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Vision Research 47 (2007) 1245–1252
Vision Research
www.elsevier.com/locate/visres

Conceptual model of human blur perception

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Received 16 October 2006; received in revised form 4 December 2006

Abstract

An empirically based, conceptual model of human blur perception is presented. It incorporates the concepts of blur detection and blur discrimination in depth, and across the central and peripheral retina, in two- and three-dimensional visual space. Key aspects of the model are its dynamic nature, predictability regarding the blur-based depth-ordering of objects, patterns of retinal defocus with far and near viewing, and interactions related to retinal defocus between the central and peripheral retina. Furthermore, a two-dimensional schematic representation of the blur-free region during near viewing is depicted in dioptric space. This model has implications with respect to accommodative control, depth perception, and refractive error development and progression.

Keywords: Blur perception; Depth-of-focus; Blur discrimination; Blur adaptation; Myopia; Retinal defocus; Space perception

1. Introduction

Blur perception is a basic attribute of the human visual system. In addition to its crucial role in ocular focusing to obtain clear retinal-imagery to resolve fine target details at the fovea (Ciuffreda, 1991, 1998), blur information also provides a cue to both the relative and absolute depth of objects in one's environment (Fisher & Ciuffreda, 1988, 1989; Mather, 1996, 1997). Thus, normal blur perception is important to accurately accomplish such critical and diverse tasks as visual scanning, ambulation, driving, and reading (Fisher & Ciuffreda, 1988, 1989). It may also have additional significance, as increased retinal defocus is believed to be an important environmentally based, myopigenic factor, especially as related to sustained nearwork (Gilmartin, 1998; Goss & Wickham, 1995; Hung & Ciuffreda, 1999; Hung, Ciuffreda, Khosroyani, & Jiang, 2002; Ong & Ciuffreda, 1995, 1997; Rosenfield & Gilmartin, 1998). Thus, understanding blur perception under naturalistic viewing conditions is paramount for optimal performance of one's daily activities, as well as providing insight into human refractive error development.

However, until relatively recently, little was known regarding non-foveally driven blur detection (Blatherwick & Hallett, 1992; Ronchi & Molesini, 1975). Furthermore, both foveal and non-foveal blur discrimination have received little attention (Campbell & Westheimer, 1958; Jacobs, Smith, & Chan, 1989; Walsh & Charman, 1988). In addition to the basic science ramifications, blur perception in the retinal periphery has recently been considered to be an important factor in myopia development with respect to the interaction of the fovea, and peripheral retina defocus profiles (Smith, Kee, Ramamirtham, Qiao-Grider, & Hung, 2005; Wallman & Winawer, 2004). Hence, once again, further work in this area may have important ramification with respect to basic blur mechanisms, as well as have clinical implications.

In the present paper, a new conceptual model of human blur perception will be presented. This model is quantitatively based incorporating both two- and three-dimensional representations of retinal defocus and blur in free space, with implications for depth perception and for myopia development.

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0042-6989/$ - see front matter
doi:10.1016/j.visres.2006.12.001

2. Key laboratory findings incorporated into the model

Over the past few years, we have been investigating various aspects of human blur perception (Ciuffreda, Wang, & Wong, 2005, 2006; Ciuffreda, Wang, & Vasudevan, in press; Vasudevan, Ciuffreda, & Wang, 2006a, Vasudevan, Ciuffreda, & Wang, 2006b, in press; Wang & Ciuffreda, 2004a, 2004b, 2005a, 2005b, 2006; Wang, Ciuffreda, & Irish, 2006; Wang, Ciuffreda, Vasudevan, 2006), that is both blur detection (i.e., the depth-of-focus, or just noticeable blur; DOF) and blur discrimination (i.e., just noticeable blur difference; JND) thresholds, with emphasis on the influence of the near retinal periphery ($\leqslant 8°$ from the fovea) in the global blur perception process. One of the key results is presented in Fig. 1. Mean blur detection and multiple blur discrimination thresholds are shown as a function of retinal eccentricity (Wang et al., 2006), with the test target consisting of a high contrast, black-and-white, isolated circular edge of variable radius. Both blur detection and discrimination thresholds increased with eccentricity, with the later being approximately 40% smaller than the former. Thus, blur discrimination was always more sensitive than blur detection, and both became less sensitive to blur as the target encroached farther into the near retinal periphery.

Other key findings included the following. First, objective blur thresholds were larger in myopic than in emmetropic eyes by 15% (Vasudevan et al., 2006a). This agreed with recent subjective blur thresholds findings (Rosenfield & Abraham-Cohen, 1999). Thus, myopic eyes were less sensitive to defocus blur. Second, blur adaptation decreased the blur detection threshold by 20% for foveal targets (Wang et al., 2006). Thus, blur sensitivity was enhanced by blur adaptation. Third, with increase in target size, blur thresholds increased (Ciuffreda et al., 2005). Thus, blur sensitivity decreased for larger targets.

In addition, the findings of others have been incorporated into our model. First, for retinal defocus and blur information in the far retinal periphery (>8°), the results of Ronchi and Molesini (1975) have been used. With their extended and complementary data, a mathematical relationship was developed to describe the DOF as a function of retinal eccentricity at the fovea, near retinal periphery (up to 8°), and far retinal periphery (up to 60°) (Wang & Ciuffreda, 2004a). It was best fit by a decelerating exponential function, $y = 6.83 - 6.08e^{-x/12.2}$, over the entire range, but by a linear function up to 8° ($y = 0.89 + 0.29x$). It was speculated that this relationship could be attributed to four primary factors (Wang & Ciuffreda, 2004a, 2005a): cone and ganglion cell retinal distribution, sharpness overconstancy, visual optics, and visual attention, thus involving interactive anatomical, physiological, optical, and perceptual components. Second, recent MRI results suggested that myopigenic retinal defocus effects were restricted to the posterior 25% of the globe, thus including approximately a 30° radius circumscribed with respect to the fovea (Gilmartin, Logan, & Singh, 2006; Gilmartin, Singh, & Logan, 2006; Singh, Logan, & Gilmartin, 2006). Third, recent qualitatively described findings related to blur both in depth (Flitcroft, 2006) and across (Wallman, 2006; Wallman & Winawer, 2004) the visual field under naturalistic conditions have been incorporated.

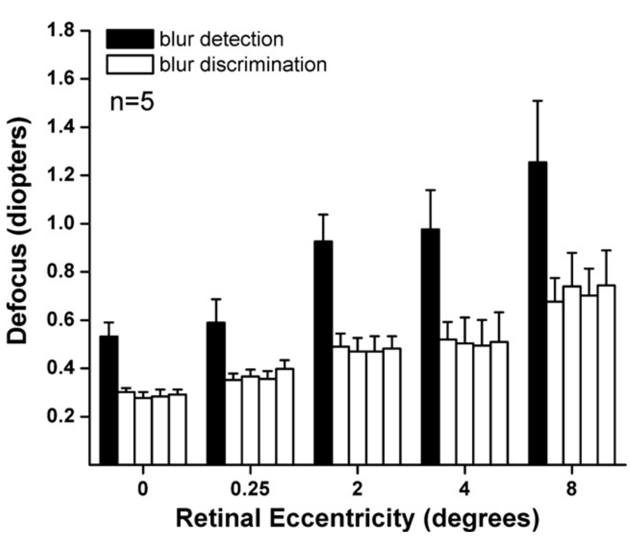

Fig. 1. Blur detection and blur discrimination as a function of retinal eccentricity. Plotted is the mean + 1SEM.

3. Two-dimensional model of blur perception

Two-dimensional conceptualization of the model is presented in Fig. 2. It shows a dioptrically scaled, schematic representation of the zone of clarity (i.e., the total depth-of-focus) projected into physical space and the four successive equiblur discrimination zones, both in depth and across the near retinal periphery, for simplicity under monocular viewing conditions; a more complex binocular representation has been presented elsewhere (Wang et al., 2006). In a recent study from our laboratory (Vasudevan et al., 2006a, 2006b), the proximal and distal halves of the depth-of-focus were found to be statistically equivalent. Thus, it has been assumed that blur sensitivity was dioptrically symmetric for both distal (i.e., myopic) and proximal (i.e., hyperopic) retinal defocus across the field with respect to its correlated point of conjugacy (see Wang & Ciuffreda, 2006 for a review).

These ideas are presented in detail in Figs. 2a–d. In Fig. 2a, the constellation of points conjugate with the retina (i.e., the zero retinal defocus plane) as a function of retinal eccentricity is presented (Ferree, Rand, & Hardy, 1931), with the refractive state of the myopic eye becoming relatively more hyperopic with increased retinal eccentricity (Stone & Flitcroft, 2004). The target, T, is positioned in front of the conjugate focal plane per the predicted near lag of accommodation (Ciuffreda & Kenyon, 1983; Morgan, 1968). In Fig. 2b, the thin solid lines represent the proximal and distal limits of clarity, or total DOF depth range. Any object situated within this region would be perceived to be "in focus" despite small differences in the magnitude of retinal defocus. This region of perceived target clarity progres-

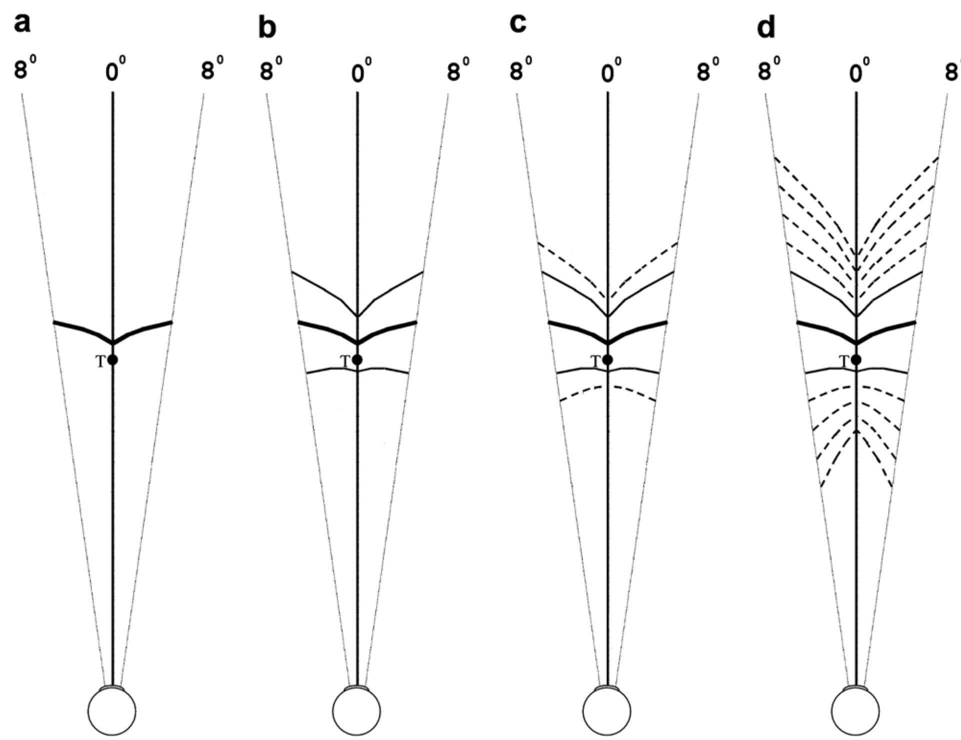

Fig. 2. Stepwise development (a–d) of the two-dimensional blur perception model (schematic representation). See text for details.

sively increases with retinal eccentricity, both dioptrically and spatially, for a given level of fixed near focus. In Fig. 2c, the dashed lines represent the initial blur discrimination threshold limits both distally and proximally. They are approximately 60% of the magnitude of the blur detection thresholds over this same retinal extent. Hence, blur discrimination is more sensitive than blur detection both at the fovea and near retinal periphery (Campbell & Westheimer, 1958; Jacobs et al., 1989; Walsh & Charman, 1988; Wang & Ciuffreda, 2005a, 2005b; Wang et al., 2006). And, an object positioned anywhere within one of these zones would be perceived with an equal degree of slight blurriness, despite small differences in the magnitude of retinal defocus. If this equiblur zone is exceeded, a just noticeable difference (JND) in object blurriness would be perceived. In Fig. 2d, three additional equiblur zones have been added to provide for the sensation of successive blurriness at the fovea and across the near retinal periphery. With fixed focus at near, as an object transverses in depth across several of these equiblur dioptric boundaries, the relative degree of blurriness would change systematically and predictably, with these blur changes providing information to the visual perceptual system regarding the object's relative and absolute distance from the observer (Fisher & Ciuffreda, 1988, 1989; Mather, 1996, 1997); see later discussion.

4. Three-dimensional model of blur perception

Fig. 3 presents a three-dimensional, dioptrically scaled representation based on the relevant experimental findings described earlier, as well as the two-dimensional version presented in Fig. 2. For a fixed level of focus at near, the zero retinal defocus plane (heavy solid line), the limits of the DOF zone of clarity (thin solid lines), and the successive equiblur zones (dashed lines) are shown for a target that would be positioned conjugate with the fovea. Progressive changes in perceived blur across the different equiblur zones is demonstrated with a series of computer-simulated pictures. As stated earlier, such progressive and discrete changes in blurriness could provide reasonable depth information for targets positioned either at the fovea or in the near retinal periphery at different physical distances in depth (Wang et al., 2006).

5. Defocus patterns related to far and near viewing

To understand human blur perception, the retinal defocus patterns must be considered as a function of both viewing distance and stimulus array, as well as a function of the distal and proximal depth intervals within the context of the DOF and equiblur zones. It will first be described with respect to the fovea and near retinal periphery, and then expanded to include the far retinal periphery.

In Fig. 4, two far viewing conditions are presented (6 m and beyond). Fig. 4a represents a far viewing condition in which there are little, if any, intervening intermediate and near targets present. This might occur when observing either a plane or bird in flight against a cloudless sky, or when aiming at the hoop during a "free throw" in basketball. The isolated object of interest would be seen clearly, as it would lie within the distal edge of the DOF (Wang & Ciuffreda, 2006). There would be no blurred stimuli present,

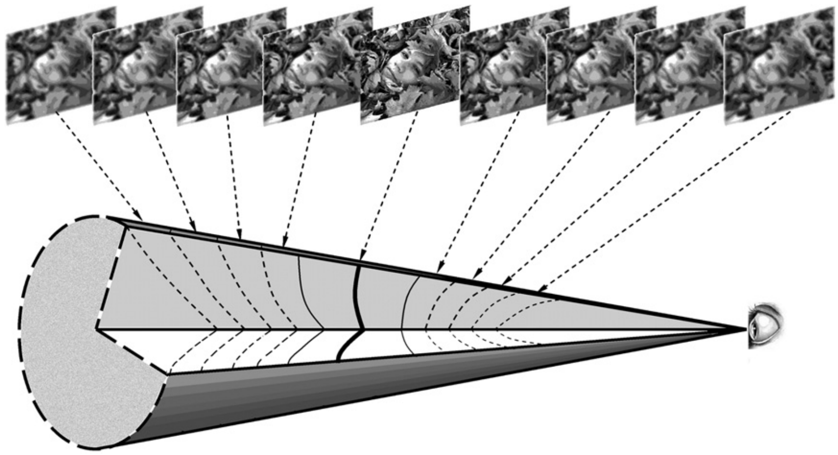

Fig. 3. Three-dimensional blur perception model and related blur imagery. See text for details.

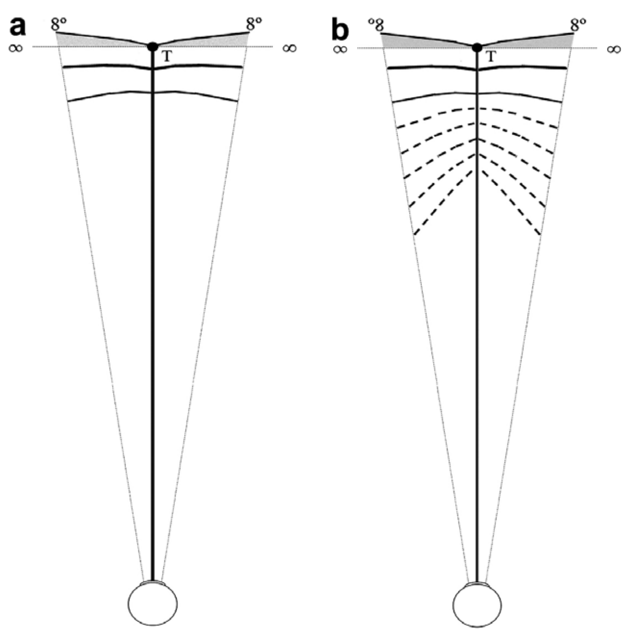

Fig. 4. Two-dimensional, schematic representation of two far-viewing conditions with related DOF and proximal equiblur planes. See text for details. T = target and ∞ = infinity.

and only about a maximum of 1D of combined distal (i.e., myopic) and proximal (i.e., hyperopic) retinal defocus present (Wang & Ciuffreda, 2006), with approximately equal amounts of defocus in each direction per hyperfocal refractive demands (Ciuffreda, 1998). In contrast, Fig. 4b presents a more typical far viewing condition. For example, this might include searching for a person in a crowded supermarket or looking at a large bird in a tree in the forest. In such cases, there is the clearly perceived object of interest, but now it is embedded within a detailed array of blur stimuli at intermediate and relatively near distances within each equiblur zone. There would be considerable blurred stimuli present now, with most of it being of the hyperopia retinal defocus variety, i.e., objects located in front of the focal plane, as compared with the more isolated far viewing condition (Fig. 4a). Thus, in this latter case (Fig. 4b), there is an

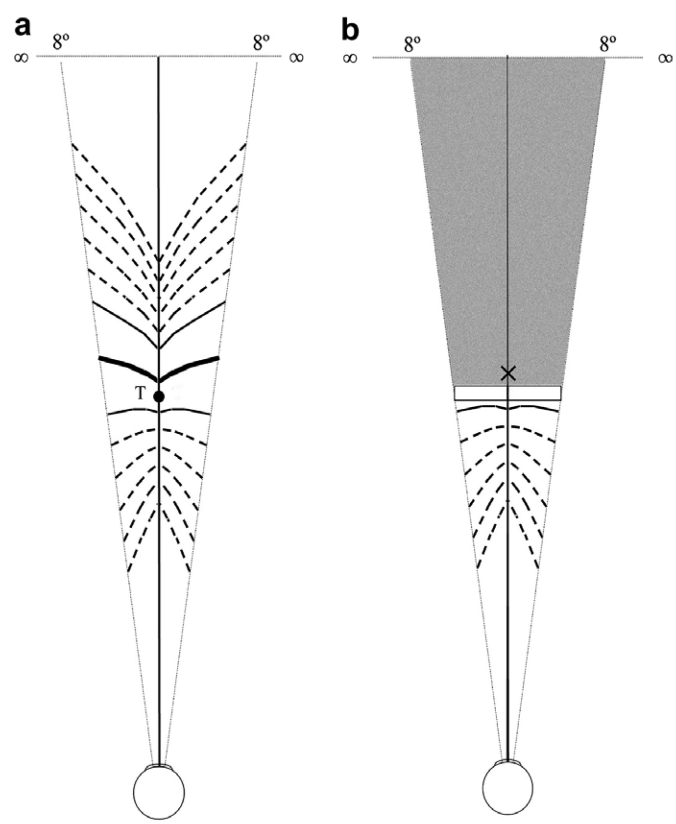

Fig. 5. Two-dimensional, schematic representation of two near-viewing conditions with related DOF and equiblur planes. Shaded area in (b) depicts occlusion of more distant objects at the fovea and near retinal periphery, open rectangle represents a book or computer screen, and the 'X' is the point conjugate with the fovea. See text for details. T = target and ∞ = infinity.

"imbalance" between the two directions of retinal defocus, and the related amount of perceived blur, whereas in the former case (Fig. 4a), the amount of retinal defocus present would be relatively small and nearly balanced between the myopic and hyperopic directions.

In Fig. 5, two near viewing conditions are presented (40 cm). Fig. 5a represents a naturalistic viewing condition in which there is both myopic and hyperopic defocus present. This might occur when looking at a cup on a crowded dining room table or when chatting with friends in a large classroom. An object of interest positioned within the DOF region would be seen clearly, while surrounding relatively distant and near objects would be perceived with varying but predictable degrees of blurriness within the successive equiblur zones. There would be a reasonable balance between the amount of myopic versus hyperopic defocus when integrated over time and weighted across both the near and far retinal periphery. Fig. 5b demonstrates another important naturalistic condition, namely reading a book or newspaper, working on a computer screen, or writing on a desk. In these situations, the object of interest would be seen clearly, as it would be positioned within the distal edge of the DOF (Ciuffreda, 1998; Ciuffreda & Kenyon, 1983; Morgan, 1968), with primarily hyperopic retinal defocus present for it and for other objects (e.g., one's hands, coffee mug, etc.) located in front of the viewing surface within the successive equiblur zones at near. Thus, there would be a marked imbalance in the weighted, time-averaged myopic versus hyperopic retinal defocus present, with the hyperopic variety greatly dominating. However, the far retinal periphery extending beyond the lateral range of the occluding object of interest would have reasonably balanced myopic and hyperopic retinal defocus present.

Lastly, in Fig. 6, the overall two-dimensional retinal defocus pattern for perceptually clear versus perceptually blurry targets is presented for near viewing (2.5D; 40 cm). Using the DOF and blur discrimination values obtained from our own studies involving the fovea and near retinal periphery (Fig. 1) (Wang et al., 2006), as well as those of Ronchi and Molesini (1975) involving the far retinal periphery, this dioptrically scaled, schematic representation of blur space (0–5D) was developed. Some key landmark values include the following: the DOF at the fovea is ±0.45D, and the DOF at 15° is ±2.5D. Thus, within our 5D, ±30° of visual blur space, at 15° of retinal eccentricity and beyond, the total DOF either equals or exceeds this dioptric region. Therefore, objects positioned in this extended region would be perceived as being "in focus". Despite the lack of blurriness at 15° and beyond, considerable retinal defocus would still be present. However, its effective myopigenic impact appears only to extend to 30° in the retinal periphery (Gilmartin et al., 2006; Gilmartin, Singh, et al., 2006; Singh et al., 2006). These values would be approximately 15% larger in myopic versus emmetropic eyes (Vasudevan et al., 2006a).

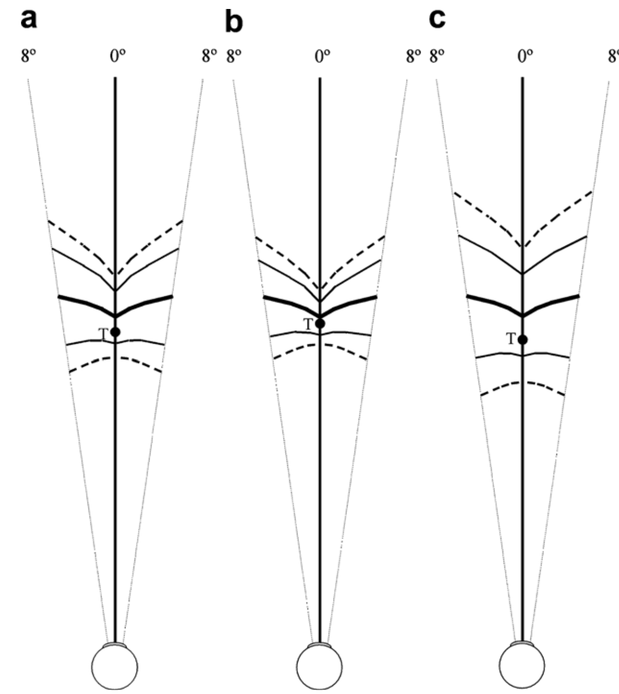

Fig. 7. Two-dimensional schematic representation showing the DOF and one equiblur region for three conditions. (a) Baseline condition. (b) Following a period of blur adaptation. (c) With an extended target. T = target.

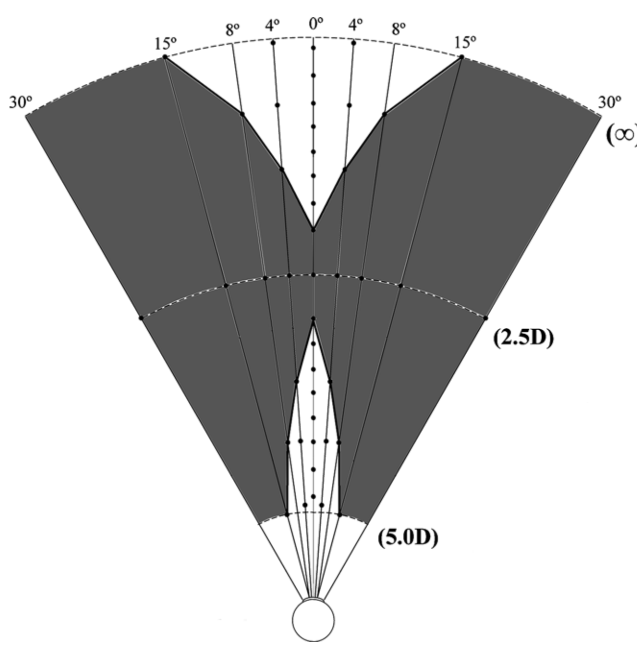

Fig. 6. Two-dimensional schematic representation of perceptually clear (shaded areas) and perceptually blurry (non-shaded areas) for 0–5D of visual space (±30°) during near (2.5D, 40 cm) viewing. Each solid dot in the non-shaded area represents a blur discrimination point; each solid dot on the heavy solid line represents the end point of the DOF region of perceptually clear imagery; each solid dot on the dashed line represents the 2.5D stimulus level. For simplicity, it is assumed that the accommodative stimulus and response are equivalent at 2.5D across the retina. See text for details.

6. Dynamic nature of blur perception

In current control system models of human accommodation (Ciuffreda et al., in press; Hung & Semmlow, 1980; Hung et al., 2002), the DOF element is considered to be static, fixed in amount (i.e., ±0.15D), and foveally driven only (Hung & Semmlow, 1980). However, recent evidence from our laboratory suggests that this is an oversimplification (Fig. 7). First, following a period of blur adaptation, the DOF decreased by 20% for a foveal target (Wang et al., 2006). For larger targets, it either decreased or increased by up to 10%. Second, the DOF increased with increased stimulus extent (Ciuffreda et al., 2005). For example, in some individuals, the increase exceeded 200% for a small foveal target of 0.25° versus an extended 8° target. Furthermore, attentional and perceptual aspects have been implicated (Ciuffreda et al., 2005). This notion of a dynamic DOF with stimulus attribute dependency is in agreement with a recent quantitative model of steady-state accommodation proposed by Jiang (2000), and an earlier conceptualization by Ciuffreda, Levi, and Selenow (1991). Jiang incorporated a pre-DOF term called "accommodative sensory gain" (ASG) based on stimulus attributes (e.g., contrast and size) and their relative effectiveness in driving the accommodative system response amplitude. Thus, as one changes gaze to various objects in the field, or sustains near focus, the effective DOF will change in magnitude continuously. Hence, understanding the dynamic nature of the DOF transcends the notion of a pure retinal-optical array and its related MTF (i.e., Modulation Transfer Function).

7. Implications for depth perception

Our current model of human blur perception with its dynamic nature has implications with respect to human depth perception. As demonstrated in earlier studies, retinal defocus blur and/or the correlated innervation to accommodation may provide one with reasonable information regarding the relative and/or absolute distance of objects in the visual field. For example, Grant (1942) found that subjects could set an isolated luminous test disk to approximately the same absolute distance as a reference disk at near using only image blur as a cue to distance. In a very recent study (Nguyen, Howard, & Allison, 2005), subjects were able to detect the relative distance of two back-illuminated vertical edges when relatively long exposure periods were permitted. Therefore, retinal blur enabled the subjects to judge target distance differentially in the absence of other depth cues. In an earlier investigation, Fisher and Ciuffreda (1988) demonstrated that motor efference and/or sensory feedback related to the blur-driven accommodative response could serve as a sufficient cue to estimate the absolute distance of an isolated target (i.e., a reduced Snellen chart) in visual space. Subjects were instructed to accommodate on, and then estimate, the absolute distance of a monocularly viewed target in a Badal optical system based on defocus blur information alone. Subjects were able to accommodate accurately on each near target (2D–6D) presented, as well as estimate their apparent absolute distance using a kinesthetic approach. The depth-ordering of the targets was precise. However, a constant bias with visual spatial compression was evident.

The perceptual differences in retinal-image blurriness attributed to the different equiblur zones contain relative depth information with respect to objects in visual space. That is, based on the differential retinal defocus and related blur, and correlated contrast changes associated with each equiblur zone, one can ascertain which object is either dioptrically closer or farther from the plane of focus as compared with another object or objects in the visual field (Mather, 1997; O'Shea, Blackburn, & Ono, 1994, 1997). In addition, as shown in earlier studies (Mather, 1996; Mather & Smith, 2002), the border between blurred regions and sharp regions can be used to establish the depth-order of objects. For example, an out-of-focus target with a blurry textured region and a blurry border was perceived to be located proximal to the plane of focus, while an out-of-focus target with a blurry region and a sharp border was perceived to be located distal to the plane of focus. Moreover, information derived from image blur can be integrated by the visual system with other visual cues (e.g., retinal disparity, size, interposition, etc.), which would assist in enabling one to judge the depth order of objects over a range of distances (Ciuffreda, 2002; Ciuffreda & Engber, 2002; Mather, 1997; Mather & Smith, 2000). Furthermore, the addition of blur information can improve the speed and accuracy in such a depth-ordering task (Mather & Smith, 2004). Lastly, all of these visual cues can be integrated with non-visual cues (e.g., proprioception) for additional cue reinforcement and resultant improved accuracy (Reading, 1983; Sun, Campos, Young, & Chan, 2004).

8. Implications for myopia

As mentioned in Section 1, there is a growing body of evidence pertaining to involvement of the far and near retinal periphery, and their interaction with the fovea, with respect to retinal defocus-based myopigenesis, at least in lower species (Smith et al., 2005; Wallman & Winawer, 2004). Myopes have relative hyperopia in the retinal periphery (i.e., larger axial length compared with equatorial diameter) when compared with their central foveal refractive state (Stone & Flitcroft, 2004; Walker & Mutti, 2002). Recently, this prolate eyeshape has been confirmed objectively using MRI techniques in human myopic eyes by Gilmartin et al. (2006), with defocus-related shape changes occurring only within a 30° radius of the fovea at the posterior pole. A similar mechanism may be invoked in humans, with the hyperopic defocus in the far retinal periphery producing mild visual deprivation.

Related to the above, a recent study performed on monkeys suggested that when the fovea was destroyed with a laser, the peripheral retina alone could provide sufficient retinal defocus-based information for emmetropization to still take place (Smith et al., 2005). However, Wallman and Winawer (2004) make a stronger statement: they suggest that peripheral defocus dominates over the central fovea during the emmetropization process. In closer agreement to Smith et al. (2005), we propose that the axial elongation typically observed in myopic eyes results from the interactive effects of retinal defocus between the fovea and peripheral retina, with both myopic and relative hyperopic retinal defocus being present simultaneously throughout different regions of the posterior pole of the retina. Furthermore, there is a weighting of those retinal defocus-based components which contributes to the growth of the eye, with the fovea being dominant.

When myopes are fully corrected at the fovea as done clinically, and their central residual refractive error approximates zero, there remains relative hyperopic defocus in the periphery (up to 0.75D or so) due to the difference in curvature between the posterior globe and peripheral retinal refractive plane (Walker & Mutti, 2002; Wallman & Winawer, 2004). This is in contrast to that found with purposeful myopic undercorrection (Adler & Millodot, 2006; Chung, Mohidin, & O'Leary, 2002), which would produce myopic defocus at the fovea and immediately contiguous areas, with relatively less hyperopic defocus in the near and far retinal periphery, thereby giving rise to overall reduced hyperopic defocus as compared with the conventional full refractive correction. This effect is due to the anterior myopic shift in the entire retinal refractive plane with undercorrection. Such an anterior shift would produce a central versus peripheral retinal defocus imbalance, as has also been suggested by Wallman and Winawer (2004), with its potentially myopiogenic consequences.

Lastly, a recent study (Morgan & Rose, 2005; Rose et al., 2006) suggested that an extended period of far viewing following nearwork plays a critical role in myopia development: it significantly inhibits myopigenesis. This situation is graphically depicted in Fig. 4a for the isolated far viewing condition, and in Fig. 5b for the semi-restricted near viewing condition. The former has minimal retinal defocus, and it is relatively directionally balanced, whereas the latter has considerable retinal defocus, and it is directionally imbalanced as it has considerably more hyperopic retinal defocus present. Such hyperopic defocus is an important environmentally based myopigenic factor (Gilmartin, 1998 ;Rosenfield & Gilmartin, 1998; Schaeffel, Troilo, Wallman, & Howland, 1990). Thus, there appears to be a time-integrated, bidirectional spatial summation effect of the hyperopic and myopic retinal defocus at the various retinal loci, which functions to modulate axial elongation. Hence, there may be an important interplay between near and far focus that is only recently being explored.

Thus, neural interactive effects in different depth planes at the same retinal loci, as well as across the lateral extent of the retina, appear to play critical roles in the development of refractive error, in particular myopia. These areas remain virgin territory for both human and animal investigations in the future.

Acknowledgments

We thank Dr. David Wong and Mr. Trevor Irish for their help with the data collection, and Drs. Rosenfield, Kapoor, and Aquilante for clinical evaluation of the subjects. Supported by NIH Grant T35 EY07079 and the Minnie Flaura Turner Memorial Fund for Impaired Vision Research.

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