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Effective 3-D shape discrimination survives retinal blur

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A single experiment evaluated observers' ability to visually discriminate 3-D object shape, where the 3-D structure was defined by motion, texture, Lambertian shading, and occluding contours. The observers' vision was degraded to varying degrees by blurring the experimental stimuli, using 2.0-, 2.5-, and 3.0-diopter convex lenses. The lenses reduced the observers' acuity from −0.091 LogMAR (in the no-blur conditions) to 0.924 LogMAR (in the conditions with the most blur; 3.0-diopter lenses). This visual degradation, although producing severe reductions in visual acuity, had only small (but significant) effects on the observers' ability to discriminate 3-D shape. The observers' shape discrimination performance was facilitated by the objects' rotation in depth, regardless of the presence or absence of blur. Our results indicate that accurate global shape discrimination survives a considerable amount of retinal blur.

Across the world, uncorrected refractive error is a significant cause of visual impairment and blindness (R. Dandona & L. Dandona, 2001; Resnikoff et al., 2004). In some regions, corrective lenses (eyeglasses or contacts) are either unaffordable or unavailable. It has recently been estimated (L. Dandona & R. Dandona, 2006) that 259 million people worldwide possess low vision due to uncorrected refractive error and have a presenting visual acuity of 6/18 (which corresponds to 3 min minimum angle of resolution [MAR]) or less. Uncorrected refractive error particularly raises problems for older adults (see, e.g., Michon, Lau, Chan, & Ellwein, 2002; Nirmalan et al., 2002). For example, in a Hong Kong study, Michon et al. found that 41.3% of the 3,441 older adults who were examined possessed a presenting acuity that was less than 6/18 in at least one eye. This percentage increased to 73.1% for those adults who were 80 years of age or older. Similar results for Nepal were reported by Pokharel, Regmi, Shrestha, Negrel, and Ellwein (1998). In the United States, it has been demonstrated (Owsley, McGwin, Scilley, Meek, Dyer, & Seker, 2007; Owsley, McGwin, Scilley, Meek, Seker, & Dyer, 2007) that older adults who are residents of nursing homes have higher rates of visual impairment from uncorrected refractive error than do similar community-dwelling older adults.

At first glance, one might think that uncorrected refractive error would have negative effects on the visual ability to perceive the shape of environmental objects. However, this is not necessarily the case. Consider Figure 1, which depicts photographs of an ordinary object (a bell pepper, *Capsicum annuum*). In the upper left portion of Figure 1, the object is clearly focused; as one proceeds in a clockwise direction, increasing amounts of blur are present. An analysis of the photographs in Figure 1 is shown in Figure 2. This figure depicts isointensity contours (isophotes): All of the points within a single dark or light band in Figure 2 have similar (or identical) intensities in the original photographs (e.g., see also Figure 3 in Koenderink, Kappers, Todd, Norman, & Phillips, 1996). Upon examination, one can see that the isophotes in Figure 2 correspond to actual 3-D features on the original object, regardless of the amount of blur. For example, note from the focused photograph in Figure 1 that this object possesses two prominent troughs. One trough is approximately vertical and travels in an upper left to bottom right direction. The second trough is approximately horizontal and runs along the bottom left portion of the object. The physical 3-D structure of these two troughs is reflected in the pattern of isophotes. Even the isophotes of the blurriest photograph contain these two prominent image features: Some of the dark and light bands run approximately vertically in an upper left to bottom right direction through the center of the image, whereas other bands run in a nearly horizontal direction toward the bottom left. As one can see from this example, patterns of isophotes in optical images contain significant amounts of information about 3-D object shape (see, e.g., Koenderink & van Doorn, 1980). Figures 1 and 2 demonstrate that this optical information about 3-D shape is available even within blurred images.

If there are significant numbers of adults around the world whose visual impairment is caused by uncorrected refractive error (e.g., refractive error was the leading cause of the visual impairments found by Michon et al., 2002), what are the consequences? Does the degradation of vi-

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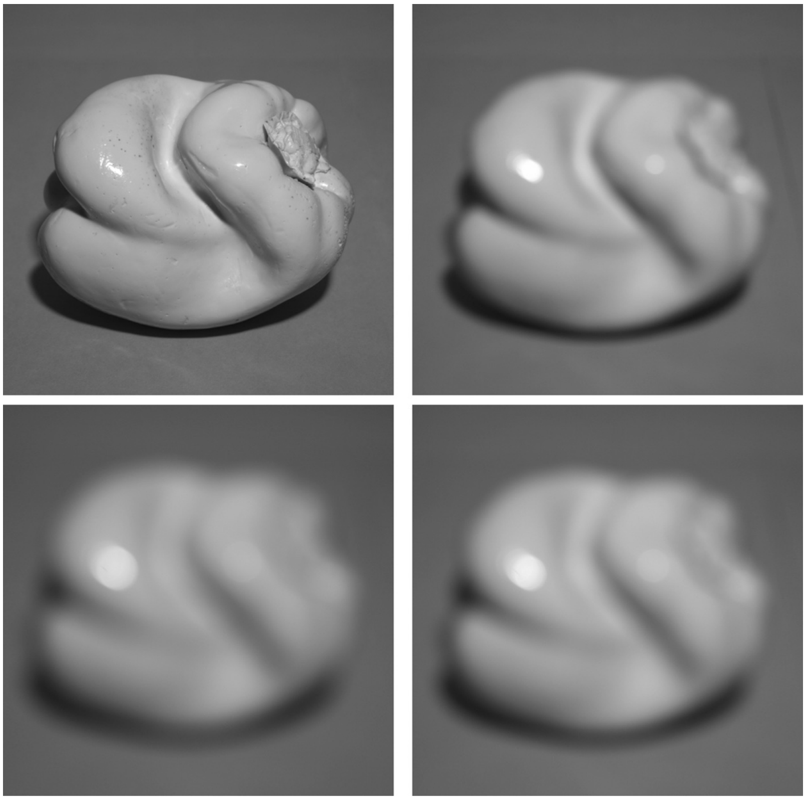

Figure 1. Photographs of a common natural object (a bell pepper, *Capsicum annuum*). A focused photograph is presented at the upper left. As one progresses clockwise from the upper left, the photographs contain increasing amounts of blur.

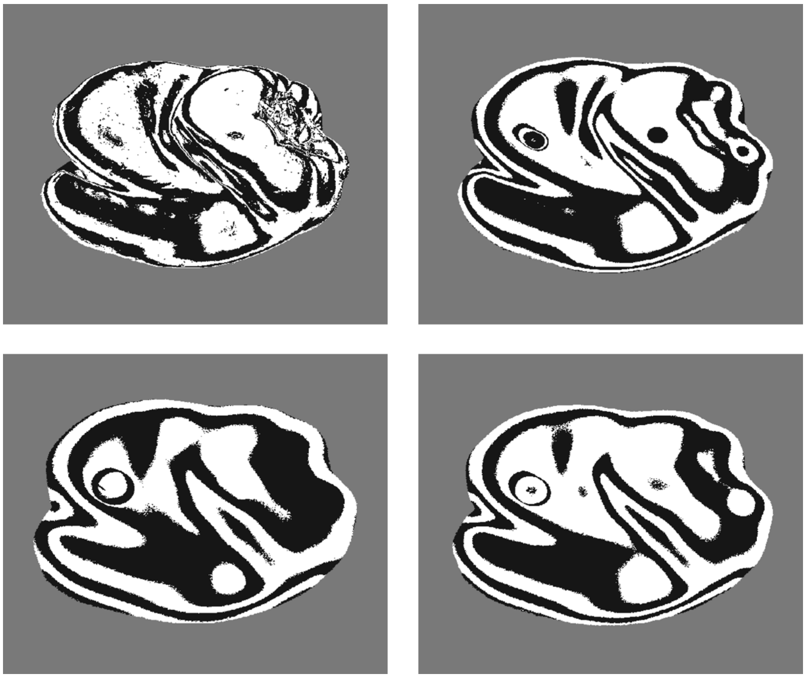

Figure 2. The isophotes (isointensity contours) of the photographs presented in Figure 1 (see the text for details).

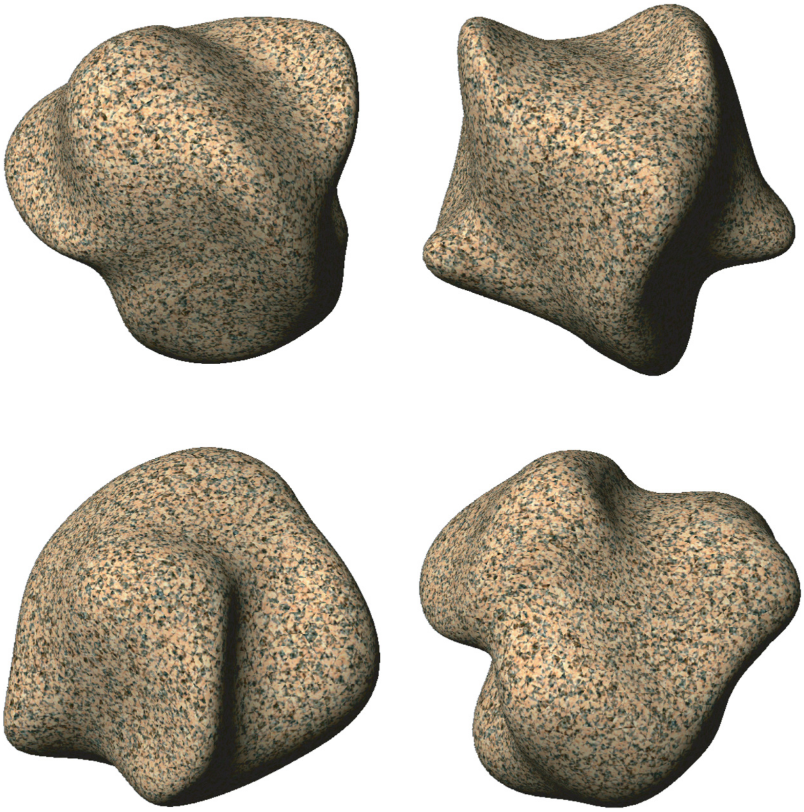

Figure 3. Representative examples of the objects used as experimental stimuli.

sual acuity that accompanies refractive error result in a deterioration of the ability to visually perceive the 3-D shape of objects? The results of the analysis shown in Figure 2 suggest that this might not necessarily be the case. Since a significant amount of information about 3-D object shape is preserved within blurred images, the ability to perceive and discriminate 3-D object shape might survive relatively large amounts of retinal blur. The primary purpose of the present study was to investigate this issue.

METHOD

Apparatus

The experimental stimuli were created by an Apple Power Macintosh G4 computer and were displayed on a 22-in. Mitsubishi Diamond Plus 200 color monitor (resolution was 1,280 × 1,024 pixels). The observers monocularly viewed the stimulus displays through a viewing hood (see Norman, Bartholomew, & Burton, 2008). Because of the viewing hood, the observers could see nothing except the experimental stimuli. The viewing distance was 100 cm.

Experimental Stimuli

A set of 1,000 randomly shaped, smoothly curved objects was used as the experimental stimuli (Norman, Swindle, Jennings, Mullins, & Beers, 2009); the average size/diameter of the objects was approximately 13.3 cm (which corresponds to 7.6º of visual angle). The objects were optically defined by texture (which resembled red granite), Lambertian shading, and occlusion contours. Four representative objects are shown in Figure 3. In some conditions, the 3-D structure of the objects was additionally defined by motion (i.e., by the kinetic depth effect; see Braunstein, 1962; Norman & Lappin, 1992; Todd, Akerstrom, Reichel, & Hayes, 1988; Wallach & O'Connell, 1953). In the moving object conditions, the objects rotated (oscillated) in depth ±22º from a *home* orientation about a Cartesian vertical axis. At each individual frame transition, the objects always rotated 2º; the *motion waveform* was thus triangular. The frame update rate was 25 Hz; the objects therefore rotated at a rate of 50 deg/sec. The object surfaces were defined by the positions and orientations of 8,192 triangular polygons. The image shading was produced by illuminating the objects with a single-point light source, which was located at infinity up and to the left of the observers' line of sight (the slant of the light source was 30º). We used a standard reflectance model (see Foley, van Dam, Feiner, & Hughes, 1996), in which the ambient and diffuse reflectance components were set to 0.3 and 0.7, respectively. The simulated objects possessed matte surfaces (i.e., the specular component of the model was set to zero).

Procedure

On any given trial, the observers were shown 2 objects in succession; each was presented for 3 sec (the interstimulus interval was 200 msec). The first object on each trial was randomly chosen from among the set of 1,000 possible objects; its initial orientation in depth about the vertical axis was also randomly chosen (because of the random selection of objects and the random determination of orientation in depth, each trial was unique; the probability of obtaining the same object in the same orientation across two or more trials was vanishingly small). On half of the trials within an experimental block, the second object possessed the same 3-D shape as the first, whereas on the remaining trials, the second object possessed a different, randomly chosen 3-D shape. The observers' task was to indicate whether the 2 objects on any given trial possessed the *same* or a *different* 3-D shape. In order to make this task more challenging, on the *same* trials, we rotated the object in depth (about a vertical axis in the image plane) from the first presentation to the second by either 5º or 45º (this angular offset was applied in either a clockwise or a counterclockwise direction, as viewed from above). Each block of 30 trials was devoted to a particular experimental condition and consisted of 15 *same-shape* trials and 15 *different-shape* trials.

There were a total of 10 experimental conditions. Eight of these 10 conditions were formed from the orthogonal combination of two levels of angular offset (5º and 45º) and four levels of optical blur (the observers' visual acuity was degraded by viewing the experimental stimuli through 2.0-, 2.5-, and 3.0-diopter convex lenses, as well as a condition without blur). This method of degrading visual acuity (called the *observer method*; see Smith, Jacobs, & Chan, 1989) has been used previously by Ball and Sekuler (1986) and Straube, Paulus, and Brandt (1990). In these eight conditions, the objects' 3-D structure was defined by motion, in addition to image shading, texture, and occlusion contours. In the remaining two conditions (2.5-diopter blur and no blur), the objects were stationary, and thus their 3-D structure was defined only by image shading, texture, and occlusion contours. For these stationary conditions, only a single angular offset of 45º was used. By the end of the experiment, each observer had made a total of 300 shape discrimination judgments (30 judgments for each of the 10 experimental conditions).

Observers

Eleven observers participated in the experiment (mean age = 21.5 years, range = 19–25 years). Five of the observers were emmetropic, and the remaining 6 were ametropic (5 were nearsighted, and 1 was farsighted). The ametropic observers' vision was corrected; the supplemental blurring lenses were then applied, as described above. The observers' acuities in the no-blur and various blur conditions were assessed with a standard ETDRS eye chart (Precision Vision, Catalog No. 2195) at a distance of 1 m. The observers' visual acuities for the various blur conditions are shown in the right panel of Figure 4. The observers' acuities in the no-blur condition (LogMAR = −0.091) were not significantly different [$t(10) = 1.53$, $p = .16$] from the acuities of the 18- to 24-year-old group whose vision was evaluated by Elliott, Yang, and Whitaker (1995). All of the observers were either undergraduate or graduate students, and all volunteered to participate in the experiment (i.e., no remuneration was provided). Three of the student observers were coauthors (the two A.M.B.s and J.S.H.), whereas the remaining 8 observers were naive and had no knowledge of the previous literature, exact hypotheses under test, and so forth.

RESULTS

The author and nonauthor observers' results did not significantly differ in either the stationary [$F(1,9) = 0.01$, $p = .92$] or the moving object [$F(1,9) = 0.89$, $p = .37$] conditions. Likewise, the results of the emmetropic and ametropic observers (whose vision was corrected prior to any additional blurring) did not differ in either the stationary [$F(1,9) = 0.35$, $p = .57$] or the moving object [$F(1,9) = 2.26$, $p = .17$] conditions. These observers were therefore considered together in the following analyses. The various amounts of optical blur (produced by viewing the experimental stimuli through 2.0-, 2.5-, and 3.0-diopter lenses) had a significant effect on the observers' visual acuities [$F(3,30) = 127.1$, $p < .0001$, $\eta^2 = .93$]. As can be seen in the right panel of Figure 4, the observers' acuities deteriorated from −0.091 LogMAR in the no-blur condition to 0.924 LogMAR in the most blurred condition (a LogMAR acuity of 1.0, 20/200, or 6/60 often represents legal blindness; see, e.g., Hollins, 1989). Figure 4 (left panel) also illustrates a small but statistically significant main effect of blur on the observers' shape discrimination performance in the eight conditions that employed object motion [$F(3,30) = 3.6$, $p < .025$, $\eta^2 = .27$]. The shape discrimination performance shown in Figure 4 is plotted in terms of the signal detection measure d' (a d' value of zero indicates chance performance, whereas increasingly positive d' values indicate higher and higher magnitudes of perceptual sensitivity to differences in shape; see Macmillan & Creelman, 1991). The addition of blur also had a significant effect in the two stationary object conditions, according to the sign test ($x = 1$, $N = 9$, $p = .04$, two-tailed; see Siegel, 1956): The observers' d' values for shape discrimination in the no-blur and 2.5-diopter blur stationary conditions were 1.77 and 1.42, respectively.

The variation in angular offset (5º vs. 45º) within the eight experimental conditions that employed object motion also had significant effects on the observers' shape discrimination performance [$F(1,10) = 318.1$, $p < .0001$,

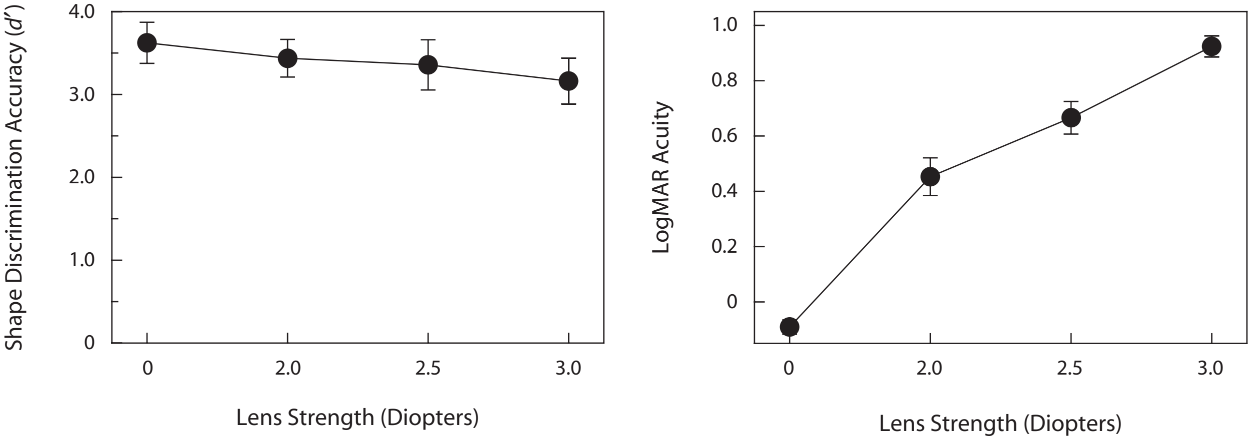

Figure 4. The left panel plots the results for the experimental conditions that employed object motion (rotation in depth). The observers' shape discrimination accuracies (d' values) are plotted as a function of the amount of optical blur (0 = no blur, and lenses of 2.0, 2.5, and 3.0 diopters produce increasing amounts of blur). The observers' visual acuities are plotted in the right panel for comparison. The error bars in both panels indicate ±1 *SE*.

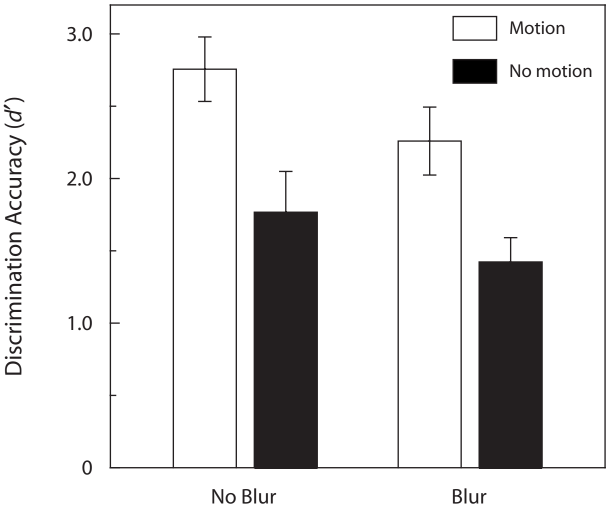

Figure 5. Experimental results (shape discrimination accuracies) for the 45º angular offset conditions. The blur in this figure represents the amount of blur produced by a 2.5-diopter convex lens. Separate results are plotted for the motion and no-motion conditions to permit comparisons. The error bars indicate ±1 *SE*.

$\eta^2 = .97$]. The observers' d' values dropped from an average of 4.4 in the 5º angular offset conditions to 2.4 in the 45º angular offset conditions. The angular offset × blur interaction was not significant [$F(3,30) = 1.0$, $p = .41$]; the effect of angular offset was thus similar for all of the levels of blur.

Figure 5 illustrates the effect of object motion (rotation in depth) on the observers' shape discrimination performance for the 45º angular offset conditions. The effect of motion was significant [$F(1,10) = 11.6$, $p < .01$, $\eta^2 = .54$]. The improvement in performance that accompanied the object rotation in depth was similar for both the no-blur and 2.5-diopter blur conditions [i.e., the motion × blur interaction was not significant; $F(1,10) = 0.1$, $p = .76$].

DISCUSSION

In our study, the observers' shape discrimination ability was influenced by several factors, including (1) the magnitude of the angular offset applied on the *same* trials, (2) the presence or absence of motion (object rotation in depth), and (3) the magnitude of blur. The influence of angular offset was not surprising. Similar studies in the past (e.g., Hayward, Tarr, & Corderoy, 1999; Norman et al., 2008; see also Vanrie, Willems, & Wagemans, 2001) have obtained viewpoint-dependent performance—that is, that the ability to recognize and/or discriminate an object's shape is influenced by changes in its orientation in depth. Objects do not necessarily look the *same* after being rotated in depth. Although it is true that our observers' judgments were adversely affected by the increase in angular offset, it is important to keep in mind that the observers were still performing well (in an absolute sense) for an angular offset of 45º. In this case, the average d' value of our observers was 2.14 (indicating a moderate sensitivity to shape that corresponds to approximately 75.6% correct, assuming unbiased responding).

The effects of motion in the present experiment are interesting and important. The significant improvements in performance that occurred when motion (object rotation in depth) was added to the no-blur experimental stimuli are typical for the *kinetic depth effect*. Object rotation in depth typically improves observers' abilities to perceive and discriminate 3-D shape (e.g., Braunstein, 1966; Norman, Todd, & Phillips, 1995). What is especially important about the present results (see Figure 5) is our finding that the presence of motion also improved the observers' performance in conditions with large amounts of optical blur. Typical computational models that recover 3-D structure from motion (e.g., Bruckstein, Holt, Katsman, & Rivlin, 2005; Hoffman & Bennett, 1986; Holt & Netravali, 1997; Koenderink & van Doorn, 1991; Ullman, 1979) require the presence of identifiable object features, such as surface texture elements or sharp corners. The 2-D projected motions of those surface features are used (along with certain assumptions, such as rigidity, fixed-axis motion, etc.) to recover information about 3-D object shape. Although traditional computational models do work when their assumptions are satisfied (see, e.g., Figure 3 in Norman & Todd, 1993), they cannot account for the facilitation in performance accompanying motion in the blurred conditions in the present experiment. This is because (1) the present objects were smoothly curved (and thus lacked sharp identifiable corners) and (2) the relatively large amounts of blur eliminated the visibility of the fine surface texture. Our results are consistent, however, with those computational models that recover 3-D structure from multiple, differently oriented views of Lambertian shaded objects (Jin et al., 2008) or that recover 3-D structure from deforming (i.e., moving) boundary contours (Cipolla & Giblin, 2000; Hernández, Schmitt, & Cipolla, 2007; Mendonça, Wong, & Cipolla, 2001; Wong & Cipolla, 2004).

A review of past research demonstrates that the effect of blur depends greatly on the type of task that an observer is asked to perform. Performance on some tasks is resistant to blur. Such tasks would include (1) motion detection (Whitaker & Buckingham, 1987), (2) motion direction discrimination (Ball & Sekuler, 1986), (3) steering (Owens & Tyrrell, 1999), (4) the monocular perception of egocentric distance (Tarampi, Creem-Regehr, & Thompson, 2010), and (5) the perception of stereoscopic depth (Julesz, 1971, p. 96). In contrast, there are many visually dependent tasks that are adversely affected by the presence of blur within retinal images: (1) reaching and grasping (Grant, Melmoth, Morgan, & Finlay, 2007; Melmoth, Finlay, Morgan, & Grant, 2009), (2) walking down stairs (Buckley, Heasley, Twigg, & Elliott, 2005), (3) self-motion detection (Straube et al., 1990), (4) the control of postural sway (Straube et al., 1990), (5) road hazard avoidance (Higgins, Wood, & Tait, 1998), (6) peripheral motion detection and sensitivity (Leibowitz, Johnson, & Isabelle, 1972; Post & Leibowitz, 1981), (7) reading (Chung, Jarvis, & Cheung, 2007; Thorn & Thorn, 1996), (8) road sign recognition (Higgins et al., 1998), (9) 2-D shape perception (of ellipses; Leibowitz, Wilcox, & Post, 1978), and (10) object recognition (Bravo & Farid, 2006; Wurm, Legge, Isenberg, & Luebker, 1993).

In their study, Wurm et al. (1993) presented their participants with 100 photographs of common food objects (apples, carrots, potatoes, etc.), and the participants were required to identify the objects. Both focused and blurred photographs were presented. Wurm et al. found substantive effects of blur: The observers' recognition errors tripled when blur was introduced (see their Figure 2). In the present study, we found only small (but statistically significant) effects of blur on 3-D shape discrimination (see the left panel of Figure 4). As for other visually guided tasks (e.g., steering vs. road hazard avoidance), it appears that when it comes to making judgments about 3-D objects, the effects of blur depend greatly on the particular task that observers are asked to perform (e.g., recognition vs. discrimination). When one considers the totality of the empirical results regarding the effects of optical blur, it seems clear that although blur does not always lead to reduced performance, it does produce significant deteriorations in important visually guided behaviors (walking down stairs, control of postural sway and balance, reaching and grasping, road hazard avoidance, etc.). The ongoing Vision 2020 initiative (e.g., Merabet & Wanye, 2008; Pizzarello et al., 2004) seeks to provide better access to eye care and affordable visual correction by the year 2020. A successful completion of this initiative (led by the World Health Organization and the International Agency for the Prevention of Blindness) will undoubtedly reduce the negative effects of uncorrected refractive error and will improve the daily lives of millions of people.

AUTHOR NOTE

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