GUI Design Solution for a Monocular, See-through Head-Mounted Display Based on Users' Eye Movement Characteristics

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Abstract. A monocular, see-through head-mounted display (HMD) enables users to view digital images superimposed on the real world. Because they are hands-free and see-through, HMDs are expected to be introduced in the industry as task support tools. In this study, we investigate how the characteristics of users' eye movements and work performance are affected by different brightness levels of images viewed with an HMD as the first step to establish a content design guideline for see-through HMDs. From the results, we propose specific cases based on the users' preferences for the brightness level of the image contents depending on the use of the HMD and the work environment. In one case, the users prefer low brightness levels, and in the other case, they prefer high brightness levels.

Keywords: Monocular, see-through head-mounted display, characteristics of users' eye movements, brightness of images.

1 Introduction

A monocular, see-through head-mounted display (HMD) enables users to view digital images superimposed on the real world. Because of their hands-free and see-through advantages, HMDs are expected to be introduced in the industry as task support tools. In fact, our previous research found that when workers performed wiring tasks by referring to a manual displayed by the HMD, human error decreased remarkably and task efficiency increased compared to using a paper manual [1]. While performance, size, weight, and resolution of the hardware have been improved, guidelines for the design of contents utilizing the see-through property have not been established. Therefore, in this study, we focus on the brightness of images, which is one of the most basic elements of the content and investigate the preferred content design with this type of HMD. In particular, we assume that wearable HMDs will be used

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in a variety of applications and in various environmental conditions in future. Therefore, through experiments considering different types of usage and in different environments, we compared a situation in which we displayed high-brightness content all over with white background and black text, and another situation in which we displayed low-brightness content all over with black background and white text. We examined differences in users' visibility, fatigue, and eye movement characteristics.

In this study, we aim to reveal the preferences of users concerning the brightness of images displayed by HMDs depending on the application and environment.

2 Method

2.1 Experimental Tasks

Because the see-through HMD is intended to be used in actual industry situations, we structured our experiments so that users referred to information on the HMD using two different patterns. In one case, users referred to information mainly by using the HMD (e.g., reading mail which is presented on the HMD). In the other case, users referred to both objects in the field of view and information on the HMD (e.g., comparing an operation order on the HMD with the actual work objects). Therefore, we provided the following two cases as the experimental tasks.

Task 1: No Interaction between HMD Information and the Real World
In this task, the subjects read only the text that was presented on the HMD. They wore an HMD (AiRScouter made by Brother; Figure 1) and sat in front of a large display (42 in, TH-42PX300, Panasonic), which simulated the actual field of view (Figure 2). The large display showed a full-color mosaic picture whose pattern changes every two seconds using 28 colors (Figure 3). The HMD displayed a variety of text words written continuously in katakana (Figure 4). The subjects were asked to find seven words of a specific type and indicate when they found them by pressing a key. The subjects repeated this task 10 times.

Fig. 1. Participant wearing an HMD

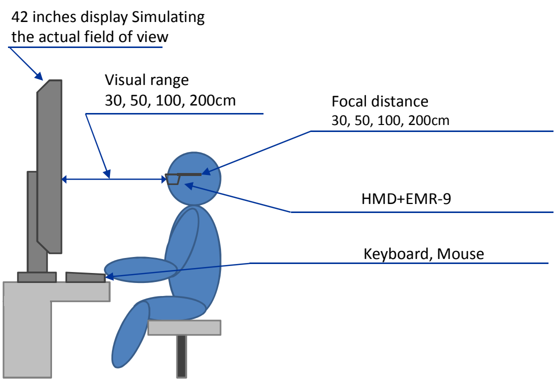

Fig. 2. Experimental Environment and Apparatus

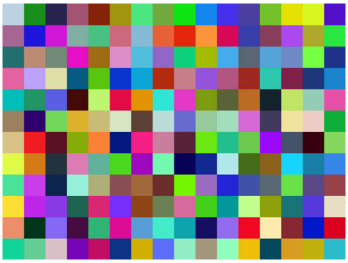

Fig. 3. Image of actual field of view of Task 1

Fig. 4. Text content of Task 1 displayed on the HMD

Task 2: Interaction between HMD and the Real World

In the first task, the subjects referred to both display, which simulated the actual field of view, and text, which was presented alternately on the HMD as needed. The large display that simulated the actual field of view showed 40 different pictograms, which were numbered and placed in random positions (Figure 5). The subjects were allowed to view words on the HMD in order one at a time using a key operation (Figure 6). They compared the word with the pictogram of the same number on the large display and pressed "X" in case of disagreement and "Z" in case of agreement. They assessed six matches and repeated this task 10 times.

To simulate actual industrial situations, we varied the distance using 30, 50, 100, and 200 cm between the users and the large display that simulated the actual field of view.

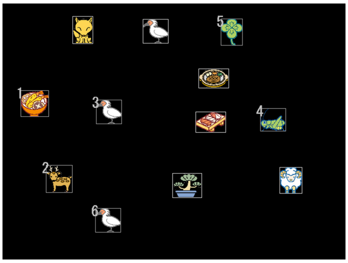

Fig. 5. Image of actual field of view of Task 2

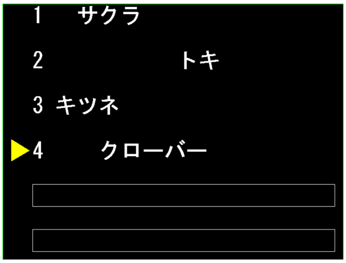

Fig. 6. A text content of Task 2 displayed on the HMD

However, the viewing angle remained constant. In addition, we varied the focus of the HMD using the same four abovementioned distances. We set 16 environments using combinations of distance and focal point, and each subject performed the above two tasks in each environment.

2.2 Experimental Conditions

We provided two experimental conditions. In one case, the background of images on the HMD was white. In the other case, the background was black. The brightness with which subjects viewed each condition was estimated, as shown in Table 1. We placed a brightness meter in the same position as that of the eye of a user wearing the HMD, i.e., the position in front of the half-mirror of the HMD that displays images. We measured the brightness of the large display that simulated the actual field of view. For each experimental environment, we measured the average value five times and averaged the results.

Table 1. Average brightness of each condition

	Visual range (cm)	The brightness of the black background (cd/m2)	The brightness of the white background (cd/m2)
Task 1 (Referring to HMD mainly)	30	24.30	64.30
	50	25.50	55.78
	100	25.60	53.73
	200	20.40	54.83
Task 2 (Referring to HMD and the actual world of view alternately)	30	18.63	50.20
	50	16.53	61.73
	100	17.57	46.23
	200	21.56	49.05

2.3 Measurements

We have summarized the steps followed for each task in Table 2.

Table 2. Measurements

	Task 1 (Referring to HMD mainly)	Task 2 (Referring to HMD and the actual world of view alternately)
Measurements	Work time: The time it took to read the content Correct answer rate: Percentage of correctly detected the genre specified item	Work time: The time taken for the comparison of one item Correct answer rate: Percentage answered correctly match / mismatch of items
	Subjective assessment: ・0-100 point rating how comfortable doing tasks after each task ・1-5 point rating eye fatigue subjects feel Eye movements: Measuring eye movements during the task with the eye-mark recorder (EMR-9 nac Image Technology) ※For convergence movement can be measured by measuring both eyes, we can obtain fixation point of the three-dimensional data Flicker value: Measured before and after each experiment with instruments flicker value (Type 2 501BTKK Takei Scientific Instruments Industry)	

2.4 Participants

The subjects were male and female adults from 18 to 24 years old. Twenty-four subjects performed the tasks using a white background, and 24 subjects used a black background.

2.5 Ethics

We obtained the informed consent of the participants.

3 Results

3.1 Task 1: No Interaction between HMD Information and the Real World

Task Performance

First, we compared the number of correct answers from subjects that performed tasks using a black background with the number of correct answers from subjects using a white background. The combinations of focal distances and visual ranges showed a higher percentage of correct answers from subjects using a black background than from those using a white background. Figure 7 shows the percentage of correct answers for each focal distance at 50 cm as the actual field of view. We focused on the differences in flicker values (which indicate psychological fatigue) before and after the experiment in order to explore the cause of these results. Figure 8 shows the differences between the flicker values before and after the experiment for tasks with white and black backgrounds. These results mean that mental fatigue increased when subjects used a white background. Therefore, we consider that in conditions with the white background (i.e., the content has high brightness), the concentration of the subjects fell because psychological fatigue of the subjects increased. As a result, the subjects' ability to accurately read the text declined.

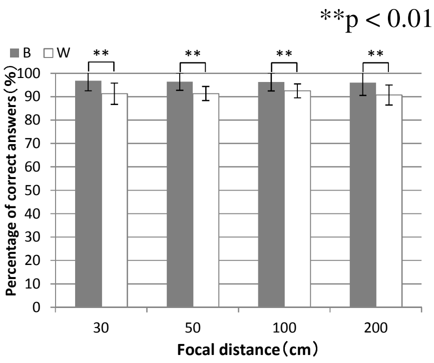

Fig. 7. Comparison of correct answers using white and black backgrounds (50cm viewing distance)

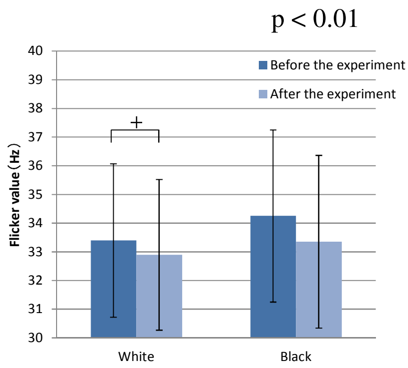

Fig. 8. Comparison of flicker values before and after the experiment using white and black back-grounds

In addition, we compared the working times needed to perform tasks with a black background with the times needed to perform with a white background. As a result, if the viewing range was short, there were some cases for which the working times with a black background were longer than those with a white background. From these results, we inferred that the see-through property was high with a black background, so mosaic images of the actual field of view obstructed the reading of the text on the HMD. However, there were no differences in 12 of the 16 combinations of viewing ranges and focal distances. Therefore, only when the viewing distance was short, reading was inhibited when using a black background; otherwise, we consider that there was no difference in the use of a black or white background.

Eye Movements

Next, we analyzed the eye movements of the subjects. In the analysis, we designated left and right eye movements as the X axis, up and down movements as the Y axis, and movements toward and away from the face as the Z axis (depth measurement). In the analysis of the movement of the line of sight on the XY plane, we focused on gaze and saccade. We defined gaze on the basis of theory that eye velocity is 5deg/sec or less" [2, 3]. We established a standard based on viewing more than three consecutive frames at the same position, which also considered the frame rate of the analyzer (62.5 fps). In addition, we defined saccades as viewing at the same position less than one frame. On the other hand, in the analysis of the Z-axis direction, we used a diopter value (1/focal length) as the indicator. Figure 9 shows the time-series changes in the diopter value of a subject during a task.

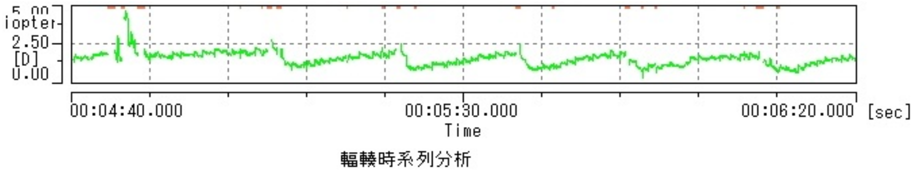

Fig. 9. Time-series change in diopter values

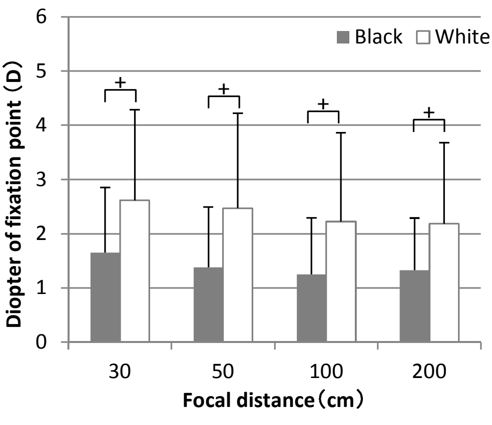

Fig. 10. Comparison of diopter values of the points of gaze with a white background and a black background (100 cm viewing distance)

We compared the average gaze time and average saccade distance during the tasks using a black background with those obtained using a white background, but there was no difference between them. On the other hand, we examined the diopter values when the subjects were gazing (diopter value of the point of gaze). The values with a white background were higher than those with a black background. Figure 10 shows the diopter values of the points of gaze when each focal distance to the actual field of view was 100 cm. This means that the subjects used a shorter focal length when viewing with a white background than when viewing with a black background. These results suggest that during the task of reading only the text on the HMD, the brightness of the image on the HMD affects the movements of the line of sight along the Z axis, although there is no effect on the movements of the line of sight on the XY plane. It is considered that this is related to an increase in the see-through property when the brightness of the images is low.

3.2 Task 2: Interaction between HMD and the Real World

Task Performance

First, we found no differences when we compared the percentage of correct answers from subjects using a black background to those using a white background. When we compared the working times of subjects using a black background to those of subjects using a white background, we found that only when the viewing distance was 30 cm, the subjects using a white background usually had shorter working times than those using a black background. However, there were no differences in working times for other combinations of focal distances and viewing distances. These results indicate that when the subjects referred to both information on the HMD and objects in the actual field of view, the brightness of the HMD images did not significantly affect performance.

Eye Movements

Next, when we compared the gaze points on the XY plane of subjects using a black background to those of subjects using a white background, we observed two characteristics. One was a pattern of viewing by superimposing the images on the HMD on the actual field of view (Figure 11), and the other was a pattern of viewing in different positions without superimposition (Figure 12), when the subjects looked at the images on the HMD and the actual field of view alternately. Eight of the twenty-four subjects using a white background used a non-overlapping viewing pattern, while only two of the subjects using a black ground used this pattern. Therefore, it was revealed that there were more subjects using a superimposed pattern when viewing with a white background than those viewing with a black background taking advantage of the see-through quality.

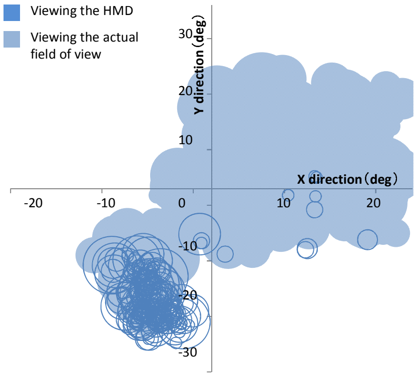

Fig. 11. Non-overlapping viewing

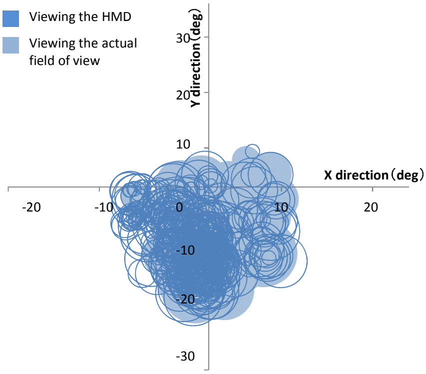

Fig. 12. Superimposed viewing

In addition, when we examined the movement of the line of sight along the Z axis, we found that there were roughly two features of the waveform of the time-series change in the diopter value. One was a sharp peak waveform (triangular wave in Figure 13), and the other was a flat peak waveform (rectangular wave in Figure 14). We found that there were many triangular waveforms when using either a white or black background with the same focal and viewing distances. However, when the viewing distance was longer than the focal distance of the HMD, there were many triangular waves when using a black background, but there were more rectangular waves than triangular waves when using a white background. When there were many triangular waves, the subjects focused on a close range for a short time for each instance. In contrast, when there were many rectangular waves, the subjects focused on a close range for a long time for each instance. The above experimental results show that the subjects took a shorter time to hold the line of sight when using a black background while referring to the text that was closer than the actual field of view on the HMD. It is considered that this is due to the fact that the see-through property is relatively low when using a white background, which requires the image brightness to be high. On the other hand, the see-through property is relatively high when using a black background, which allows the image brightness to be lower. Thus, in the former, there is a tendency for subjects to refer to information on the HMD and the actual field of view more distinctly, while in the latter, there is a tendency for subjects to refer to information on the HMD more superimposed on the actual field of view (Figure 15).

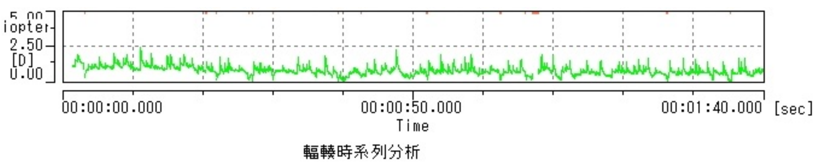

Fig. 13. Original waveform of diopter value (Example of the triangular wave)

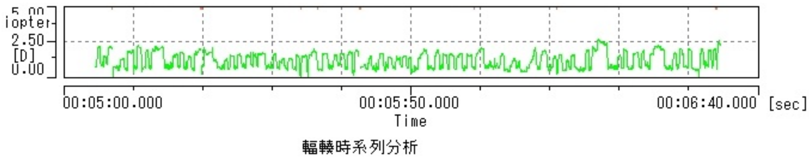

Fig. 14. Original waveform of diopter value (Example of the rectangular wave)

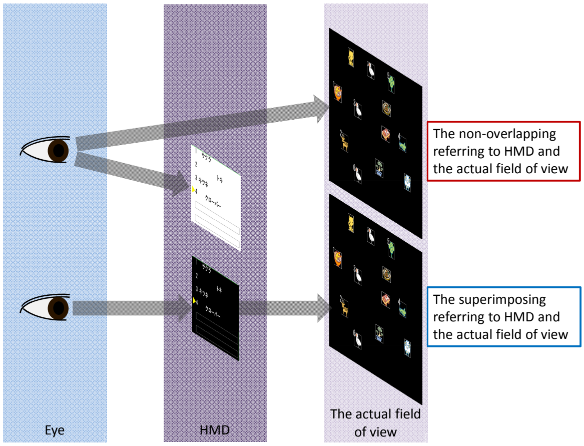

Fig. 15. Eye movements between the actual field of view and image on the HMD for black and white backgrounds

4 Discussion

First, for Task 1, with no interaction between the HMD and the real world (i.e., reading the information on the HMD at all times), if the user reads information on the HMD for a long time, mental fatigue is reduced when the image brightness on the HMD is low. However, if the brightness of the HMD images is low, the focus of the user moves away more easily because of the increase in the see-through characteristics. Therefore, the content might be difficult to read depending on the environment of the real field of view. Thus, when users view content with low brightness, they prefer white letters on a black background, for example, when using an HMD to read a newspaper or article in a taxi or train. However, when using the HMD outside in very bright or complex environments, increasing the brightness of images and reducing see-through properties would also be effective.

Second, for Task 2, with interaction between the HMD and the real world (i.e., watching both the information on the HMD and objects in the real field of view), if the brightness of the images on the HMD is high, the users watch the objects in the actual field of view and the information on the HMD separately in different positions. On the other hand, if the brightness of images on the HMD is low, the users have a strong tendency to watch the information on the HMD superimposed on the object in the actual field of view. Probably, this is also caused by the reduction in the see-through property when the brightness of the HMD images is high. Thus, when viewing content with low brightness, users prefer white letters on a black background when it is important to get information from the HMD and the actual field of view at the same time, for example, when watching airplanes on the runway while viewing instruction in an HMD during the operation of an airplane. On the contrary, when viewing content with high brightness, users prefer black letters on a white background when it is important to get asynchronous information, for example, disrupting working and conveying such instructions while working.

5 Conclusion

In this study, we experimentally investigated the effect of differences in the brightness of HMD images on the characteristics of users' eye movements and work performance. From the results, we have proposed that when the brightness of the content is low, users prefer white text on a black background, and when the brightness of the content is high, they prefer black text on a white background depending on the use and environment. In future, on the basis of these suggestions, we will also consider more detailed design elements in the content and would like to connect our results to the establishment of a guideline for developing content design for see-through HMDs.

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