean of the two PSEs was taken as the PU. Fig. 2B shows typical responses, again plotted on a polar plot. Distance from the center corresponds to x (where a radius of 1 corresponds to 100% "d" and a radius of 2 corresponds to 100% "p"). The psychometric function (Eq. [2]) is fitted through the data obtained from a typical subject for each of the eight experimental conditions (see above). The PU is shown as a thick radial line half way between the two 50% points.

RESULTS

The tilted visual background pulled the SVV and PU in the direction of the background tilt by a maximum of 6.5° and 28°, respectively. A simple vector model of the relative weighting of the visual and nonvisual components,[14] in which the directions indicated by the visual and nonvisual cues are represented as vectors in the veridical directions (Fig. 3), indicates that these angles correspond to average visual contributions of 30% and 32% for the SVV and PU, respectively, in our subject population. Fig. 4 shows the amount of SVV and PU that were pulled toward the orientation of the visual background plotted as a function of the amount of blur applied to the background image. The influence of the visual background declined with increasing blur. Plotted through these data are sigmoids from which the thresholds (84% levels) were obtained. This reduction in performance was reached at a blur of 13 ± 2 arc min for the SVV and 11 ± 2 arc min for the PU. Standard deviations of the sigmoids were 6.1 and 5.7 arc min for the SVV and PU, respectively.

DISCUSSION

Blur had a dramatic effect on the use of vision as a cue to orientation. The visual influence was reduced to 84% of its efficacy at around the same blur radius of 11 to 13 arc min for both the SVV and PU. This blur is roughly equivalent to 20/240 vision or 2 diopters of blur—well within the range of optical correction that is often provided by prescription glasses. Since the component of vision that is responsible for influencing the SVV is conveyed by lower spatial frequencies than that which most influences the PU,[17] this indicates that it is the degradation of vision *per se*—and the associated increase in variance—rather than the exact spatial frequency content that is affecting vision's contribution. An uncorrected visual error of only 2 diopters is thus predicted to have a significant effect on the use of vision as a cue to orientation in general.

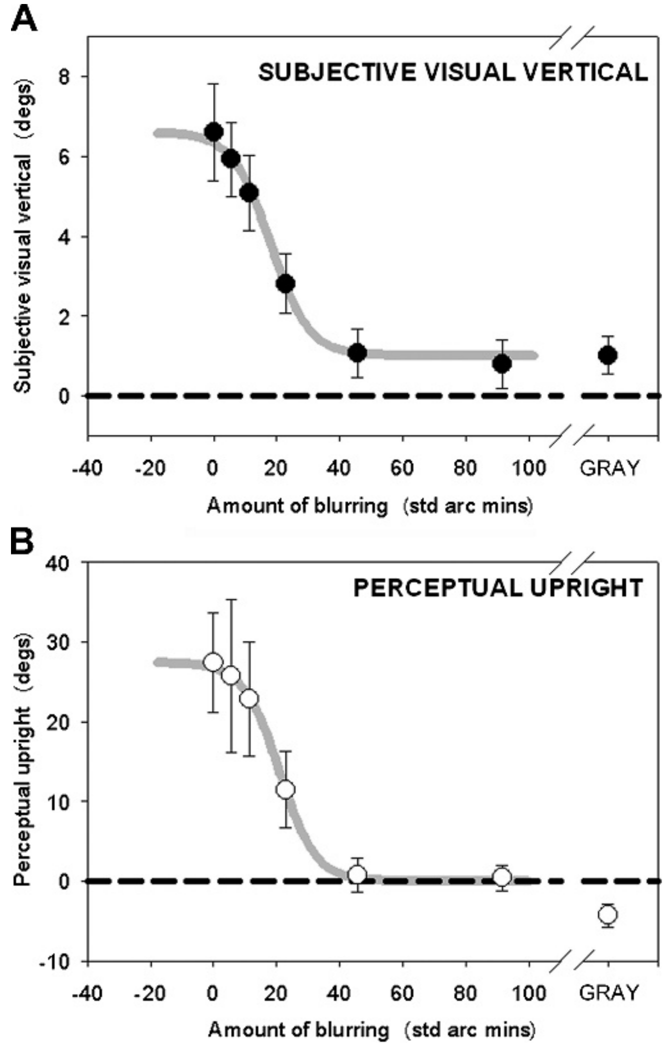


FIGURE 4.

The effect of blur on the SVV (A) and the PU (B). The vertical axis shows the amount each measure was shifted in the presence of the tilted visual backgrounds shown in Fig. 1, plotted as a function of the amount of Gaussian blur (see Methods). Plotted through these data are sigmoids from which the thresholds (84% levels) were obtained. This reduction in performance was reached at a blur of 13 ± 2 arc min for the SVV and 11 ± 2 arc min for the PU. Standard deviations of the sigmoids were 6.1 and 5.7 arc min for the SVV and PU, respectively. PU indicates perceptual upright; SVV, subjective visual vertical.

Comparison with Perceptual Effects of Blurring

The threshold for detecting blur in the central field is around 0.52 arc min.[42] This is considerably below the values reported here of around 12 arc min. That is, blur may not have a significant effect on the perception of upright even when an observer can easily detect that the image is blurred in the central field even though aspects of orientation perception are essentially unaffected.[43] A blur of 12 arc min corresponds to a line resolution of 12 arc min or a spatial frequency of 2.5 c/d.[44] This suggests that the visual orientation system has an acuity of about 2.5 c/d, which is the achromatic acuity threshold at an eccentricity of about 27°.[45] The fact that visual information has to be blurred to this extent before affecting the perception of upright suggests that the relevant visual information, even concerning the polarity and arrangement of objects, is coming through a low-resolution part of the visual system that can tolerate a high degree of unreliability in the visual signal.

The Effect of Blur on Balance

Vision is an important contributor to the perceived direction of gravity[14,46] especially in older people.[47–49] Since upright is obtained by a combination of visual, body, and gravity cues, changes in any of these cues can potentially reduce the reliability of the overall estimate of the gravitational vertical, which is used as a reference for balance. It is important to understand factors that may affect balance control and the tendency to fall.[50] Although a correct prescription is correlated with less falling (Haran et al.[51] but see Elliott and Chapman[52]), the connection is by no means confirmed. Multifocal glasses may actually contribute to instability problems,[53] and the magnification associated with spherical lens can induce errors in distance judgments that can adversely affect gait.[54,55] Blur[35,56,57] and impaired vision in general[58] are known to increase postural instability, and our study may help illuminate how this might happen. Our studies suggest that blur of 12 arc min, equivalent to about 2 diopters or a visual acuity of 20/240 will reduce the effectiveness of being able to use vision to obtain a reliable estimate of vertical. Optical correction of blur may be important not only for resolving fine visual detail but also for improving the more reflex and proprioceptive aspects of vision required for maintaining orientation. The retina beyond around 30° may not normally be critical for maintaining self orientation because the resolution in the far periphery is below the threshold for the visual orientation system. People forced to rely on peripheral vision, even with normal peripheral acuity, may thus be impaired in their ability to use visual cues for orientation. Our experiments investigated only the central 42° of the field. Field size affects the effectiveness of the rod-and-frame illusion[26,59] and the effectiveness of visual cues on perceived body orientation.[60] Further experiments are needed to assess whether other mechanisms may be available that may allow the far periphery to overcome its limited acuity.

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