Rivalry and Interference with a Head-Mounted Display

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Perceptual factors that affect monocular, transparent (a.k.a "see-thru") head-mounted displays include binocular rivalry, visual interference, and depth of focus. We report the results of an experiment designed to evaluate the effects of these factors on user performance in a table look-up task. Two backgrounds were used. A dynamic moving background was provided by a large screen TV and an untidy bookshelf was used to provide a complex static background. With the TV background large effects were found attributable to both rivalry and visual interference. These two effects were roughly additive. Smaller effects were found with the bookshelf. In conclusion we suggest that monocular transparent HMDs may be unsuitable for use in visually dynamic environments. However when backgrounds are relatively static, having a transparent display may be preferable to having an opaque display.

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General Terms: Human Factors

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1. INTRODUCTION

The popularity of small, portable, or wearable computing devices is increasing. The reason for such devices is to allow users to remain mobile while simultaneously taking advantage of computing power. Small, wearable, head-mounted

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displays (HMDs) are being developed enabling users to have a high-resolution display available without having to carry a bulky LCD display or be restricted to the small screen of a PDA [Systems 2001].

HMDs may have a variety of configurations. The display may be monocular (worn over one eye) and opaque as was the case with an early model called the Private Eye^{TM}. The display may be monocular and transparent or binocular (worn over both eyes) and transparent. Binocular opaque HMDs are useful for immersive virtual reality applications. Monocular transparent displays are preferred when interacting with the world while looking at the display [Feiner et al. 1997].

Many applications of HMDs involve displaying information pertaining to a real-world task at hand. Specific potential applications include aircraft inspection, to aid the user in a preflight inspection [Ockerman and Pritchett 1998]; bridge inspection, helping the user to produce a bridge inspection report [Sunkpho et al. 1998], terrestrial navigation, providing users with visual navigation aids in order to perform an orienteering task [Thomas et al. 1998]; and gaming and portable video entertainment, playing video games or watching movies [Systems 2001].

In augmented reality approaches the information presented via the display is colocated with the relevant real-world image [Feiner et al. 1997; Starner et al. 1997]. However, more commonly HMDs are simply of interest as highly portable, lightweight display devices that afford handsfree operation.

1.1 Perceptual Issues

There are a number of perceptual factors that may pose difficulties for monocular transparent HMDs. The sections that follow describe some of these.

1.1.1 *Binocular Rivalry.* Usually both eyes receive approximately the same image of the environment. However, with the transparent monocular configuration of the HMD each eye views a different image. One eye views the real world and the other eye views the virtual image shown in the HMD optically superimposed on the real world (Figure 3). To create the transparent effect two images are combined in an optical weighted average using a half-silvered mirror.

Binocular rivalry is the term given to the phenomenon that occurs when dissimilar images are presented to the two eyes [Blake 2000; Breese 1899; Lee and Blake 1999; Mazumder et al. 1997]. The brain reacts by going into an unstable state. In this unstable state there are alternating periods of "monocular dominance" [Blake 2000]. Figure 1 illustrates some patterns that instigate binocular rivalry. Some important characteristics of binocular rivalry include the following.

— The duration of any dominant and suppression phase is unrelated to the duration of prior phases [Blake et al. 1990]. In other words, the duration of eye dominance for a given eye is unpredictable and can range anywhere from 0 to 10 seconds [Blake et al. 1990; Sohmiya and Sohmiya 1986].
— Introducing a transient or animation in the suppressed eye generally returns that eye to dominance [Blake et al. 1990; Wolfe 1984].

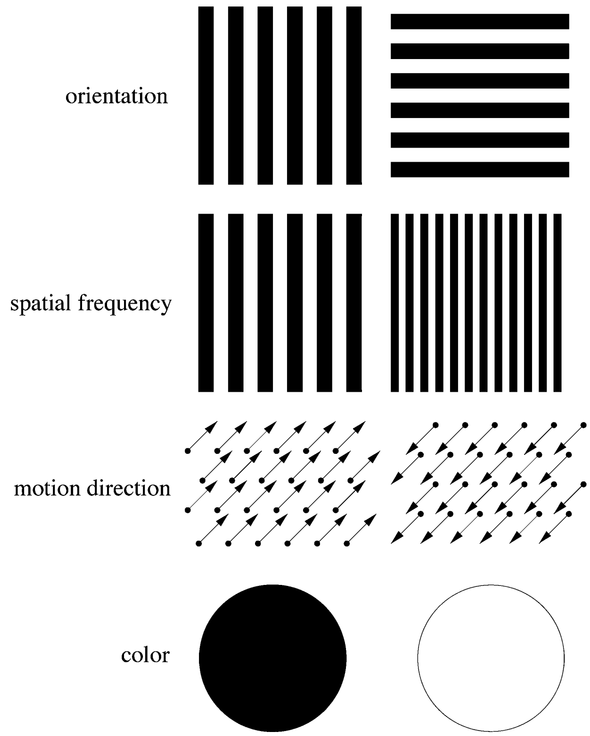

Fig. 1. Pairs of patterns that when shown, one to each eye, stimulate binocular rivalry.

—At any point in time, overall dominance often appears as a fragmented mixture of the two eyes' views [Alais and Blake 1999; Meenes 1930]. Different images usually result in piecemeal dominance. Different parts of the two eyes' images appear intermixed resulting in a dynamic patchwork appearance [Alais and Blake 1999].

—Binocular rivalry is not something of which we have conscious control [Blake 2000]. An object that is normally visible disappears from conscious awareness for several seconds at a time.

A number of authors, including a recent panel on tactical displays for infantry soldiers [Blackwood et al. 1997] have identified binocular rivalry as a potentially serious perceptual problem relating to HMDs [Peli 1999; Laramee and Ware 2001].

There have also been studies involving a monocular HMD night vision system for pilots of Apache helicopters. In this type of system infrared images of the environment are displayed to one eye while the other eye views the environment directly. Rush et al. [1990] reported that some pilots experience trouble switching attention to the other and sometimes resort to closing one eye, a potential hazard.

1.1.2 *Visual Interference.* *Visual interference* is the term used to describe the notion of when two images are not clearly distinguishable from each other.

Fig. 2. Text in the foreground with objects at three different focal distances in the background.

Two images are said to interfere if it is difficult for an observer to separate them visually. In a study of transparent pop-up menus Harrison and Vicente showed that the more similar the patterns, the greater the visual interference [Harrison et al. 1995; Harrison and Vicente 1996]. However, they found that only when transparency exceeded 50% was performance significantly degraded.

1.1.3 *Depth of Focus.* HMDs are constructed so that the virtual image appears at a fixed focal distance from the user, typically one to two meters. However, real-world imagery may be at any focal distance. Less interference can be expected if the virtual image and real-world imagery are at different focal distances because one of the images will be blurred and users can choose to attend to either the HMD or the real-world image. The eyes will automatically bring the attended image into focus. Since blurring removes high spatial frequency information this can be expected to minimize interference with high spatial frequency text.

Figure 2 shows text at one focal distance, and background objects at three different simulated focal distances. The fruit which is closer to the focal distance of the text makes the text harder to read whereas the text in front of the tree is easier to read.

1.1.4 *Phoria.* Simply put, phoria is the direction of gaze of the eye when there is nothing at which to look. Prolonged occlusion of one eye can result in changes in phoria [Ellerbrock and Loran 1995; Sethi 1986]. Phoria has been measured with active use of a monocular HMD for work processing. Peli [1990] reported that following 45 minutes of use with a word-processing task one of three subjects had a measurable change in phoria. Mon Williams et al. [1993] studied subjects wearing HMDs for short-term use. They found that for most of their 20 subjects, the changes in phoria disappeared within 5 minutes, but one subject had phoria lasting for approximately 40 minutes and two reported long-lasting headaches. However, these effects appear to be transitory and all researchers have noted a rapid return to normal when the display is removed.

When an observer looks at an instrument or a display with only one eye, the brain is obliged to maintain focus on the image for that single eye even though as a result the other eye will have out-of-focus imagery [Rosenfield and Ciuffreda 1994]. This is different from the normal situation where both eyes refocus at the same time as we change the object of our attention. Instrument myopia is the effect that occurs when focus is changed for a short while as a consequence of monocular viewing through an instrument such as a microscope. Since the situation is similar for a monocular display, the same effect may be expected to occur. However, any effects appear to be small and transient [Peli 1998].

1.1.5 *Eye Movements.* People use coordinated movements of both the eyes and the head to conduct visual searches of the environment. HMDs do not allow redirection of gaze through head movements and so all scanning must be done with eye movements. Ordinarily, when the distance to a new target involves a small angular movement, the eye is moved first, followed by the head [Leigh and Zee 1983; Uemura et al. 1980]. When the angular distance is large, the head normally moves in conjunction with the eyes. Trying to read material with the eyes persistently off axis is likely to be a cause of strain.

This may present a problem with HMDs since they are fixed with respect to the head; compensatory head movements will not center the display in the visual field and all scanning of the display must be done with eye movements. Peli [1999] pointed out that this factor can especially be a problem with menus and icons that are normally placed close to the edge of the screen. He suggested that angles of more than 10 degrees off the center would be very uncomfortable to maintain. Following this principle, Peli suggested that the horizontal span of a HMD screen used as a computer terminal should be no more than 20 degrees.

1.1.6 *Eye Dominance.* People usually have a dominant eye; that is, imagery from that eye is "preferred" over the other eye. In binocular rivalry situations the dominant eye imagery is seen more frequently and for longer than nondominant eye imagery [Collins and Blackwell 1974]. Thus normally HMDs should be worn over the dominant eye although this will make real-world imagery viewed in the other eye relatively harder to perceive.

Other problems have been reported with heads-up displays (HUDs) [Morphew 1985]. In a study of HUDs used in tactical fighter aircraft Roscoe [1993] reported:

(1) Thirty percent of pilots reporting disorientation from the use of heads-up Displays;
(2) Pilots reporting trouble with focusing on the HUD instead of the real world;
(3) Pilots reporting confusion in maintaining aircraft orientation.

Some head-mounted displays displace the line of sight from normal and this may cause problems in eye–hand coordination [Rolland et al. 1995].

1.2 Previous Work

In a preliminary study to investigate some of these factors we had subjects perform a table selection task using a transparent monocular head-mounted display [Laramee and Ware 2001]. We varied background complexity (a movie

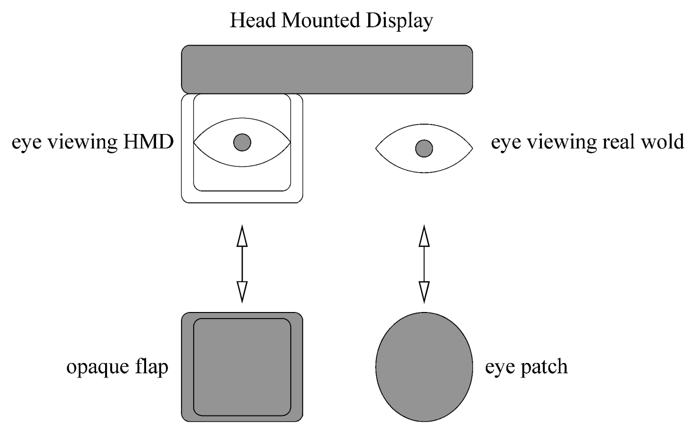

Fig. 3. In some HMD configurations the user wore a patch over one eye or an opaque flap was placed over the HMD (or both).

shown on a large television monitor with the sound off, an untidy bookshelf, and a uniform wall) and the distance to the background. At the near viewing distance the HMD imagery was approximately at the same focal depth (1 meter) as the background. As expected, we found that the television imagery was the most disruptive, resulting in a 37% increase in response times and a higher error rate. We failed to find an effect from varying the focal distance. However, although this study suggested that problems can occur with HMDs it said nothing about the relative contribution of binocular rivalry and visual interference.

1.3 Isolating Rivalry and Interference Effects

It is possible to separate the effect of rivalry and interference by comparing different HMD configurations. If one eye is covered and the other eye sees only an opaque HMD no rivalry or interference should occur: all the user sees is the display. Binocular rivalry will occur, however, if the user uncovers the eye and sees real-world imagery. Similarly, by comparing opaque display performance with transparent display performance we can isolate the effect of visual interference.

This method rests on the assumption that what a covered eye sees does not cause rivalry. To test this we added two further conditions. In one, subjects performed the task viewing the monitor directly with both eyes (no HMD). In the other, subjects also viewed the monitor directly but one eye was covered. This also allowed us to compare HMD performance with viewing a monitor directly.

2. METHOD

As in our previous study we used a table look-up task to evaluate performance while wearing the HMD or directly viewing a monitor in various configurations as shown in Figure 3:

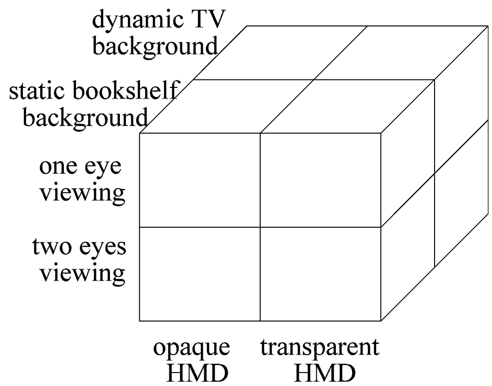

Fig. 4. A 2^3 matrix that summarizes the HMD configurations we evaluated.

(1) both eyes viewing the computer monitor (no HMD worn);
(2) one eye viewing the computer monitor directly (no HMD worn, other eye patched);
(3) one eye viewing the opaque HMD;
(4) both eyes: one eye viewing the opaque HMD, and the other eye viewing the bookshelf in the real-world background;
(5) both eyes: one eye viewing the opaque HMD, and the other eye viewing the TV in the real-world background;
(6) one eye viewing the transparent HMD with the bookshelf in the background, and the other eye patched;
(7) one eye viewing the transparent HMD with the TV in the background, and the other eye patched;
(8) both eyes: one eye viewing the transparent HMD, and the other eye viewing the real world, both with the bookshelf in the background; and
(9) both eyes: one eye viewing the transparent HMD, and the other eye viewing the real world, both with the TV in the real-world background.

The viewing conditions are summarized in Figure 4. We evaluated each combination of opacity, transparency, number of eyes, and background. However, there is a redundant condition shown in Figure 4, the one eye, opaque, bookshelf background configuration and the one eye, opaque TV background configuration. This redundancy was removed in the actual experiment. Note that the two control conditions of both eyes viewing the computer monitor directly and one eye viewing the computer directly are not shown in the figure.

2.1 HMD

Our HMD was a modified i-glasses ™ display [Systems 2001] with a 450 × 266 resolution display. We converted this to a monoscopic display by removing the left eyepiece. We also rearranged the optics for the right eye as shown in Figure 5. A beamsplitter blended external imagery with display imagery. About 30% of the light from external imagery was transmitted. This produced

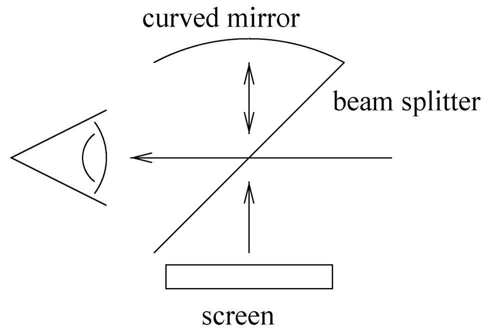

Fig. 5. Real world imagery was combined with display imagery as shown.

Q2: WHICH AISLE CONTAINS: LETTUCE

ITEM	AISLE	PRICE ($)	DISCOUNT
RELISH	10	$7.99	NO SALE
ONIONS	10	$4.99	% 20 OFF
PLUMBS	12	$7.99	% 10 OFF
TOWELS	11	$8.99	% 10 OFF
PEANUTS	0	$3.99	NO SALE
GRANOLA	14	$4.99	% 20 OFF
CELERY	2	$3.99	% 10 OFF
SOAP	4	$3.99	NO SALE
LETTUCE	3	$4.99	% 20 OFF
BLEACH	9	$3.99	% 10 OFF

Fig. 6. Task screen: subjects were required to answer the question presented at the top by selecting the appropriate table cell using the mouse.

a virtual image of a computer display at a focal distance of approximately 1.0 meters combined with real-world imagery that was optically unaltered except for having reduced luminance.

When viewed through the HMD the display imagery and the external imagery were roughly comparable in brightness. In order to block the left eye view for some conditions the subject wore an opaque eye patch. In order to convert the transparent HMD to an opaque HMD we added a flap that when closed blocked real-world imagery.

2.2 Task

The user's task was to answer questions such as, "What is the price of lettuce?"[1] presented at the top of the HMD screen. The answer was obtained by scanning a table as illustrated in Figure 6. Users provided the results using a normal mouse. Questions were randomly ordered and item names[2] (in the left column)

[1]The font used was Java's 20 pt. bold "Dialog" style.

[2]There was a total of 65 items from which the application chose 12 at random.

were randomly ordered for each question. The user was required to use a mouse (on a conveniently placed desktop) to move a cursor and click on the cell containing the correct response. Each table cell had an equal probability of containing the correct answer.

Whenever a user made an error, the application would indicate this by sounding a system beep. The purpose was to help subjects prioritize accuracy over response time.

2.3 Backgrounds

The effects of both binocular rivalry and visual interference were evaluated with two different backgrounds: a static, fully populated bookshelf, and a dynamic background—a 32-inch TV showing a movie with the sound off. The content of the TV images was the same for each subject. Both backgrounds were viewed from approximately two meters.

The effect of the HMD itself and the patch were evaluated with two control conditions. The user was asked to perform the same application task without the HMD at all, viewing the 15-inch computer monitor directly, and again using only one eye (again, looking directly at the computer monitor).

2.4 Procedure

Following an introductory training session each subject answered 12 questions in each of 9 experimental conditions replicated twice. Thus each subject completed 18 blocks of questions. A block consisted of answering 12 questions in one of the nine conditions described earlier (for a total of 216 questions per subject). The blocks were presented in random order within each subject The questions were presented in random order within each block. The three independent variables were: monocular versus binocular viewing, transparency of the HMD, and the type of real-world background. The two dependent variables were response time (based on one mouse click per question) per question and number of errors.

2.5 Equipment

The application was written in Java 1.2 running on top of Red Hat Linux 7.0. The PC had a Pentium III (Coppermine) 600 MHz processor and 192 MB of RAM. The HMD was as described in Section 2.1.

2.6 Subjects

A total of 12 students and faculty from the University of New Hampshire volunteered as participants. They were tested for eye dominance, were paid $15 for participation, and could voluntarily withdraw without penalty at any time. Participants were asked for open-ended feedback at the end of the experiment.

3. RESULTS

The results are summarized in Figure 7. This shows the response times averaged across all subjects for each of the seven HMD configurations tested plus the two control conditions The effects of binocular rivalry and interference due

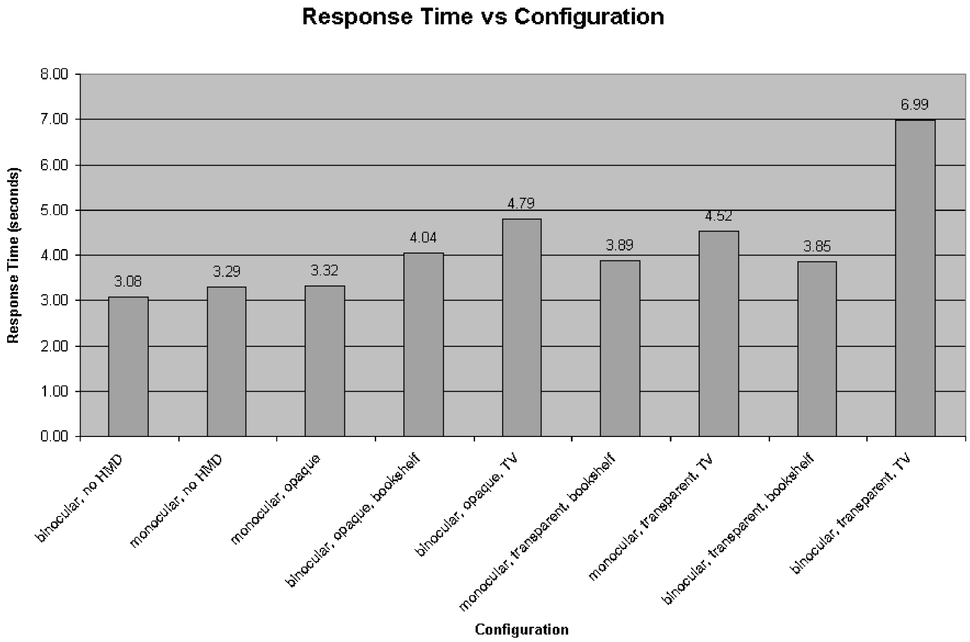

Fig. 7. Average response time versus each of nine HMD configurations. The configurations are labeled with the number of viewing eyes, the HMD opacity (or transparency), and the type of background (bookshelf or TV).

Table I. Summary of Binocular Rivalry and Transparency Effects with TV Background

	Opaque (sec)	Transparent (sec)	Mean (sec)
Monocular	3.32	4.52	3.92
Binocular	4.79	6.99	5.89
Mean	4.05	5.76	

Table II. Summary of Binocular Rivalry and Transparency Effects with Bookshelf Background

	Opaque (sec)	Transparent (sec)	Mean (sec)
Monocular	3.32	3.89	3.61
Binocular	4.04	3.85	3.95
Mean	3.68	3.87	

to transparency are summarized in Tables I and II. The monocular/binocular comparison allows us to assess the effects of binocular rivalry and the opaque/transparent comparison allows us to assess the effects of visual interference. With the TV background there was a 51% increase in response times attributable to binocular rivalry and a 43% increase in response times attributable to visual interference. These data are summarized in Table I. An analysis of variance revealed both of these factors to be highly significant

($p < 0.01$) and there was no significant interaction between the two factors. The combined effect of rivalry and interference was 112%.

The pattern was quite different with the static imagery of the bookshelf background (Table II). In this case there were no significant main effects but there was a significant interaction between the opaque–transparent and monocular–binocular conditions ($p < 0.01$). A subsequent analysis showed a highly significant effect for the monocular/binocular variable with the opaque display ($p < 0.01$). There is approximately a 21% increase in response time due to binocular rivalry, but only when the opaque display is used.

Comparing the two control conditions (binocular vs. monocular direct monitor viewing) we found that covering one eye resulted in a 6% increase in response time. This difference was not significant. Comparing monocular opaque HMD viewing with monocular direct monitor viewing reveals an insignificant 1% performance degradation. This shows that HMD can be as effective as a monitor display but only under optimal viewing conditions which would not normally be obtained.

There were no significant effects of error rate.

3.1 Anecdotal Results

One user reported that the monocular transparent configuration of the HMD did not make the task any more difficult than the (monocular) opaque condition. However, for the TV background subject showed a 36% performance penalty which is the same as the average. Another user reported that having the TV in the background required an increase in concentration in order to complete the task. Several of the participants initially complained that they couldn't read anything in the HMD or see the mouse pointer in the binocular transparent HMD configuration with the TV in the background. These users required a short interval to visually adjust to this configuration before actually starting the task. However, this initial period of adjustment is not reflected in the results which means that we may have underestimated the magnitude of the problem.

3.2 Discussion

The results presented here are consistent with our hypothesis that binocular rivalry and visual interference negatively affect task performance. Overall the effects of binocular rivalry are not as large as we had anticipated especially for the bookshelf background. The rivalry literature led us to suspect that the HMD viewing eye might only see the display about 50% of the time and this could cause a doubling in task performance times.

We found only a 22% increase in response times attributable to rivalry for the bookshelf background but only in the opaque condition. One explanation for this can be based on the observation that introducing a transient in one eye usually returns that eye to dominance [Blake et al. 1990; Wolfe 1984]. In our case the mouse pointer supplied a transient for the eye that viewed the HMD and this may account for the better than expected performance. Also, the text itself is a transient since the letters (the questions and the answers) changed with each question. A transient in the HMD display may reduce the effects of binocular rivalry. This explanation may also account for why the TV backgrounds are much more disruptive (although still not as bad as expected), as the TV supplied frequent visual transients.

One of the factors that was not tightly controlled in our study was the relative luminance of the environment seen through the HMD and seen with the other eye. We tried to roughly equate luminance between the display and the environment. However, our display necessarily reduced the overall luminance of the environment by a little over 50%. Other kinds of displays might cause a smaller reduction in seen environment luminance. The overall brightness of the environment, relative to the display, is likely to also be an important factor in display legibility. In bright environments the display will be relatively dim and in dim environments it will be relatively bright. Such factors need to be investigated and strategies developed to automatically adjust display luminance.

Overall, our results indicate nontrivial restrictions on the user of these kinds of displays. They suggest that transparent monocular HMDs are unsuited for use in crowded or dynamic environments or where maintenance of visual attention is critical. They are also unsuitable for individuals operating moving vehicles. However, the bookshelf results suggest that these displays are usable when the background is static and the relatively small performance decrement is acceptable.

4. FUTURE WORK

Future work in this area could go in multiple directions. For example, there is some evidence that rivalry effects may be controllable with practice. Rush et al. [1990] reported that Apache helicopter pilots became better at switching attention between their head-mounted infrared display and the clear view with the other eye. However, studies are needed to understand how they did this and many unanswered questions still remain such as the following.

(1) What are the long-term perceptual effects of HMDs?

(2) How much can users adapt to the perceptual effects of HMDs?

(3) Can users learn to mitigate or “block out” the effects of binocular rivalry by selectively attending to the image of an individual eye?

(4) Can users learn to reduce the effects of visual interference by preventing other images from dividing their attention?

In addition to studying the long-term perceptual effects of HMDs more research should be done in order to evaluate the effects of HMDs on motor skills and hand-eye coordination. In other words, would simple tasks involving hand–eye coordination be affected by the use of an HMD? Also we may expect that the degree of transparency and the relative luminance of the HMD will be important factors.

Future work could include an experiment whose subjects provide only verbal responses. Having the test subject click on the answer cell with the mouse slows them down and changes the task somewhat from simply seeing the information on the screen to seeing and reacting accordingly. The motivation for such an experiment comes from the observation that speech, not mouse-based, interfaces may become more common for wearable computers. It might also be interesting to see the result from a transparent HMD configured to use both eyes. Some other experimental factors that could be addressed in future studies include the following.

(1) The luminance of the display. Increasing the display luminance relative to the real world is likely to influence display and background legibility. Strategies for automatically adjusting display luminance will also be important.
(2) The resolution of the display and the display size. As discussed earlier, making eye movement to the edges of large displays is likely to cause strain. Thus optimizing display resolution and the amount of the visual field covered is of critical importance.
(3) Transparency level. Finding the ideal transparency level would be useful and strategies for automatically adjusting transparency based on the environment may be needed for more advanced displays.

The above factors, as well as the others reviewed in the introduction are all likely to be important in designing HMD configurations that are usable in the widest possible range of circumstances.

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