

Binocular Rivalry and Head-Worn Displays

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Objective: We provide a review and analysis of much of the published literature on binocular rivalry that is relevant to the design and use of head-worn displays (HWDs). **Background:** This review draws heavily from both the basic vision literature and applied HWD literature in order to help provide insight for minimizing the effects of binocular rivalry when HWDs are worn. **Method:** Included in this review are articles and books found cited in other works as well as articles and books obtained from an Internet search. **Results:** Issues discussed and summarized are (a) characteristics of binocular rivalry, (b) stimulus factors affecting rivalry, (c) cognitive variables affecting rivalry, and (d) tasks affected by rivalry. **Conclusion:** This paper offers a set of recommendations for minimizing the effects of binocular rivalry when HWDs are used as well as recommendations for future research. **Application:** Considerations of the basic vision literature on binocular rivalry will provide insight for future design solutions for HWDs.

INTRODUCTION

Historically, a number of technological advances have been derived from the ability of humans to augment the use of their visual system through the interface with artificial devices (e.g., telescopes, microscopes, periscopes). During the past several decades, one advance has been the development of head-worn displays (HWDs). An HWD presents pictorial, symbolic, or sensory information to either one eye or both eyes of a user by way of one or two miniature visual displays mounted on the head via a helmet or other kind of arrangement (e.g., Melzer & Moffitt, 1997; Patterson, Winterbottom, & Pierce, 2006; Peli, 1999; Velger, 1998).

When synthetic information is presented to one eye, the device is called a monocular HWD; when the same synthetic information is presented to the two eyes, it is called a biocular HWD; and when synthetic information with binocular parallax (i.e., binocular disparity, the cue for stereoscopic depth perception) is presented to the two eyes, it is called a binocular HWD. Various kinds of information can be displayed on an HWD, such as text and graphics (e.g., flight symbology)

and real-time imagery with movement (Patterson et al., 2006). Also, one can perform different kinds of tasks while using an HWD, such as the cognitive processing of linguistic information, visual targeting, passive entertainment, and active immersion and locomotion.

Because HWDs can offer advantages over traditional displays, such as increased presence and ease of mobility (Velger, 1998), attempts have been made over the years to implement HWDs in various applications. One such application is the Joint Helmet-Mounted Cueing System (JHMCS), developed by Vision Systems International for use by the U.S. Air Force in a variety of fighter aircraft. The JHMCS involves a semitransparent monocular HWD that is used for the display of targeting symbology as well as other critical flight information. This HWD is viewed by one eye at the same time that the pilot views the natural world, or a simulation, with both eyes (a type of augmented vision).

The ability to augment vision with synthetic information or to present a virtual reality scene with an HWD could be important in many other applications, such as entertainment or other personal use (Hakkinen, 2004; Velger, 1998),

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dismounted infantry soldier displays (Glumm et al., 1998), command and control (Galster, Bolia, & Brown, 2005), medical procedures or training (Rolland, Biocca, Hamza-Lup, Ha, & Martins, 2005), maintenance training simulation (Wenzel, Castillo, & Baker, 2002), or high-performance racing (Velger, 1998).

Despite the potential advantages of HWDs, there can be problems with their use (Keller & Colucci, 1998). For example, Wenzel et al. (2002) found that aircraft maintenance workers reported problems such as eyestrain, headache, nausea, and dizziness when an HWD was used for aircraft maintenance training purposes, and Kooi (1997) reported significantly greater eyestrain with the use of HWDs relative to that found with a computer monitor. Morphew, Shively, and Casey (2004) found that self-reported nausea, disorientation, and oculomotor strain were greater with an HWD than with a standard computer monitor when an unmanned aerial vehicle control task was performed (however, see Peli, 1998). Laramee and Ware (2002; see also Hakkinen, 2004) found that response times for a table look-up task were elevated when the table was displayed on a semi-transparent monocular HWD.

In a study by Behar et al. (1990), a large number of helicopter pilots reported at least one visual complaint, such as visual discomfort, headache, blurred vision, or double vision, associated with flying an aircraft equipped with an Integrated Helmet and Display Sighting System (IHADSS), a monocular transparent HWD. About 70% of pilots noted that vision occasionally and unintentionally alternated between their left and right eye either during or after flight. Moreover, Rash, Verona, and Crowley (1990) stated that aviators using the IHADSS reported difficulty making the necessary attention switches between the eyes. An additional problem with HWDs is simulator sickness, which can be caused by a number of factors, such as vestibular-visual cue conflict (Draper, Viirre, Furness, & Gawron, 2001; Draper, Viirre, Furness, & Parker, 1997; Ehrlich, 1997).

These and other problems arise because HWDs present an unnatural viewing situation, a topic discussed by Patterson et al. (2006). In particular, HWDs may create a situation in which the two eyes receive very different stimulation, resulting in what is termed *interocular differences*. Such interocular differences can occur with different types of HWDs in different ways:

Monocular HWDs present information to one eye of a user while the other eye views a real-world or simulated outdoor scene. (The eye that sees the HWD information may also view the real-world scene when the monocular HWD is semitransparent.) Because only one eye receives the HWD information, interocular differences in stimulation are created. For example, in the case of a semitransparent monocular HWD, in which images from the HWD symbology are presented to one eye while both eyes view a real-world scene, images in the eye that receives the symbology could conflict with the images of the real-world scene in the other eye.

Biocular HWDs typically present the same information to the two eyes of a user, whereas *binocular HWDs* usually present the same information to the two eyes of a user but with a gradient of binocular parallax, thus providing the cue for stereoscopic depth perception. When the two eyes view the same or similar information, the potential for interocular differences to be created arises whenever there is significant optical misalignment or image distortion between the two eyes' views.

In other biocular or binocular applications, the user may be able to select one or the other eye with which to view complex imagery, such as a computer interface or sensor imagery, while viewing real-world or simulated real-world imagery with the opposite eye. This scenario would introduce significant interocular differences. In partial-overlap biocular or binocular displays, which are used to increase the overall size of the field of view, only a central region of the display is shown to both eyes, and areas to either side are seen by only one eye (i.e., a composite of binocular and monocular viewing), which creates interocular differences in the monocular regions (Velger, 1998, p. 56).

When the two eyes receive different stimulation on corresponding retinal areas, which precludes binocular fusion, a condition exists for creating a phenomenon known as *binocular rivalry*. Binocular rivalry refers to a state of competition between the eyes, such that one eye inhibits the visual processing of the other eye (Blake, 1989; Breese, 1899; Fox, 1991; Howard, 2002; Howard & Rogers, 1995; Levelt, 1965). The visibility of the images in the two eyes fluctuates, with one eye's view becoming visible while portions of the other eye's view are rendered invisible and suppressed,

which reverses over time, causing perceptual confusion.

Many authors (e.g., Blake, 2001, p. 5; Breese, 1899; Fox, 1991) have noted that the perceptual confusion arises because the two eyes signal to the brain that two different objects exist at the same time in the same location. Importantly, during binocular rivalry, portions of stimulation in one or the other eye fail to gain access to higher visual processing stages or conscious awareness (Howard, 2002, p. 285). Patterson et al. (2006) stated that binocular rivalry is important to study because it represents a visual process by which information or signals may be missed during HWD use. It is these authors' contention that binocular rivalry is a major reason why HWDs have not gained more widespread acceptance over the years.

Much of the evidence for the existence of rivalry when HWDs are used under real-world conditions is anecdotal in nature or based on subjective measures. For example, questionnaires and general feedback from pilots and other users are probably most often used to evaluate potential effects of rivalry with the use of HWDs in aviation (e.g., Behar, et al., 1990; Rash et al., 1990). Another frequently used technique is rating or tracking target stimuli visibility. For instance, Hershberger and Guerin (1975) used ratings of visibility to document the potential effects of 12 different parameters (e.g., luminance, transparency, resolution, etc.) affecting binocular rivalry with monocular HWDs. The difficulty involved with investigating a phenomenon such as rivalry, which may be intermittent and piecemeal, especially under applied conditions, may in some cases necessitate the use of primarily subjective methods. However, it is not clear that observers are always aware of decrements in performance attributable to rivalry.

For monocular HWDs, the existence of rivalry has caused several researchers to be wary of their use or to recommend that they be used only out of the user's direct line of sight (Hakkinen, 2004; Laramee & Ware, 2002; Peli, 1990). Hakkinen (2004), for example, stated that the occurrence of rivalry with a monocular HWD results in an annoying and straining experience for the user. In military applications, binocular rivalry is suspected to contribute to the visual problems, noted previously, associated with the U.S. Army's Apache helicopter IHADSS (Behar et al., 1990)

and to decrease the visibility of flight symbology in the U.S. Air Force JHMCS (Winterbottom, Patterson, Covas, Rogers, & Pierce, 2006; Winterbottom, Patterson, Pierce, & Taylor, 2006).

Using objective psychophysical procedures, Winterbottom, Patterson, Covas, et al. (2006) and Winterbottom, Patterson, Pierce, et al. (2006) found that binocular rivalry was present during the viewing of a simulated semitransparent monocular HWD. These studies used flight database imagery (i.e., an outdoor scene) and simulated HWD symbology that were relevant to the training of U.S. Air Force pilots.

In these studies, observers viewed a static outdoor scene and alphanumeric symbology under three viewing conditions: a simulated monocular HWD condition whereby the outdoor scene was viewed with both eyes and the HWD symbology was viewed with one eye (superimposed on the outdoor scene in that eye); a dichoptic condition whereby the outdoor scene was viewed with one eye and the symbology was viewed with the partner eye; and a binocular-fused condition whereby both outdoor scene and symbology were viewed by both eyes. A briefly presented small target was used as a rivalry probe stimulus, which is similar to methods reported in the basic literature (e.g., Fox & Check, 1968).

These authors found that recognition thresholds for the probe stimulus were elevated in the monocular HWD condition and in the dichoptic condition, indicating the presence of suppression. In both studies, the binocularly viewed outdoor scene exerted a suppressive effect on the monocular imagery but not vice versa. Winterbottom, Patterson, Covas, et al. (2006) also found that directed visual attention to either the outdoor scene or the HWD symbology did not alter the occurrence of the rivalry.

A phenomenon labeled "luning" within the applied literature on HWDs (e.g., Velger, 1998, p. 56) refers to the perceived darkening of contours defining the border between the monocular and binocular segments of displays in which there is partial overlap of the two eyes' views. It resembles a phenomenon called "permanent suppression," which is an aspect of binocular rivalry suppression in which a contour in one eye continuously suppresses a corresponding background area in the other eye. For both luning and rivalry, the same suppression processes are probably operative. Grigsby and Tsou (1994) noted that

binocular rivalry and luning are probably the most troublesome problems associated with partial-overlap displays.

Despite widespread acknowledgement in the applied vision literature of the potential for binocular rivalry to cause problems when HWDs are viewed (e.g., Patterson et al., 2006; Velger, 1998, pp. 53–55), there has been relatively little systematic applied research into the factors that minimize the occurrence of binocular rivalry under real-world operational conditions. The measures used in basic research to determine the existence of binocular rivalry have limited generalizability for many tasks that entail the use of HWDs.

For example, a common objective measure of suppression reported in the basic literature is the test probe method (e.g., Fox & Check, 1968; Wales & Fox, 1970), wherein the ability to detect, recognize, or respond to a small, briefly presented probe stimulus is degraded, which is taken as evidence of suppression. The suppression is induced by the viewing of dissimilar induction stimuli – the stimuli that provoke the rivalry. However, many tasks involving the use of HWDs entail the detection or recognition of relatively large stimuli presented for relatively long durations. Of course, it is assumed that the suppression revealed by the test probe method would operate to impair the visibility of portions of symbology, natural scenes, or objects viewed in applied situations, but there is little direct evidence supporting this assumption.

Other measures of binocular rivalry used in basic studies include subjective measures of rivalry alternations for which the observer indicates which eye's stimulus is visible at a given moment. Here, one can measure the existence of "exclusive visibility" (i.e., one or the other eye's image is exclusively visible) or mixed visibility (i.e., piecemeal rivalry whereby a patchwork of portions of the two eyes' images is seen). Although subjective measures would be relevant to the use of HWDs, they suffer from problems relating to demand characteristics or response bias wherein the response criterion of an observer, as to when an image appears visible, changes.

Moreover, the basic research on rivalry has typically used, as rivalry induction stimuli, images of sine wave gratings, Gabor stimuli, or random-dot displays, which are typically viewed dichoptically. Although these types of stimuli provide

important information about basic visual processes, their generalizability to the use of HWDs in the real world has not been substantiated. In short, in the basic literature, there are not many studies that illuminate how binocular rivalry would affect the kinds of tasks that would typically be performed when HWDs are worn in applied settings, and in the applied literature, there are not many studies conducted with adequate methodology to allow a clear identification of binocular rivalry as a mediating factor on performance.

Thus, there remains a large amount of applied research to be done on whether and how binocular rivalry affects the use of HWDs. Nonetheless, a key belief that undergirds this review is that binocular rivalry presents a potentially significant problem for HWDs, as documented previously, and that directions for future applied research, as well as new insights for potential design solutions for HWDs, can be gained by a thorough understanding of the basic literature on binocular rivalry. Thus, the purpose of this paper is to provide a review of many of the basic studies on binocular rivalry, in addition to many applied studies, in order to provide some recommendations for the use of HWDs as well as directions for future research. We begin with a discussion of the characteristics of binocular rivalry suppression.

CHARACTERISTICS OF BINOCULAR RIVALRY

Results from basic studies show that binocular rivalry can be provoked by interocular differences in orientation, hue, luminance, contrast polarity, form, size, and motion velocity and that it can occur over a wide range of light levels throughout the binocular visual field (Blake, 2001, pp. 8–9). The inhibition or suppression that binocular rivalry engenders acts upon a given area of the retina, not upon the stimulus per se (e.g., Blake, 1989; Blake & Fox, 1974).

Moreover, suppression takes time to develop. Stimuli presented for a duration of less than about 200 ms (Anderson, Bechtoldt, & Gregory, 1978; Blake, Westendorf, & Yang, 1991; Wolfe, 1986) or that are flickered repetitively (O'Shea & Crassini, 1984) do not provoke rivalry but, instead, may be seen as one combined image. Suppressed stimuli that are abruptly increased in luminance or contrast

(Blake & Fox, 1974) or are suddenly moved (Fox & Check, 1968; Walker, 1975; Walker & Powell, 1979) likely will become dominant.

As noted by Howard (2002, p. 295), dominance in rivalry correlates poorly with sighting tests of eye dominance (e.g., Washburn, Faison, & Scott, 1934). Sighting tests of eye dominance are one of three types of eye dominance tests, the other two being acuity dominance and rivalry dominance (Coren & Kaplan, 1973). The lack of correlation between sighting dominance and rivalry dominance is likely attributable to the operation of different underlying processes, with sighting dominance being based on perceived visual direction and rivalry dominance being based on inhibitory interactions.

However, other researchers have reported that sighting eye dominance affects rivalry dominance, causing the dominant-eye imagery to be seen more frequently (Collins & Blackwell, 1974). Also, Rash et al. (1990) stated it is likely that sighting dominance interacts with binocular rivalry to affect a pilot's ability to attend to one or the other eye. Thus, it remains to be determined whether operators could be screened on the basis of their sighting dominance and then selected for different types of HWDs.

Basic studies reveal that during suppression there is a general loss of sensitivity for all classes of stimuli that fall within the suppressed area of the retina (Blake, 2001, p. 16; Fox, 1991). This loss of sensitivity lengthens reaction time to briefly presented probe stimuli (Fox & Check, 1968; O'Shea, 1987) and can make large changes in a given stimulus (e.g., orientation) undetectable (e.g., Blake & Fox, 1974; Fox & Check, 1968; Walker, 1975). The loss of sensitivity can impair the ability of observers to visually guide attention to targets in the visual field (Schall, Nawrot, Blake, & Yu, 1993).

The collective results of a number of studies (e.g., Holopigian, 1989; Norman, Norman, & Bilotta, 2000; Ooi & Loop, 1994; Smith, Levi, Harwerth, & White, 1982; Wales & Fox, 1970) indicate that the average magnitude of the loss of sensitivity is on the order of 0.5 log units (or, equivalently, 1.5 d' units), which is similar to the magnitude of inhibitory effects found with other suppressive phenomena, such as visual masking. A temporal analysis of the periods of dominance and suppression indicates that they are sequentially independent random variables (Fox &

Herrmann, 1967; Lehky, 1995), which is consistent with the typical experience of observers, who report that they cannot predict suppression duration.

The size and shape of the visual field that is rendered invisible during suppression (i.e., the zone of suppression; e.g., Kaufman, 1963) varies over successive suppression events but is never tightly matched to the contours that constitute the rivalry-inducing stimulus. When that stimulus is small, the zone of suppression is larger than the stimulus, but when the stimulus is larger (e.g., image of a face), only portions may be suppressed at any given time, resulting in a visual field that appears as a patchwork or mosaic of dominance and suppression areas (Howard, 2002, p. 286).

Generally, the size of the zones of suppression are on the order of 6 to 15 arcmin for images containing high spatial frequency information (e.g., 6–10 cycles/°; Blake, O'Shea, & Mueller, 1992; Kaufman, 1963; Liu & Schor, 1994), but the zones of suppression may be larger with images containing low spatial frequency information (O'Shea, Sims, & Govan, 1997), with increasing retinal eccentricity (Blake et al., 1992; Howard, 2002, pp. 286, 297), and with low levels of illumination (O'Shea, Blake, & Wolfe, 1994) and high stimulus contrast (Liu & Schor, 1994). However, for individual suppression events, the size of a suppression area varies widely, in a haphazard pattern. Blake (2001, p. 11) noted that the zones of suppression within a given eye may show intraocular and interocular grouping with synchronized alternations based on common features, such as common hue (e.g., Alais & Blake, 1999; Kovacs, Pappathomas, Yang, & Fehér, 1996; Lee & Blake, 2004).

There are reports that binocular fusion can minimize the occurrence of binocular rivalry. For example, in a basic study, Blake and Boothroyd (1985) found that when fusible contours and rival contours were viewed at the same time, binocular rivalry did not occur and the stimuli were perceived as fused and stable. Kooi (1993) reported that rivalry was reduced by the introduction of a fusible window frame in both binocularly viewed and monocularly viewed scenes.

However, as we discussed previously, Winterbottom, Patterson, Covas, et al. (2006) and Winterbottom, Patterson, Pierce, et al. (2006) reported that binocular rivalry continues to exert some influence when monocularly viewed symbology is superimposed on an outdoor scene that is

viewed binocularly. This difference in results between the Blake and Boothroyd (1985) study and the Winterbottom, Patterson, Covas, et al. (2006) and Winterbottom, Patterson, Pierce, et al. (2006) studies is likely attributable to different methodologies.

With partial-overlap biocular or binocular HWDs, only a portion of the imagery is viewed binocularly and, thus, some fusion is present. Here, the phenomenon of luning occurs, which was described earlier. Whereas some authors of applied studies contend that luning is less noticeable after about 30 min of use (Grigsby & Tsou, 1994) and that it is not noticeable when an observer engages in a demanding task (J. Melzer, personal communication April 18, 2006), there is evidence that luning increases reaction time (Klymenko, Harding, Beasley, & Rash, 2001) and decreases detection performance (Kruk & Longridge, 1984) for targets appearing close to the monocular flanking regions of the partial-overlap HWD.

To minimize the effects of luning, Grigsby and Tsou (1994) recommended a partial overlap area of at least 40°, whereas Melzer and Moffitt (1997) and Klymenko, Verona, Martin, Beasley, and McLean (1994) recommended the introduction of false contour lines between the monocular and binocular regions. However, although the introduction of false contours decreases the appearance of fragmentation and luning, it remains to be empirically determined whether false contours, in fact, reduce suppression.

Another factor that may influence the occurrence of suppression in partial overlap binocular HWDs is the use of a convergent or divergent design. With convergent binocular overlap, the left eye views the right monocular flanking region and the right eye views the left monocular flanking region. With divergent binocular overlap, the left eye views the left monocular flanking region and the right eye views the right monocular flanking region.

Melzer and Moffitt (1997) and Klymenko et al. (1994) reported that luning appears to be less with a convergent design relative to a divergent design. Klymenko, Harding, Beasley, Martin, and Rash (1999) tested the effect of field-of-view configuration on visual performance by measuring response times and accuracy in a demanding target acquisition task. These authors showed that convergent overlap resulted in better performance relative to divergent overlap (although perfor-

mance was still best for the full binocular-overlap design). Thus, a convergent design is better if a partial-overlap configuration must be used in order to increase the size of the field of view.

This distinction between convergent and divergent overlap may be related to the idea that rivalry may be caused by the occurrence of ecologically invalid monocular images. Shimojo and Nakayama (1990) pointed out that the two eyes naturally have slightly different views in a 3-D scene whenever a foreground occluder blocks a portion of a background surface or object; the right eye may see a portion of the background that the left eye does not see, or vice versa. In an unnatural viewing situation such as a partial-overlap HWD, if one or the other eye views an image not seen by the other eye in a way that is inconsistent with the physics of occlusion, binocular rivalry ensues (see also Hayashi, Maeda, Shimojo, & Tachi, 2004). Of course, this kind of viewing arrangement is typically used in studies on rivalry and is consistent with earlier statements that the necessary conditions for provoking binocular rivalry involve perceptual confusion about object identity at a given location in space.

Summary and Implications

Binocular rivalry is provoked by interocular differences in luminance, contrast polarity, size, hue, and motion velocity. The suppression attendant to binocular rivalry takes about 200 ms to develop, and stimulus transients tend to return portions of a suppressed stimulus to dominance (which likely suppresses portions of a stimulus in the other eye). Suppression involves a general loss of sensitivity that can render all classes of stimulation invisible, and it can impair guided visual attention.

Monocular HWDs. Binocular rivalry likely occurs with many semitransparent monocular HWDs, for which both eyes view an outdoor scene and one eye views the information presented on the HWD. Thus, although binocular fusion may decrease the occurrence of rivalry to some extent, suppression still occurs when monocularly viewed imagery is seen in combination with binocularly viewed imagery.

For opaque monocular HWDs, wherein information is presented to one eye and the other eye (not both eyes) views an outdoor scene or other information, significant rivalry occurs, as shown by Winterbottom, Patterson, Covas, et al. (2006)

and Winterbottom, Patterson, Pierce, et al. (2006) in their dichoptic viewing condition and reported by Hakkinen (2004) and Peli (1990). Thus, significantly more problems in terms of performance decrements owing to the occurrence of suppression are to be expected with opaque monocular HWDs. We strongly recommend that such HWDs not be used.

One potential way to counteract the occurrence of rivalry is to manipulate the time course of stimulation. Given that the perception of fusion and stereoscopic depth appears very quickly (e.g., within 10–20 ms; Patterson, 1990), whereas rivalry-induced suppression takes a longer duration to develop (e.g., 200 ms), in certain applications one could attempt to present monocular HWD information in brief exposures that would be readily apprehended before the onset of suppression. An alternative method may be to restore suppressed symbology to dominance by increasing its contrast by an amount equal to 0.5 log units (or a d' of 1.5). Future research should test these possibilities.

Biocular and binocular HWDs. Although binocular fusion may decrease the occurrence of rivalry to some extent, suppression still occurs when a binocular HWD is viewed in a partial-overlap configuration. HWD designers should be aware that trading off binocular overlap against field of view could lead to the occurrence of suppression (luning). For these designs, methods that reduce unnatural and unpaired monocular images may help reduce the suppression that accompanies binocular rivalry and luning.

If image quality or detection of low-contrast targets is important, full overlap may be a better solution. If wide field of view is critical, a partial overlap of at least 40° is recommended, but even then suppression may occur in the periphery. The introduction of a foreground window frame, or false contour, may increase the ecological validity of an unnatural viewing condition. The window frame or false contour may be interpreted by the visual system as a valid foreground occluder, thus decreasing the suppression that occurs due to the existence of the unnatural monocular region associated with partial overlap displays.

STIMULUS FACTORS AFFECTING RIVALRY

Basic research shows that once rivalry is provoked, the factors we discuss in this section

determine the rate of alternation and whether the stimulus in one eye dominates the stimulus in the other eye in terms of predominance (i.e., the total proportion of time a stimulus is visible during prolonged viewing).

The rate of rivalry alternation is likely to increase with increased orientation differences between stimuli in the two eyes (e.g., Abadi, 1976). Also, stimuli with a greater amount of contour density tend to dominate those with less contour density (Levelt, 1965).

In basic research, interocular differences in contrast are critical variables in terms of predominance; interocular differences in luminance play much less of a role (e.g., Levelt, 1965). Stimuli with greater contrast will dominate those with lower contrast (Blake & Camisa, 1979; Fox & Rasche, 1969; Hollins, 1980; Levelt, 1965), and the rate of alternation increases when both stimuli are of high contrast (Alexander, 1951).

O'Shea et al. (1994) examined rivalry between orthogonal square-wave gratings at one of three luminance levels – 55 cd/m² (photopic), 0.55 cd/m² (mesopic), and 0.0007 cd/m² (scotopic, below the operation of color vision, which begins to appear at 0.01 cd/m²) – and found that contrast affected the time course of rivalry. They found that alternation rate decreased, and suppression duration increased, as luminance decreased to scotopic levels but that rivalry still occurred. Hollins (1980) used as rival stimuli orthogonal spatial frequency gratings and found that rivalry occurred for a range of grating Michelson contrasts of about 0.003 to 0.3 (see also Liu, Tyler, & Schor, 1992).

The relationship between rivalry dominance and spatial frequency appears quite complex, and many studies have produced results that are difficult to interpret. Nonetheless, a few generalizations can be made. Stimuli composed of a broad range of spatial frequencies tend to dominate those with a narrow range of frequencies (Fahle, 1982; Humphriss, 1982; see also Hollins, 1980; O'Shea et al., 1997). Moreover, high spatial frequency stimuli in one eye may appear to stand out in depth relative to low spatial frequency stimuli in the other eye (Yang, Rose, & Blake, 1992).

When wavelengths are different enough to produce percepts of different hues, such differences can provoke rivalry. Moreover, when stimuli are already engaged in rivalry (e.g., vertical lines to one eye, horizontal lines to the other eye), rival

stimuli of the same hue tend to rival less (i.e., more often various portions of the stimuli in the two eyes are seen together as a composite) than stimuli of different hues. For example, Hollins and Leung (1978) found that exclusive visibility was less when both rival targets were blue (455 nm) and that exclusive visibility was greater as the difference in hue increased.

The basic literature shows that moving stimuli dominate static stimuli, as first reported by Breese (1899), and this effect of the potency of motion often has been used to support the role of attention in binocular rivalry (i.e., the motion captures attention; see also Blake, Yu, Lokey, & Norman, 1998).

Wade, de Weert, and Swanston (1984) investigated speed across the range of 0°/s to 0.41°/s and reported that a moving grating will dominate a static grating, especially at higher speeds of the moving grating, and that faster stimuli dominate slower stimuli when they differ in direction of motion. Blake, Zimba, and Williams (1985) used random dot patterns and found that when the interocular difference in motion direction exceeded 30° (at a speed of 1.5°/s), rivalry occurred. When stimuli moved in the same direction but at different speeds, rivalry occurred and was less piecemeal as interocular differences in velocity increased. The smallest interocular difference in velocity was 0.75°/s versus 1.5°/s, or 1 octave, which provoked significant piecemeal rivalry.

Summary and Implications

A given stimulus viewed by one eye will typically dominate a rival stimulus seen by the other eye if the former possesses greater contour density, higher contrast, or faster motion. Rivalry provoked by interocular differences in contrast can occur across a wide range of luminance levels: from scotopic levels, in which only rod vision functions, up to bright photopic levels, which include cone functioning. Thus, rivalry occurs across a range of luminance levels and contrasts that would include levels and contrasts typical of HWDs.

Monocular HWDs. For semitransparent monocular HWDs, in which the two eyes view a real-world outdoor scene and only one eye receives information from an HWD, portions of the outdoor scene would likely possess higher contrast, greater luminance, and a broader range of spatial frequencies. This means that portions of

the outdoor scene would likely dominate portions of the information presented on the HWD. However, when the two eyes view a simulation of an outdoor scene (e.g., a flight simulator display), portions of that simulated scene may or may not possess higher contrast, greater luminance, or a broader range of spatial frequencies relative to the information presented on the HWD.

In either case, simulated or real-world, portions of the outdoor scene would likely dominate portions of the information on the HWD because the outdoor scene is binocularly fused and escapes suppression (Winterbottom, Patterson, Covas, et al., 2006; Winterbottom, Patterson, Pierce, et al., 2006), which would also be true when a real-world outdoor scene is viewed. The monocularly presented HWD information does not escape suppression, however.

Given that a real-world or simulated scene would likely contain a range of contrasts, wavelengths (hues), and motion, it is recommended that future research investigate whether presenting information on a monocular (semitransparent) HWD with high contrast (i.e., 0.5 log units greater than the value that allows a stimulus to be suppressed) will reduce the occurrence of binocular rivalry, especially for tasks used with HWDs under real-world operational conditions, or whether such contrast increments would mask other information in the outside world.

Although semitransparent HWDs allow both eyes to see an outdoor scene, this is not true with opaque HWDs. These latter displays present synthetic information to one eye, and the other eye (not both eyes) views an outdoor scene or other synthetic information. Thus, a patent dichoptic-viewing arrangement exists, and there would likely be significant interocular differences (in contrast, shape, hue, etc.) and therefore very robust rivalry, as shown by Peli (1990), Hakkinen (2004), Winterbottom, Patterson, Covas, et al. (2006), and Winterbottom, Patterson, Pierce, et al. (2006). Again, we recommend against the use of these kinds of HWDs.

Binocular and binocular HWDs. For partial-overlap binocular HWDs, targets or other kinds of important information may need to be presented with relatively high contrast, especially if they are positioned close to or in the monocular regions of the HWD.

These recommendations are based on the results of basic research that has, in part, involved

the use of test probe methods for documenting the existence of suppression, as well as the use of unique dichoptic stimuli for inducing rivalry. It is not clear to what extent results from these studies generalize to the scenes and objects encountered when HWDs are used in real-world applications.

COGNITIVE VARIABLES AFFECTING RIVALRY

The research discussed in the last section focused on the physical attributes of rivalry-inducing stimuli as indexed by alternation rate and predominance. Some studies, however, examined the extent to which cognitive variables can influence the temporal course of rivalry alternations, independent of the physical conditions of stimulation.

In basic research, two general kinds of cognitive variables have been investigated: (a) those in which information conveyed by rivalry stimuli resonate with information already resident in the observer, which include familiar or meaningful stimuli, or stimuli that induce affective states; and (b) those that enhance the processing power of stimulation by engaging the voluntary attention of the observer.

With respect to the meaning or emotional significance of stimuli, studies by Engle (1956) and Hastorf and Myro (1959) showed that erect faces dominated more than inverted faces did during binocular rivalry (see also Ono, Hasdorf, & Osgood, 1966), but low-level stimulus features such as luminance and contrast were not controlled in these studies. Blake (2001, pp. 14–15) and Yu and Blake (1992) also noted that the subjective response measures used in the aforementioned studies may have been susceptible to demand characteristics and response bias. Yu and Blake (1992) also found that recognizable stimuli, such as faces, predominated more in rivalry than did nonsense patterns that were equated for spatial frequency, luminance, and contrast. Here, predominance was measured objectively with a reaction time technique, as well as subjectively.

In a different line of research, Blake (1988) employed a dichoptic reading paradigm in which one eye viewed a stream of meaningful text while the other eye viewed a stream of nonmeaningful text. Blake (1988) found that during rivalry the observers could not prevent the meaningful text from being suppressed by the nonmeaningful text

during some portion of the viewing period (i.e., rivalry alternations occurred between the meaningful and nonmeaningful text). Zimba and Blake (1983) also showed that meaningful linguistic stimuli possessed no special status during rivalry.

With respect to voluntary attention, the idea that attention can affect binocular rivalry goes back to Helmholtz (1866/1962) and James (1890). A century later, Lack (1969) examined the effect of practice on the voluntary control of binocular rivalry alternations. In his study, the observers experienced 10 30-s trials on 10 consecutive days but received 1, 4, 7, or 10 days of practice controlling the rivalry alternations. He found that observers could control their rate of rivalry alternation with practice, with observers receiving 10 days of practice being able to either decrease by half or double their alternation rate. In a different study, Lack (1978, p. 61), using an objective letter recognition task during four test sessions on 4 consecutive days, found that observers were not able to control the magnitude of rivalry suppression and thus concluded that observers could control only the alternation rate.

In a different basic research study, Collyer and Bevan (1970) studied the ability of observers to voluntarily control dominance switches using an objective shape recognition task (without extended practice). They reported that with a 3-s advance knowledge of target location and eye, there was only a 10% improvement in performance. When observers were instructed to hold one eye's field dominant for the duration of an entire session, there was a 16% improvement. Thus, some degree of subjective control was possible.

More recently, Ooi and He (1999) reported that suppression was prematurely terminated when observers attended to a rival stimulus relative to when the observers attended to a nonrival stimulus. Chong, Tadin, and Blake (2005) found that dominance durations during binocular rivalry could be extended by about 50% by endogenous attention – that is, when observers performed an attentionally demanding task on the rival stimulus. However, this increase in duration may have been a byproduct of the divided attention imposed by the stringent requirements of the attention-demanding feature tracking task.

Chong and Blake (2006) showed that both exogenous attention and endogenous attention can serve to influence the initial dominance of a rival stimulus via an increase in effective stimulus

strength. Patterns with spatially connected features, or other kinds of structural commonalities within stimuli (Neisser & Becklen, 1975; Ooi & He, 1999), can lead to the features becoming suppressed in synchrony, and this suppression may be under attentional control (e.g., Alais & Blake, 1999, Kovacs et al., 1996).

However, in an applied study, recall that Winterbottom, Patterson, Covas, et al. (2006; see also Meng & Tong, 2004) found that voluntary attention had no systematic effect on binocular rivalry for either dichoptically viewed stimuli or stimuli viewed in a partially fused condition. Thus, although purposeful control of rivalry may be possible if enough practice is provided, as in Lack (1969), the evidence for purposeful control of rivalry suppression is not conclusive. Howard (2002, p. 309) has argued that the effects of high-level or top-down variables on binocular rivalry, such as context, meaning, and/or dispositional factors, are small when compared with the effects of low-level factors, such as stimulus orientation, contrast, or color. Clearly, more research is needed on the topic of practice to determine whether it may be an effective strategy to mitigate the effects of rivalry.

From an applied standpoint, U.S. Army pilots have logged hundreds of thousands of hours in the Apache helicopter using the IHADSS (Lipert, 1990), a monocular transparent HWD, and although they regularly report visual difficulties, some of which may be attributable to rivalry (Behar et al., 1990), the system has proven to be highly useful.

Some anecdotal reports indicate that pilots gradually adapt to monocular displays such as the IHADSS and JHMCS, suggesting that extended practice may allow users to control the incidence of rivalry suppression to some extent, whereas other anecdotal reports indicate that rivalry may continue to be an issue even with practice. Users may learn to manage the rivalry (e.g., by influencing alternation rate) rather than truly eliminate it. This issue deserves further research, particularly in military applications, in which selection and practice could be systematically implemented as a method of potentially reducing rivalry. For commercial and entertainment applications, in which selection and extended practice are not feasible, other methods of reducing rivalry may be required.

It might seem that eye movements could be a method individuals could use to control rivalry.

For example, eye movements might interact with the shape and orientation of contours in a scene to create motion of images on the retina and, thereby, create luminance transients, which would terminate suppression (e.g., horizontal eye movements sweeping across vertical contours, or vertical eye movements sweeping across horizontal contours, would create such transients; but see van Dam & van Ee, 2006). However, eye movements would likely have both positive and negative effects, especially with monocular HWDs: If the eyes scan the HWD image, it might terminate suppression of information on the HWD and yet possibly increase suppression of information from the outside world, or vice versa. A further complication is that in some air vehicles, the sensors are slaved to the pilot's head movements and information on the monocular HWD would change with the pilot's head position.

Summary and Implications

The effects of cognitive variables are relatively weak, as compared with physical variables, in their effect on the time course of rivalry. Linguistic information does not seem to affect binocular rivalry at all. Pictorial information with meaning appears to have only a modest effect on suppression or dominance duration and no effect on the magnitude of suppression. Previous studies reported that attention may be able to retard the incidence of suppression but not prevent it from occurring nor alter the magnitude of suppression.

It is possible that dominance durations may be extended when observers perform an attentionally demanding task on a rival stimulus and that observers can exert some degree of subjective control to improve probe detection by a modest amount. However, other recent studies, one of which involved the simulation of a semitransparent monocular HWD, have found no effect of attention on rivalry. Practice may help individuals control the rate of rivalry alternations but not the magnitude of suppression. Overall, the reported effects of cognitive variables on rivalry are conflicted, and these conflicts may be attributable to differing methodology.

Monocular HWDs. For semitransparent monocular HWDs, it is not known whether extended practice would serve to enable a user to control, to a significant degree, any binocular rivalry that occurs. Given that practice may be more useful

for rivalry control when it is done in the context of real-world applications, it is recommended that future research study the effects of practice of attentional control on the occurrence of rivalry when HWDs are used in real-world situations. For military applications, training to reduce unwanted effects from rivalry may be an option. In commercial applications, other methods of reducing rivalry may be more feasible.

Biocular and binocular HWDs. For partial-overlap HWDs, the presence of rivalry in the form of luning may be affected by practice and/or task demand. Future research should examine whether practice or task difficulty affects target recognition when targets appear near the monocular regions of a partial-overlap HWD.

TASKS AFFECTED BY RIVALRY

Recall that the suppression phase of rivalry is accompanied by an elevation in threshold for all classes of stimuli presented within the suppression zone. Given that the visual system is composed of parallel pathways – with one pathway primarily involved in the functional analysis of spatial pattern information and object identification and the other pathway primarily involved in the functional analysis of motion information and the integration of vision with action (for review, see Patterson et al., 2006) – then this would imply that binocular rivalry is a process that occurs with diverse visual pathways. Nonetheless, whether binocular rivalry will affect the performance of certain tasks when HWDs are used will likely depend upon the time course of responding.

Because suppression takes some time to develop and typically alternates between areas of the two retinæ, stimuli that provoke rivalry should still be visible some of the time. Tasks that are not based on the immediate detection or recognition of stimuli should be less affected by rivalry than tasks for which detection or recognition must be immediate. Tasks that require continuous responding, such as the control of heading using optic flow information or engaging in visual search, would likely be disrupted to some degree by rivalry. It remains to be determined whether rivalry impairs tasks such as heading or altitude control.

The effect of binocular rivalry on directing visual attention may seem similar to the concept of “cognitive tunneling,” which refers to a perse-

verance of attention to a given information channel at the expense of attending to a different, more important, channel (Yeh & Wickens, 2001). However, because binocular rivalry involves a process of visual suppression between two eyes, rivalry and cognitive tunneling are different phenomena.

Summary and Implications

Tasks that are not based on immediate detection or recognition should be less affected by rivalry than tasks for which detection or recognition must be immediate. Tasks that require continuous responding would likely be disrupted by rivalry. Future research should explore exactly which types of tasks are affected by binocular rivalry in real-world situations for which HWDs would be used.

GENERAL SUMMARY

The following points, based on our review of the literature, summarize our findings regarding binocular rivalry and the design and use of HWDs:

1. Binocular rivalry is provoked by interocular differences in many kinds of image characteristics, such as contrast polarity, size, hue, and motion velocity. Suppression involves a general loss of sensitivity that can render all classes of stimulation invisible except for brief exposures. There is evidence that binocular rivalry occurs with monocular HWDs as well as with binocular HWDs with partial overlap.
2. A given stimulus viewed by one eye will typically dominate a rival stimulus seen by the other eye if the former possesses greater contour density, higher contrast, a wider range of spatial frequencies, or faster motion. Rivalry occurs across a wide range of luminance levels and contrasts that are typical of HWDs.
3. For monocular HWDs, the use of repeated brief exposures (i.e., under 200 ms), as well as high stimulus contrast (i.e., 0.5 log units above typical value), may minimize or eliminate suppression of the displayed information. It is recommended that opaque monocular HWDs not be used.
4. For binocular partial overlap HWDs the appearance of luning and fragmentation may be reduced through the use of false contours. A partial overlap area of at least 40° and the use of a convergent design are also recommended to minimize the effects of suppression in the monocular flanking areas. However, the use of these techniques may not eliminate suppression of targets in the monocular flanking regions. The HWD designer will have to determine the importance of increased field of view relative to the disruption brought about by fluctuations in target visibility.

5. Practice over a number of days (e.g., 10 days) may help individuals control the rate of rivalry alternations. When observers perform an attentionally demanding task on a rival stimulus, dominance durations may be extended, which is an effect equivalent to a doubling of stimulus contrast. Research is needed to determine how training to reduce effects of rivalry suppression can be most quickly and effectively achieved and whether eye movements play a positive or negative role on the visibility of information from an HWD or an out-the-window view. This would be particularly useful in military applications, in which selection and training can be systematically implemented.
6. Target detection/recognition has been shown to be delayed due to binocular rivalry for some simple tasks relevant to HWDs. However, it remains to be determined whether binocular rivalry actually degrades performance on more complex tasks that would be executed when HWDs are used in real-world settings.

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