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The utility of defocus blur in binocular depth perception

Dhanraj Vishwanath
School of Psychology, University of St Andrews, Fife KY16 9JP, UK; e-mail: dv10@st-andrews.ac.uk

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Abstract. The question of whether defocus blur is a quantitative cue for depth perception is a topic of renewed interest. A recent study suggests that relative defocus blur can be used in computing depth throughout the visual field, particularly in regions where disparity loses precision. However, elements of the study's experimental design and theoretical analysis appear to undermine this claim. First, the study did not provide evidence that blur can be used as a quantitative depth cue. It only measured blur discrimination thresholds, not perceived depth from for blur. Second, the study's conceptualization of the complementary use of blur and disparity, and related conjectures, are based on the specific viewing geometry and fixation distance tested. They do not appear to generalize to natural viewing situations and tasks. I suggest a different way in which defocus blur might affect depth perception. Because depth-of-focus blur is a cue to egocentric distance, it could contribute to quantitative depth perception by scaling depth relations specified by other relative depth cues.

Keywords: defocus blur, binocular disparity, depth of focus, depth perception, distance perception.

1 Ordinal versus quantitative depth from blur

Previous studies have examined the role of relative blur and concluded that it only contributes to ordinal (qualitative) depth judgments (Mather & Smith, 2002; Marshall, Burbeck, Ariely, Rolland, & Martin, 1996). A recent study (Held, Cooper & Banks, 2012) challenges these findings by claiming that blur is used to derive quantitative depth under binocular viewing. A key element of this claim is the geometric similarity between retinal disparity and blur. Consider the quantitative depth separation $z_1 - z_0$ perceived while fixating object 0 located at a distance z_0 (Figure 1a; adapted from Figure 1 of Held et al., 2012). Held et al. drew attention to the geometric similarity between the relation of blur (β) and disparity (δ) to $z_1 - z_0$ (Equations 1 and 2) to derive Equation 3 linking disparity and blur magnitude (A is the pupil diameter and I is the interocular distance):

$$\beta \approx \left| \frac{1}{Z_1} - \frac{1}{Z_0} \right|, \tag{1}$$

$$\delta \approx I \left(\frac{1}{Z_1} - \frac{1}{Z_0} \right), \tag{2}$$

$$\frac{\beta}{\delta} = \frac{A}{I}. \tag{3}$$

They claim that disparity is used to compute $z_1 - z_0$ when it has a small value, whereas defocus blur is used when it has a large value. They base this claim on showing that disparity discrimination is worse than blur discrimination for larger values of z_1. However, Held et al. never tested if quantitative depth separation $z_1 - z_0$ can be estimated from blur. Their task measured discrimination thresholds for judging the ordinal depth between two objects beyond fixation (i.e., $z_2 > z_1$; see Figure 1b). To show that blur is used to derive depth separation, they would have had to measure judgments of perceived depth magnitude ($z_1 - z_0$ or $z_2 - z_1$) and show that these covary in some systematic way (regardless of accuracy) with differences in blur ($\beta_1 - \beta_0$ or $\beta_2 - \beta_1$). Discrimination thresholds are routinely used as a bias-free measure to understand computation of depth from visual cues. However, such measurements are usually done in the context of an existing body of evidence showing that perceived depth varies

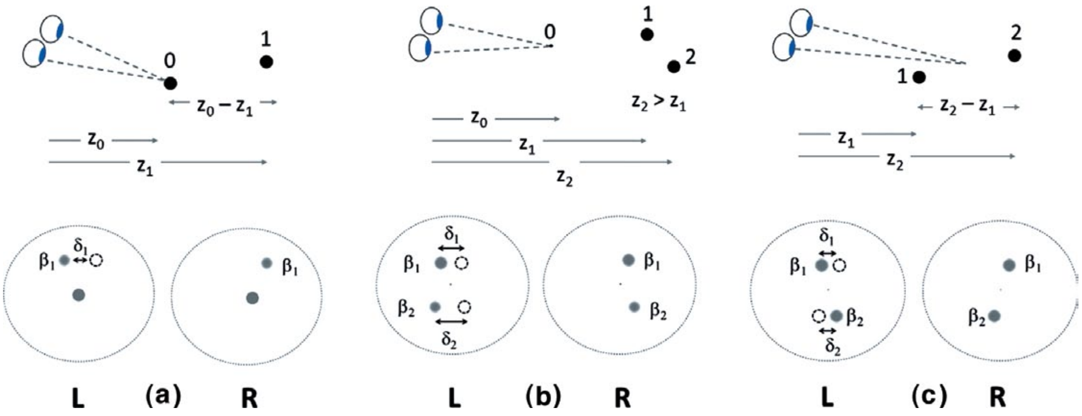

Figure 1. Cartoon of viewing geometries (top) and binocular retinal images (bottom) for judging depth between two points. Disparities are indicated in the left eye image (dotted circles represent the location of the object image in the right eye). (a) Geometry specified in Held et al. (Figure 1) to derive Equation 3 (see text). The observer fixates an object "0" to judge the magnitude of separation ($z_1 - z_0$) between "0" and "1." The object "1" is imaged away from the fovea with blur β_1 and disparity δ_1. (b) Task geometry in Held et al.'s experiment. The observer fixates a point "0" and discriminates the ordinal depth relation $z_2 > z_1$ between two points beyond fixation ("1" and "2"). This can be done by comparing relative blur $\beta_2 > \beta_1$ in the retinal image without computing quantitative depth $z_2 - z_1$ or $z_1 - z_0$ or even comparing $z_2 > z_1$. For greater values of z_1, this arrangement produces large absolute disparities and diplopia. (c) Natural task geometry for judging perceived depth separation ($z_2 - z_1$) between two points: the observer fixates a region in between "2" and "1." Both points will have similar levels of blur (β_1, β_2) for most fixation distances, but relative disparities ($\delta_1 - \delta_2$) will enable precision judgments of depth separation appropriate to the viewing distance.

predictably as a function of the value of these cues (e.g., perspective, disparity, and texture). No such evidence has previously been found for relative blur and Held et al.'s experiment does not provide it.

More problematic is the fact that Held et al.'s task directly confounded the discrimination of ordinal depth relations with the discrimination of the blur difference itself (a two-dimensional task). This type of confound is particularly prevalent in studies that depend solely on measures of discrimination thresholds to infer metric derivation of depth from retinal cues (see Todd, Christansen, & Guckes, 2010)(1). Held et al. tested a single configuration where the two depth planes (z_1 and z_2) were both located beyond fixation and higher blur is always associated with the farther depth plane (Figure 1b). Therefore, the ordinal task can, in principle, be done by just discriminating blur differences in the retinal image. Subjects could have readily made this association especially with training provided. Two subjects were authors, and of the two naïve observers tested, one confirmed that they used magnitude of blur rather than depth to make the judgment (Held et al., 2012). Held et al. pilot tested a configuration with closer depth planes, but this does not eliminate the confound, because in this case the closer plane is always correlated with greater blur.

2 The relative discriminability of blur and disparity in the visual field

Held et al. (2012) drew conclusions about the role of blur in binocular depth perception on the basis of discrimination data from a single fixation distance (28 cm). Crucially, their report does not highlight the fact that the availability of detectable and discriminable blur depends on fixation distance (z_0) and eccentricity and, therefore, its potential utility as a depth cue will be restricted to a limited region of visual space. Held et al. cite only estimates of foveal discrimination thresholds to make the wider case for blur as a depth cue (e.g., Burge & Geisler, 2011; Walsh & Charman, 1988). For spatially extended objects (e.g., Figure 1 of Held et al.), the farther object will be imaged several degrees away from the fovea, precluding the kind of discrimination judgment used to measure foveal thresholds (comparing spatially coincident or adjacent target). Thus, peripheral blur detection thresholds are more relevant. Figure 2a plots empirically measured thresholds for blur detection for different eccentricities on a

(1) The potential use of a two-dimensional strategy is always a source of worry in cue-based depth tasks, though there are several ways to minimize or eliminate this potential confound, particularly if one can demonstrate systematic quantitative variation in depth settings with the cue value. The problem becomes more intractable when the task is just an ordinal judgment, as it is here.

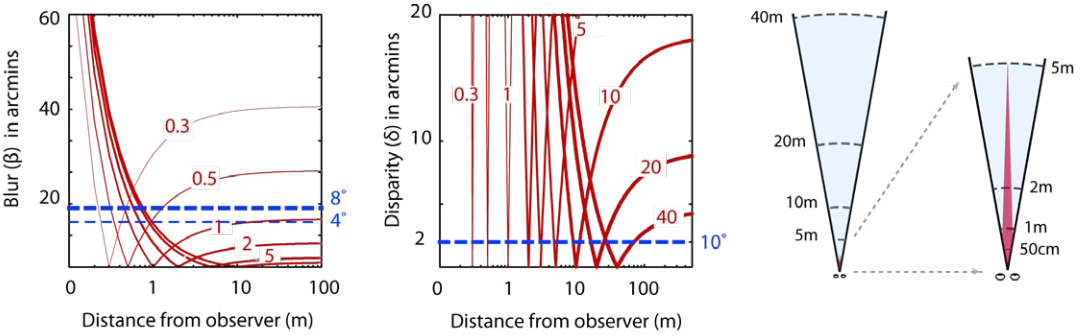

Figure 2. (a) Plot of defocus blur (blur circle diameter β on retina) for a point in space as a function of its distance from the observer for six different fixation distances (0.3–10 m) assuming a 4.5-mm pupil. A point at fixation is imaged sharply (where the curves touch the abscissa) but points away from fixation are increasingly blurred. Dashed lines indicate blur detection thresholds in the near retinal periphery (4°, 8°; Wang et al., 2006). (b) Plot of absolute disparity δ as a function of distance for eight fixation distances (assuming a conservative 54-mm IOD). Blue dashed line is the disparity detection threshold at 10° eccentricity (Blakemore, 1970). (c) Regions of visual space where disparity and depth-of-focus blur are detectable and discriminable based on data from Blakemore (1970) and Wang et al. (2006). The right image is an enlargement of the left image. Blue areas indicate regions of usable disparity and red areas indicate regions of usable blur.

graph of blur magnitudes for different fixation distances. When the farther object is at a modest 8° eccentricity, defocus blur will be detectable only when the near object is less than about 70 cm away based on data cited by Held et al.(2) Moreover, because defocus blur asymptotes with increasing distance beyond fixation, the change in blur beyond the point at which it can be detected will likely be below discrimination thresholds for most fixation distances.

How does availability of detectable disparity compare to blur? Foveal disparity detection is far more sensitive, with thresholds near hyperacuity levels ($\delta < 10$ arcsec; Blakemore, 1970; Howard & Rogers, 2002). Thresholds for disparity detection do increase with retinal eccentricity to about 2 arcmin at 10° eccentricity (Blakemore, 1970), but this is still well below available δ for a wide range of fixation distances and depth intervals (Figure 2b). Moreover, disparity discrimination thresholds in near eccentricity increase more gradually for pedestal disparity than at the fovea. For example, discrimination thresholds for a 60-arcmin pedestal are similar from 0°–10° eccentricity having a value of about 5–6 arcmin (Blakemore, 1970). Also, disparity detection and discrimination thresholds decline more gradually in the near periphery for low spatial frequencies (Howard & Rogers, 2002). Thus, in contrast to blur, disparity is detectable and discriminable for a large range of fixation distances and depth separations (Figure 2c).

3 Binocular visual geometry and the utility of blur for motor tasks

The utility of a depth cue for motor tasks depends on its detectability and discriminability under natural task conditions rather than those defined in the laboratory. Held et al.'s conjectures regarding the use of blur for precision depth judgments and motor tasks are based on an artificial binocular task geometry (Figures 1a and b) and fixation distance (28 cm) that create large absolute disparities and diplopia for the farther object. What could be the utility of programming motor tasks or determining precise depth for objects seen only in double vision? In natural viewing, one generally fixates a region between two points (Figure 1c; e.g., the center of an object to be grasped) or one free scans. The fixation distance Held et al. tested is significantly shorter than even most natural close-range visual

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(2) Wang, Ciuffreda, and Irish (2006) foveal detection thresholds (based on a method of adjustment) are 2–6 times higher than consensus estimates of about 0.1 dioptres, which suggests that their peripheral values may also be high. However, the lower foveal detection estimates in other studies are based on discriminating between sequential presentation at the same visual location or comparing spatially adjacent comparisons (Watson & Ahumada, 2011). Stimulus configuration under typical viewing of spatially extended objects (Figures 1a and c) will rarely permit such close spatial discrimination. Thresholds under natural viewing will likely be somewhere between these empirical values. Even assuming one-third the value of Wang et al.'s thresholds would yield a maximum distance for detectable blur in near periphery of about 2–3 m fixation, still far below the range of operation of disparity (see Figure 3).

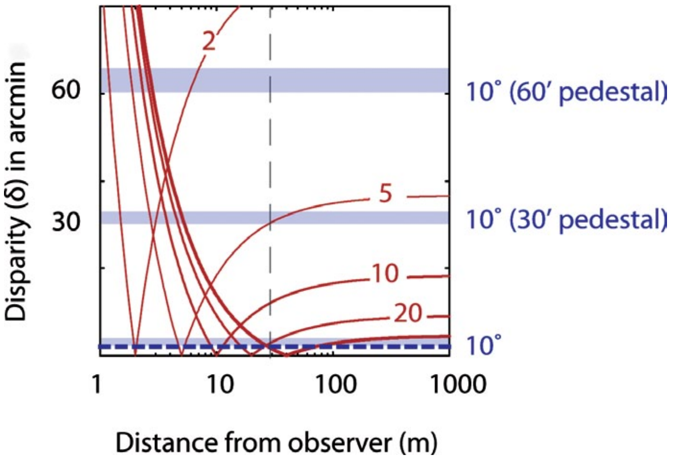

Figure 3. Disparity detection and discrimination in near-eccentric vision. Red lines indicate absolute disparity as a function of distance from the observer for five fixation distances (assuming 54-mm IOD). The thick blue dashed line at the bottom of the graph is the disparity detection threshold at 10° eccentricity. The width of the light blue shaded area is the discrimination threshold for zero pedestal. The widths of the two upper blue shaded regions indicate discrimination thresholds for pedestal disparities of 30 and 60 arcmin at 10° eccentricity (Blakemore, 1970). Note that there are no pedestal disparities greater than 60 arcmin for fixation distances beyond about 4 m. For a fixation distance of 5 m, there are discriminable disparities for objects all the way from less than 1 m up to 30 m beyond fixation (gray dashed line), even for an eccentricity of 10° (middle thin blue dashed line).

fixation (reading, manual tasks), and would only be used for fine depth tasks and judgments that do not create large disparity pedestals. For farther fixation distances, both absolute disparity pedestal and diplopia reduce sharply beyond fixation, but relative disparities will still be detectable and discriminable. For example, beyond about 4-m fixation, there are no absolute divergent disparities exceeding 60 arcmin; however, these disparities are of sufficient size to be detectable and discriminable (even outside the fovea) to beyond 40 m (Figure 3). Thus, disparity is exquisitely suited for making precise depth judgments appropriate to different viewing distances: small depth intervals at near viewing and large depth intervals at far viewing.

This is not the case for blur. According to Held et al.'s data, when fixating an object less than a foot away (28 cm), blur becomes more discriminable than disparity only when a point is more than 3 cm away from fixation. However, such close visual inspection would typically be used only to discriminate fine depth changes on the order of millimeters, for which disparity is ideally suited. Similarly, on the basis of their data, fixating an object at 50-cm (typical of manual tasks) blur would only be discriminable for point separations of more than 15 cm, which is outside the range of most normal grip apertures. For distances of only 1 m, point separations would have to exceed 80 cm before blur kicked in. Moreover, these values for blur are based on assuming the task geometry where one fixates one point to determine the distance to another point (Figure 1a). Geometries such as Figure 1c will provide even less discriminable blur but more optimal relative disparity information.

In summary, for most natural depth judgment tasks, disparity is detectable and discriminable for a large range of fixation distances, depth separations, and eccentricities (Blakemore, 1970; Howard & Rogers, 2002), whereas detectable and discriminable blur will be restricted to near fixation distances (Figure 2c). Held et al. have demonstrated that defocus blur is more discriminable than disparity at near fixation and high levels of diplopia, but this does not imply that blur can be used to derive quantitative depth as they claim. The depth separations at which they find blur becomes more discriminable bear little utility to fixation-distance-relevant depth judgments. The results therefore do not alter the view that relative defocus blur is likely only an ordinal depth cue (Mather & Smith, 2002; Marshall et al., 1996). This analysis also suggests that it is unlikely that ubiquitous effects in stereoscopic display systems such as the "puppet-theatre effect" and "gigantism" are primarily due to a mismatch between disparity and blur acting as complementary depth cues, as claimed by Held et al. These effects occur even at viewing distances of 15 m and beyond (e.g., cinema viewing). At such fixation distances, defocus blur is well below detection/discrimination thresholds (Figure 2a) and, therefore, no comple-

(3) These effects occur even in the absence of artificially introduced "incorrect" blur in the image.

Movie 1. Depth-of-focus blur gradients and depth perception. Photographs of natural scenes with blur gradient applied above and below the central horizontal region of interest (ROI) demarcated by the black dotted lines. There are no differences in relative blur in the ROI between the blurred versions and the original photographs. Compare the impression of depth in the ROI between the blur and no-blur versions of the images (click on the image; a higher quality clip is available for download on the i-Perception Web site). In the plant images, there is a more definitive sense of separation between leaves and a greater sense of three-dimensionality. In the rock images, there is a greater impression of the undulation of the rock, even though the undulations (bulges and indentations) are orthogonal to the direction of the blur gradient (vertical).

mentarity between disparities and blur is expected.(3) Rather, these effects can be more conventionally explained in terms of the mismatch between depicted familiar object distance/scale and the image distance/scale and disparities.

4 Blur and quantitative depth perception

How might blur contribute to quantitative depth perception? The pattern of blur due to the change in depth-of-focus with viewing distance has been shown to be a quantitative cue to egocentric distance perception (Vishwanath & Blaser, 2010). Depth-of-focus reduces for closer viewing distances, producing a characteristic increase in defocus blur in regions away from the central zone of fixation. The potential role of depth-of-focus blur in near-distance perception was first inferred from the photographic technique of tilt–shift miniaturization (Vishwanath, 2007). Here, objects in photographs of real life scenes appear much closer and miniaturized when blur gradients are simulated in the image with optical or software techniques. This more robust statistical relationship between viewing distance and depth-of-focus (particularly when viewing along a ground plane) suggests that blur may be more useful as an egocentric distance cue than a depth cue for most animals that lack binocularity.

However, distance information is required by the visual system to derive absolute depth relations from relative depth cues (Howard & Rogers, 2002). Depth-of-focus blur could contribute to depth perception by scaling relative depth cues (e.g., shading and perspective) to disambiguate absolute depth relations in the absence of vergence and binocular disparities. The video sequence in Movie 1 demonstrates an effect that appears to support this idea.

The images consist of original photographs of natural scenes and an altered version with a generic blur gradient added to the upper and lower regions. Consistent with the role of blur as a distance cue, the objects in the blurred version of each image appear closer. Furthermore, depth among components of the scene is also visibly enhanced, an observation confirmed with naïve observers (Vishwanath & Hibbard, 2009). This enhancement cannot be explained as a direct effect of relative blur on depth perception because there is no difference in the relative blur of objects/parts in the central region between the two versions of each image. Moreover, the blur applied is not locally consistent with depth structure depicted in any of the images. A potential explanation is that such enhancement of depth impression is due to the scaling of relative depth specified by the pictorial cues via the distance information provided by blur (Vishwanath, 2010).

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