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RESEARCH ARTICLE

The Effect of Video See-Through HMD on Peripheral Visual Search Performance

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ABSTRACT A video see-through head mounted display (VSHMD) has a digital camera set attached to the front of the HMD, which is a promising personal display device bringing a user into a realistic mixed world on demand. However, VSHMDs have an inherent risk of diminishing visual performance owing to the limited field of view (FOV) and poor display resolution etc. We investigated influences of VSHMD on the peripheral visual search performance of wearers. Nineteen participants performed a covert visual feature search task. All participants performed the tasks in four FOV conditions: 15°, 30°, 45°, and 60° with three types of viewing devices including VSHMD. The results showed that the VSHMD deteriorated the user's peripheral visual search performance worse than the HMD, whereas no deterioration found in the FOV restriction or the low resolution of stimuli. This result implies that low display sharpness and additional video signal chain of VSHMD cameras may induce diminished peripheral visual perception. Designers should consider this effect when developing any augmented reality or mixed reality system. Such investigations will raise an important guideline for the practical usage of VSHMD and tele-operation.

INDEX TERMS Video see-through HMD, peripheral vision, virtual reality, mixed reality, tele-operation.

I. INTRODUCTION

Video see-through head-mounted display (VSHMD) such as Meta Quest is an HMD that has built-in video cameras. They capture a real view in front, convert it into digital images, and display it on HMD in real time so that you see the real world in digital form. VSHMD has two main advantages. First, it offers a natural mixture of a real and a virtual scene because they are both digital. Second, it can present a fully immersive perspective view with a wide viewing angle (up to 100°). These advantages are suitable for implementing Augmented Reality (AR) and Mixed Reality (MR) throughout a wide vision range with relatively low heterogeneity in rendering between virtual objects and real scenes. Moreover, as an extended application, when VSHMD switches a see-through camera to another camera located in another place, the wearers experience moving to that location instantly to engage in remote operations. Szczurek et al. [1] summarized overall issues on the MR interface for remote operations. On the other hand, Optical see-through HMDs such as MS HoloLens do not use cameras. It utilizes half-reflective glasses. Users can see the real world through the glasses, and a virtual image is projected on the glasses via an optical relay system. It has the advantage of viewing the clear real world without displaying delay. Optical see-through HMDs are more suitable for AR applications.

However, several drawbacks of see-through display impede its success [2]. Psychological and psychophysical

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safety issues also related to those shortcomings, which require thorough investigation to avoid unexpected accidents [3]. Previous studies have revealed the effects of see-through displays in real use cases. Priot et al. [4] investigated the effects of hyper-stereopsis on visual perception of helicopter pilots during the first flight of a night-flight training program using a see-through HMD. More investigations are essential for the practical use of see-through technology in various industry fields. Tsai et al. [5] proposed 'dihedral corner reflector array' to extend field of view (FOV) with a sufficient relief distance in optical see-through HMD.

When we focus on the VSHMD, which is the main topic of our investigation, it inherits two types of deterioration: 1) visual displacement and 2) deterioration of viewing. Visual displacement occurs due to positional decoupling between the eyes and the video see-through camera, resulting in sensory conflict for visuomotor tasks. Lee et al. revealed a limitation of task performance on the excessive visual displacement condition of VSHMD [6]. However, Lee et al. also demonstrated that, as a practical use case, 55 mm of visual displacement does not seriously affect the visuomotor tasks. It means that human adaptation could overcome the visual displacement problem to some extent [7]. On the other hand, deterioration of viewing is still under critical issue. It is possibly causing problems in visual search task. It results from limitations in FOV, low display resolution, and display delay. Especially, a functional decline in peripheral vision notably raises the risk of unawareness of dangers. In a previous study, the effect of the outside view on attentiveness in using optical see-through type displays was investigated [8]. The study revealed that attentiveness was better when the distance between the AR image and the outside view was larger. Similarly, the decline in peripheral vision while wearing VSHMD resembles the phenomenon of tunnel vision. The non-clinical tunnel vision experience may cause by emotional arousal. High perceptual or cognitive load on central vision may aggravate the tunnel vision effect. It deteriorates peripheral visual function or reducing the functional visual field [9], [10]. Therefore, investigating the extent of peripheral visual function while wearing VSHMD is critical to prevent possible human errors.

The focal (or central) vision is within the 30° visual field (VF), where human recognize an object through eye movement to bring the image inside the focal vision [11]. When an object is outside the focal vision, people typically move their eyes rather than turn their heads, presumably minimizing neck strain. However, when wearing an HMD, users tend to utilize head movements rather than eye rotation The blurred image that the HMD provides, in particular in the peripheral VF, and possibly also the distortion of the view due to the curvature of the display do thus seem to be likely causes for longer search times [12].

According to the study, In particular, to address the safety issue, Qian et al. designed and compared two methods to compensate for the loss of awareness due to the occlusion caused by Optical see-through HMDs, which should be of concern in VSHMD as well [13]. Furthermore, a blurred or distorted image, particularly in the peripheral location, may cause a low performance level. However, low resolution of display is unavoidable in HMDs. We hypothesize that a lower display resolution would deteriorate the performance on HMD and VSHMD conditions to a similar extent.

Several studies have shown that a low resolution of peripheral visual information does not affect peripheral visual function. In the study of Chung et al. [14], reading speeds for various print sizes were measured at various eccentricities, from 0° (fovea) to 20° of VF, and it was found that reading speed increased with print size only up to a certain level at which the speed remained constant. Moreover, even larger print sizes did not facilitate the maximum reading speed. Watson et al. [15] demonstrated the effect of level-of-detail (LOD) degradation in the peripheral view of HMDs on visual search performance. Their results indicated that peripheral LOD degradation can be used to reduce color or spatial visual complexity by almost half in some search tasks without a significant reduction in performance. It seems to contradict our assumption. However, our study focused on the unavoidable degradation of HMD resolution to investigate the asymmetric deterioration of visual search performance across the whole VF.

In general, there are two experimental methods for studying human visual search performances in various visual fields [16]. First, in the overt visual search paradigm, participants were instructed to move their eyes or heads to search for the target stimulus. In contrast, in the covert visual search paradigm, participants were instructed to restrict their eye and head movements. Participants were instructed to search for the target only by covertly shifting the focus of attention without eye movements. Many studies have revealed distinct differences in visual search functions between the central and peripheral visual fields, namely the eccentricity effect: targets presented near fixation points are detected more accurately than those placed in the peripheral location [17], [18].

Wearing a VSHMD certainly deteriorates the overall visual function. That is because the degradation of resolution in VSHMD is unavoidable. However, it is essential to investigate whether this deterioration affects the entire VF equally, and if not, at which VF degraded the visual performance seriously. This investigation practically addresses safety issues. Even if the deterioration of visual function is inevitable, the level of decreased performance in peripheral vision needs to be carefully estimated in any practical VSHMD application.

II. MATERIALS AND METHODS

A. PARTICIPANTS

Nineteen participants (23.7±4.4 years old; 10 men, 9 women) volunteered for the current study. All participants had normal vision and were naive to the purposes and methods of the experiment. There were no self-reported abnormalities or motion sickness susceptibilities. Two participants had a great

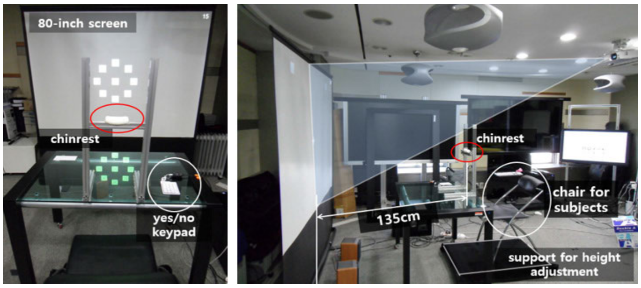

FIGURE 1. **Depiction of the experimental environment. The distance between participants and projected screen is 135 cm. They stare at the center of the screen during the experiment. The resolution of the projected screen is 1024 × 768.**

deal of previous experience with 3D or HMD, seven had some experience, and ten had little experience. All participants provided informed consent before testing and responded to a preliminary questionnaire. We received informed consent involved in the study. All participants underwent a standard eyesight test before the experiment.

B. APPARATUS

To stabilize eye level and head movement, we installed a chinrest on a table using a rigid stand, positioned 1.35 m in front of an 80 inch projector screen. A chair on a support allowed height adjustment to fit each participant's stature while the chinrest position remained fixed at 1.35m. A 'yes/no' keypad was placed on the table to allow participants to respond to the visual stimuli. A tactile marker on the keypad enabled participants to easily discern the 'yes' button from the "no" button without looking. We used a projector model DVM-D85M at 4500 ANSI. A speaker set provided click sounds when visual stimuli appeared and notifications whether participants provided correct or incorrect responses. Figure 1 shows the overall view of the test room.

C. CONDITIONS

1) BASELINE: BARE EYE CONDITION

The bare eye condition served as a baseline. Before starting, the participants practiced for five minutes with their normal viewing condition. This practice helped them to understand the whole test process.

2) BARE EYE WITH BLINDER GLASSES (BLD)

We prepared FOV blinder glasses (BLD) to investigate the effect of restricted FOV. The procedure was the same as that of the baseline except for the restriction of peripheral vision. As shown in Figure 2(a), the blinder glasses were made of cylindrical blinders attached to glass frames so that even those who wear glasses could wear that. Participants could see the real view only up to 70° FOV, which was identical to the FOV of the HMD and VSHMD condition.

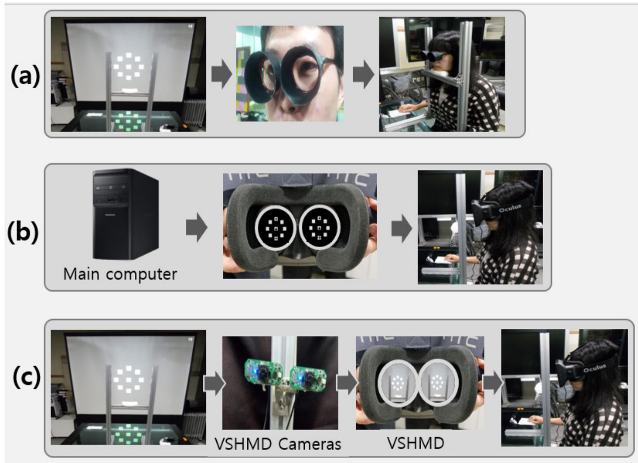

FIGURE 2. **Viewing conditions and the devices used. (a) bare eye with blinder glasses (BLD), (b) stimuli displayed directly on head-mounted display (HMD), and (c) video see-through display in HMD (VSHMD).**

3) VIEWING WITH HMD (HMD)

In this condition, participants performed experiments while wearing HMD, which condition refers to the general usage of HMD. The main computer output the visual stimuli to the HMD, not to the projector screen. So participants did not need to look at the projector screen because visual stimuli were provided directly by the HMD. The central viewpoint of visual stimuli was fixed regardless of participants' head movement so that they did not need to fix their heads. We used Oculus Rift DK1 (Figure 2(b)). It has 1280 × 800 resolution, which provides a side-by-side split display. The refresh rate is 60Hz, and the maximum field of view is 110°. It has 8.44 horizontal arcmin per pixel and 6.75 vertical. Considering 3.5° of the visual angle of the stimuli size, 0.56° (8.44 arcmin) of the visual angle of Oculus Rift DK1 was sufficiently fine for the experiment. The field of view was restricted to 70°, the same as other conditions - BLD and VSHMD. Since we used an old model, we could investigate VSHMD's inherent defect more directly, showing even more apparent results than current models. The investigation would be identical regardless of the models.

4) VIEWING WITH VIDEO SEE-THROUGH HMD (VSHMD)

We implemented a VSHMD using the same Oculus Rift model. Two cameras (30 fps, 640 × 480 CMOS, Logitech HD 1080p) captured the visual stimuli displayed on the projector screen, as shown in Figure 2(c) and Figure 3. The camera (in Figure 3) captured and relayed the screen images to the HMD in real time so that the participants could see the stimuli as a video see-through display. During the experiment, participants should fix their viewpoint on the central fovea of the stimuli. For participants' convenience, we mounted only cameras on the fixed position (the circle in Figure 3) rather than fix their heads on the chinrest. VSHMD provided comparable quality in display resolution to '3) HMD condition'.

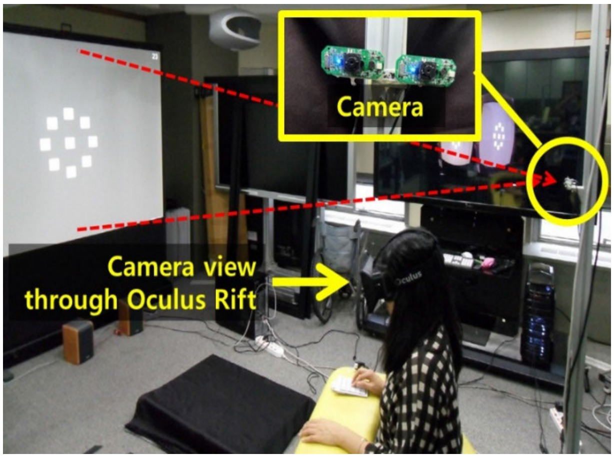

FIGURE 3. In VSHMD condition, participants saw the screen only through cameras mounted at 135 cm away from the projected screen, which is the same as the BLD and Bare eye condition.

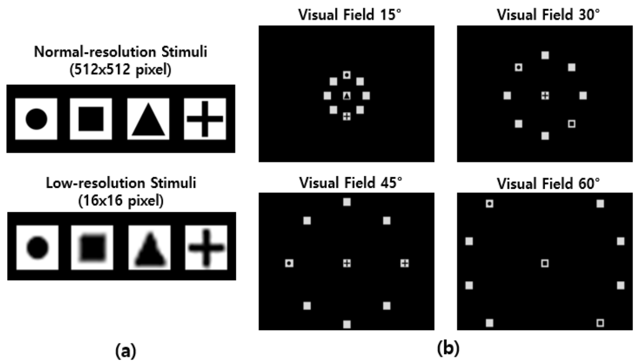

FIGURE 4. (a) Shape of stimuli used in the experiment. Each stimuli had 2 types of resolutions, Normal (512 × 512 pixel) and Low (16 × 16 pixel). The low-resolution stimuli are relatively hard to be perceived than the normal. (b) Stimuli applied to 15°, 30°, 45° and 60° of the visual field. Participants should identify whether one of two symbols around the peripheral zone is same to the symbol on the center.

D. STIMULI

We developed a display program with Unity 3D v5.2, which outputs visual stimuli according to experimental progress. We used a main computer of Intel Core i7-4790 (3.6GHz) 16GB RAM with Windows 10 Pro. The visual stimuli were composed of four types of black symbols inside a white rectangle box with a visual angle of 3.5°. We designed two levels of stimuli resolution to investigate whether degradation of the stimuli resolution would affect feature search performance: 512 × 512 (Normal-resolution) and 16 × 16 (low) (Figure 4(a)). The Low-resolution stimuli could be perceived, but not as easy as normal resolution stimuli. The background color was black to minimize the light reflected on the screen.

As shown in Figure 4(b), there were four VFs of 15°, 30°, 45°, and 60°. This experimental paradigm is distinguishable from the traditional feature search, which was the bottom-up visual search process influenced by stimulus saliency called the "pop-out" effect. Normally, Reaction time (RT) and correct responses (CR) are unaffected by the number of distracters [17], [18], [19]. However, in this study, more stimulus increased the task difficulty, which means "pop-out" did not affect the visual search performance significantly. This manipulation took the effect on the task performance by the top-down process [20].

E. PROCEDURE

Participants placed their chin on the chinrest in the bare eyes and the BLD condition. When the experiment began, a white fixation mark (cross) appeared at the center of the display for 1.5s (Figure 5). After fixation, a stimulus in the center (central stimulus) with two visual stimuli on the given visual field appeared for 0.2s. 0.2 second is too short time for human to shift their eyes to peripheral stimuli, so that they have to depend on instant peripheral visual performance to identify them. The two visual stimuli were composed of either two distractors or one distractor and one target (the same symbol to the central stimulus). Participants used covert attention to detect the target. The two stimuli appeared in different positions to each other so that the peripheral vision range fully covered the given visual field.

The participants were required to press the "yes" key within 2 second if one of the stimuli was identical to the central symbol. Otherwise, they had to press "no". To help the participants maintain their attention during the experiment, a feedback audio signal informed whether their responses were correct or not. If they did not respond within the 2 second, the response was considered as incorrect. After 2 second, the fixation mark (cross bar) appeared immediately for the subsequent trial.

There were 160 trials for each viewing condition: 40 trials per viewing each VF, with the sequence randomized for counterbalance. To minimize random responses, we advised participants not to press the button if they were not confident in their perception. The experiment used a with-in-participant design, so all participants undertook four sessions: a baseline and three viewing conditions (BLD, HMD, and VSHMD). The total experiment took approximately 45 min. After the experiment, the participants completed a questionnaire concerning their experience of sickness and ocular fatigue. We also interviewed the participants concerning any notable feelings or experiences, which may ascertain hidden features that might have affected their performance.

III. RESULT

IBM SPSS 22.0 analyzed the performance data of the reaction time (RT) and correct response ratio (CR). Due to non-normality of VF and resolution across viewing conditions, we used the Friedman and Wilcoxon tests. There were significant effects of RT as shown in Figure 6 (Friedman test, $\chi 2$ (3) = 46.524, $p < 0.001$) and CR (Friedman test, $\chi 2$ (3) = 53.716, $p < 0.001$) among all VF conditions. RT was significantly different for all VFs (Wilcoxon's signed rank test, VF15 and VF30,

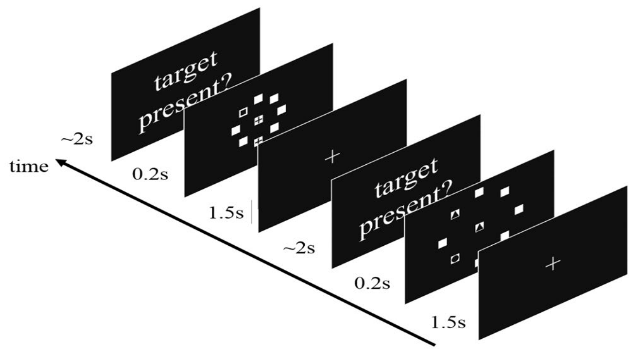

FIGURE 5. Schematic illustration of the feature search sequence. After 1.5 second of fixation, the visual stimuli presented for 0.2s. Participants responded whether a stimulus identical to the central stimulus by pressing "yes" or "no" button within 2s. The eccentricities (VF) of stimuli were presented in random order.

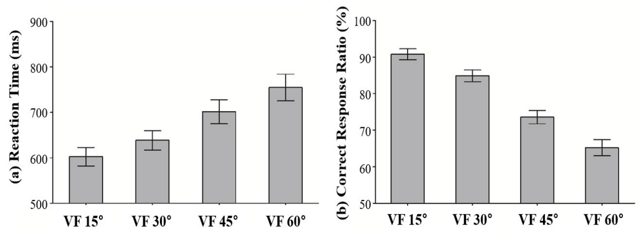

FIGURE 6. Average (a) Reaction time (RT) and (b) Correct response ratio(CR) in all conditions. Across each eccentricities (VF) from 15° to 60°, visual search performances were significantly different.

$Z = -3.269$, $p < 0.01$; VF15 and VF45, $Z = -3.824$, $p < 0.001$; VF15 and VF60, $Z = -3.824$, $p < 0.001$; VF30 and VF45, $Z = -3.119$, $p < 0.001$; VF30 and VF60, $Z = -3.783$, $p < 0.001$; VF45 and VF60, $Z = -3.522$, $p < 0.001$) (Figure 6(a)). The results showed that RT increased significantly with high VF. CR was also significantly different among all VFs (Wilcoxon's signed rank test, VF15 and VF30, $Z = -3.662$, $p < 0.001$; VF15 and VF45, $Z = -3.823$, $p < 0.001$; VF15 and VF60, $Z = -3.824$, $p < 0.001$; VF30 and VF45, $Z = -3.823$, $p < 0.001$; VF30 and VF60, $Z = -3.823$, $p < 0.001$; VF45 and VF60, $Z = -3.703$, $p < 0.001$) (Figure 6(b)). CR decreased significantly with increasing VF.

There were no significant differences between the normal and low-resolution visual stimuli for all viewing conditions as shown in Figure 7.

Significant differences in RT and CR were observed among the four viewing conditions as shown in Figure 8 (RT: Friedman test, $\chi 2$ (3) = 34.005, $p < 0.001$, CR: Friedman test, $\chi 2$ (3) = 34.200, $p < 0.001$). The RT and CR values between the baseline and BLD conditions were not significantly different. RT and CR in the HMD condition were faster and higher than in the VSHMD condition (RT: Wilcoxon's signed rank test, $Z = -3.824$, $p < 0.001$; CR: Wilcoxon's signed rank test, Z = z3.382, $p < 0.001$). Certainly, the HMD and VSHMD conditions had an equivalent viewing quality with the same HMD device. The only difference is the method of showing visual stimuli, see-through or direct display in HMD.

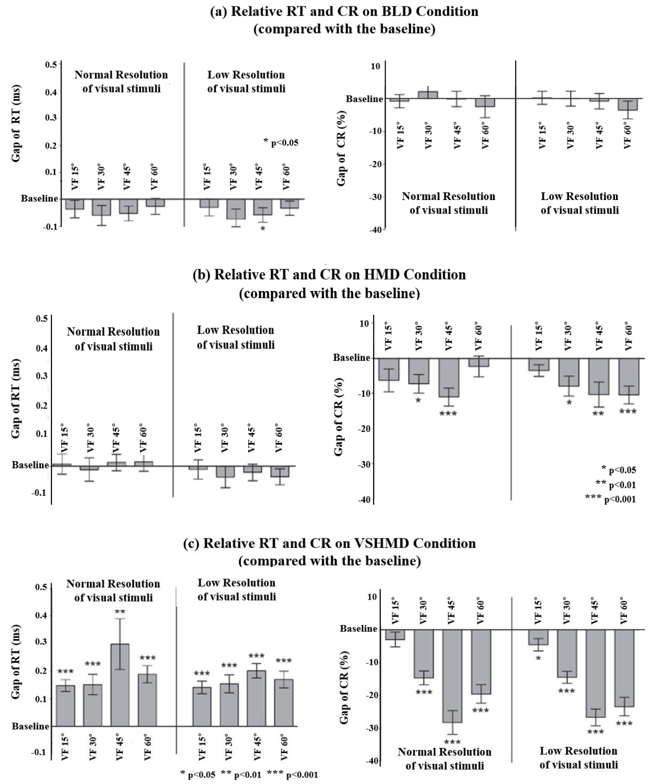

FIGURE 7. The relative RT and CR on each condition. Positive Y values indicate longer response time or higher correct ratio than the baseline. No significant difference between Normal-resolution and Low-resolution were found throughout all eccentricities (VF).

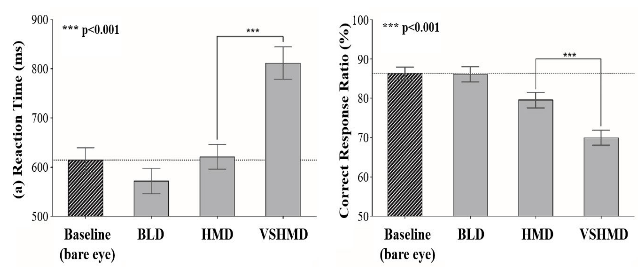

FIGURE 8. Average (a) RT and (b) CR throughout all viewing conditions. We investigated average visual search performances in four conditions - the baseline, BLD, HMD and VSHMD. As a key result, performance was significantly worse in VSHMD condition compared with other conditions.

However, an approximately 30% increase of RT in the VSHMD compared to the HMD indicates significant deterioration of visual search performance. Approximately 15% decline of CR in VSHMD compared with the HMD also suggests that the user may have more difficulty in viewing the see-through world with VSHMD.

IV. DISCUSSION

Peripheral visual performances were investigated by way of measuring reaction time and correct responses at various eccentricities that is VF. As predicted, visual search was more difficult when the target appeared further from the central

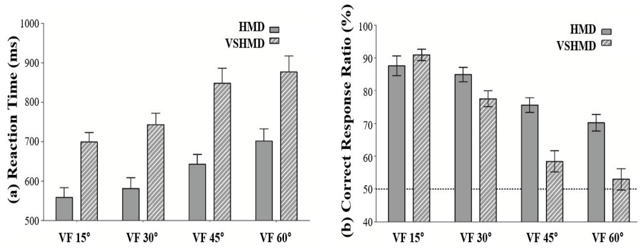

FIGURE 9. Comparison of (a) RT and (b) CR between the HMD and VSHMD. Despite using the same display device, video see-through display generated critical impairment in peripheral visual perception even though it does not deteriorate the image resolution.

vision. In our experiment, there was no difference in the overall visual search performance between the baseline and wearing blinder glasses (BLD). The FOV restriction was not a factor in the deterioration of the peripheral visual search.

There was no difference between the two resolution stimuli as well: normal and low. Performances at low stimuli resolution were slightly worse but not significantly worse. It is certain that low-resolution stimuli may be more difficult to perceive. However, the stimuli resolution may have a small effect on visual search performance. It does not seem to be a critical factor influencing peripheral visual search.

Most importantly, as shown in Figure 9, we found a significant deterioration of visual search performance on a video see-through display. The additional display signal route through the see-through camera in VSHMD significantly degraded the visual task performance. This decline started from 30° of eccentricity, which is known as the central visual field boundary. Moreover, the performance gap between the two conditions tends to widen as the eccentricity (VF) increases. Compared to the HMD condition, the correct response in the VSHMD showed a steeper decline as the VF increased. Eventually, at 60° eccentricity, the CR in the VSHMD condition converged to approximately 50%, which is almost close to the value of the random choice responses, whereas in HMD, the CR was approximately 70%. Moreover, it may deteriorate not only peripheral visual performance but also the sense of realism, immersion, and in term of human factors, simulated sickness, visuomotor degradation etc., which should be investigated more as future works.

Low FOV and poor resolution are unavoidable disadvantages of VSHMDs. The lower display resolution in video see-through viewing is more critical factor in peripheral visual search performance deterioration. For a more in-depth study, we need to investigate the effect of display contrast, saturation, brightness, etc., as potential causes of the diminished peripheral visual perception.

In HMD, peripheral vision deterioration is one of the significant issues. When you wear the video see-through HMDs such as Oculus Quest Pro or HTC XR, you must be more careful to avoid unexpected accidents caused by the unawareness of peripheral vision. Interestingly, when wearing an optical see-through HMD, the user's head movement is less than VSHMD. We often see HMD wearer moves their head too much. Kollenberg, et al. revealed this phenomenon using an eye tracker system [12]. We found that this phenomenon is more serious, especially in video see-through HMD.

Recently, safety issues related to the see-through display have emerged. Aerospace, military, and engineering areas requiring top-rated technologies have applied see-through technologies as visualization devices. And the see-through display can also offer advantages in low-vision rehabilitation and vision enhancement [21]. However, it may interrupt the facilitation of a sufficient range of visual perception such as navigation and wayfinding. For instance, in navigation, it is important to monitor side views continuously to avoid hazards when changing directions. Researchers have yet to undertake general studies designed to facilitate the use of video see-through displays.

VSHMD has a wide variety of promising applications that could cover from AR/MR to tele-operation. However, its degradation of peripheral vision arising from see-through video signal chain addition can induce risks in tele-operation, such as unexpected collision or no awareness of risky environments during remote manipulations. In some cases, these risks are more serious when the vision range of the tele-operation equipment differs from that of the operator. This study implies that the operators, designers, and developers should be aware of these features of VSHMD sufficiently. Our contribution is to ascertain matters of critical importance in anticipation of the widespread use of VSHMDs to support informative services. Highlighting important peripheral information may ensure the user's safety. Such considerations will serve as important guidelines for designing VSHMDs.

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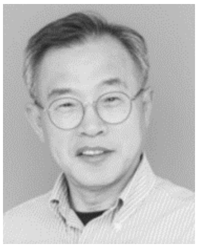

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