Article

MatchMR: Exploring the effects of scale and color differences on users' perception in mixed reality devices

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Abstract: With continued technological innovation in the fields of mixed reality (MR), wearable-type MR devices, such as helmets, have been released and are frequently used in various fields, such as entertainment, training, and education. However, because each product has different parts and specifications in terms of the design and manufacturing process, users feel that the virtual objects overlaying real environments in MR are visualized differently depending on the scale and color used by the MR device. In this paper, we compare the effect of scale and color parameters on users' perception in using different types of MR devices to improve MR experience. We conducted two experiments (scale and color), and our experimental study showed that the subjects who participated in the scale perception experiment clearly tended to underestimate virtual objects, compared with real objects, and overestimate color in MR environments.

Keywords: Mixed-reality; perception; Scale; Color; HMD

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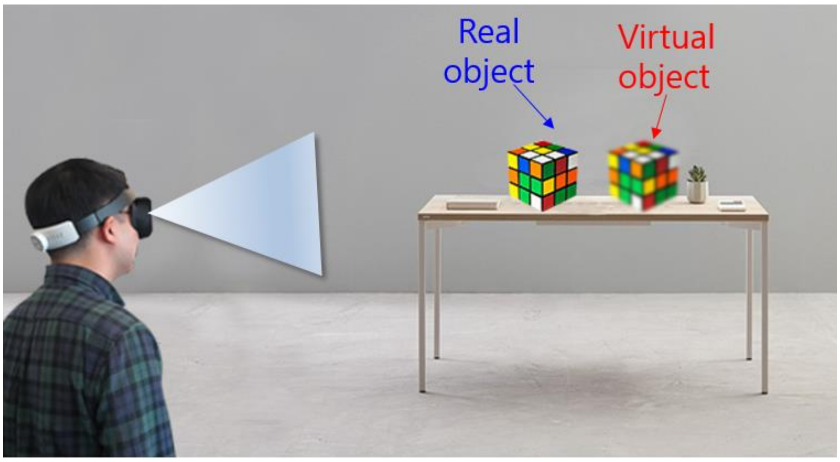
1. Introduction

Recently, mixed reality (MR) has received significant attention as a key technology for entertainment, training, and education, because it has the potential to make real spaces smarter and more interactive [1, 2]. MR helps people to use augmented virtual objects by spatially registering useful information, and it offers various situations in which users can visualize and interact to improve their performance in completing actual tasks [3]. Additionally, MR devices (e.g., a helmet-type head-mounted display) for visualization are a major class of new instruments in scientific research and engineering applications. Nonetheless, MR devices are heavy, and their viewing angle is relatively narrow, compared with the human viewing angle [4]. Moreover, because each MR device has a different design configuration and specification in terms of its parts, people often differently perceive the same virtual object, depending on the MR device used [5].

Therefore, it is necessary to resolve visual differences between different MR devices to obtain a mixing consistency, i.e., a perceived coherence between virtual and real objects. For example, imagine a situation where a user is wearing a helmet-type MR device, when the user sees a computer-generated virtual cube that looks like a real cube, he/she recognizes the scale and color of that cube differently, depending on the MR device used (See Fig. 1). Thus, consistency between different MR devices in the perceived scale and color of virtual objects will need to be established.



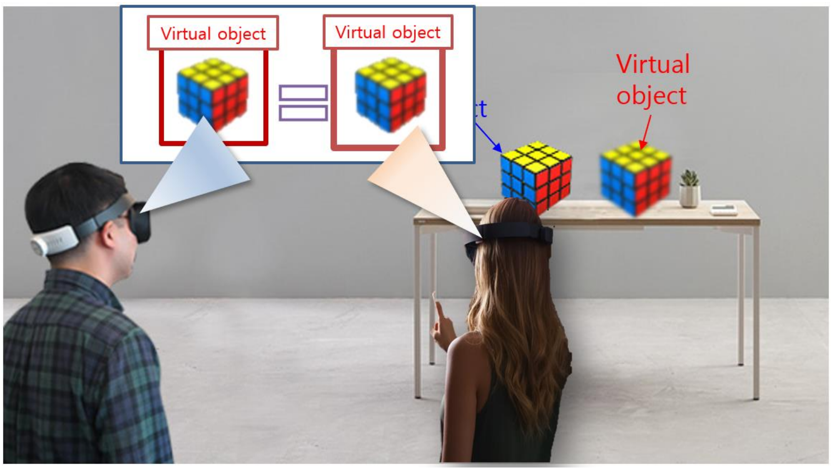


Figure 1. A user's perception in an MR environment. When comparing a virtual object with a real object in an MR environment, the user must be able to perceive the scale and color using different MR devices (top). Additionally, the user should be able to recognize the same size and color, irrespective of the MR device worn (bottom). In our case, we assumed that people wearing different MR devices had different perceptions.

Fig 2. shows the parameters that affect users' perception in a typical MR environment. To begin with, it should be noted that we referred to related research works to define which factors would affect users' perception [6–8]. In our paper, we divided the parameters that affect users' perception, such as color, scale, naturalness, visibility, and readability, in an MR environment into three groups: device characteristics, the environment, and object characteristics. Firstly, the device characteristics were related to issues concerning different specifications (e.g., the field of view and brightness). Secondly, the environment parameters, such as the light condition, refers to elements affecting the MR environment in real spaces. Lastly, the object characteristics, shown in Fig.2, were related to how a computer-generated virtual object is represented, such as its texture quality and viewing setting, which is presented to the user looking at the virtual object.

Using these parameters, our paper focuses on the device characteristics in terms of the display type (e.g., video or optical see-through head-mounted display) to measure users' perception (e.g., scale and color), and the remaining parameters were used as control variables in our evaluation. It should be noted that the video see-through head-mounted display (HMD) is based on stereoscopic visualization, which allows a dual-webcam module to be attached to an immersive HMD display and have two image sources, i.e., the real world and the computer-generated world. On the other hand, the optical see-through HMD is a device that has the capability of mixing virtual objects and allowing the user to see through them, and it has only one image source, i.e., the computer-generated world [9].

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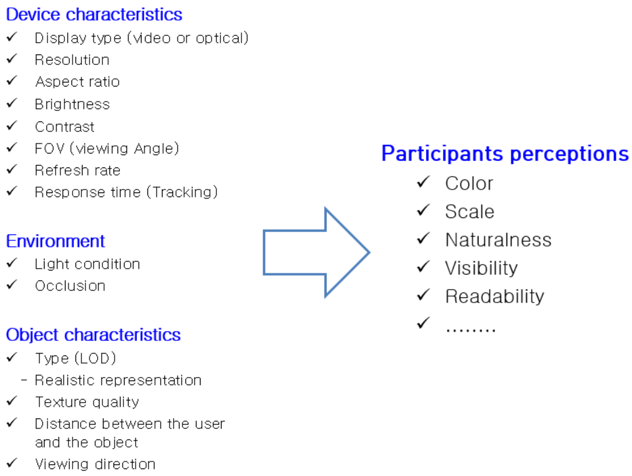

Figure 2. Parameters affecting users' perception: Input elements that affect users' perception (left); examples of users' perception of MR environments (right).

Thus, this paper proposes a novel method for evaluating users' perception of virtual objects in using heterogeneous MR devices to improve MR experience. Specifically, we explore the correlation in visual perception between real and virtual objects in using mixed reality devices. To find the relationship between two different objects in users' perception, we ran comparative experiments to assess users' perception in terms of, for example, the effects of the scale and color differences in using various MR devices. This study resulted in the creation of what is called the MatchMR, which allows different MR devices to induce the same user experience (in terms of, e.g., scale and color).

The remainder of our paper is organized as follows: Section 2 discusses works related to our paper. Section 3 provides details of the proposed experiment, involving scale perception and different MR devices, and discusses the results. Section 4 provides an experimental evaluation of color perception and the main findings. Finally, in Section 5, we summarize our results and contributions and conclude with directions for future research.

2. Related Works

We outline three areas of research that are directly related to the main theme of this work (i.e., MR devices, users' perception in VR/AR/MR environments, and MR consistency).

MR devices. A mixed reality (MR) device is a visualization platform that merges real and virtual worlds. Virtual objects overlay a real environment in MR and thus give users additional information [10]. Most previous works have mainly used smart phones to provide images that synthesize real and virtual environments, but they did not consider the presentation of synthesized images directly to the human eye. More recently, MR devices with a helmet-type HMD that synthesizes spatially registered virtual objects overlaying a user's view have been introduced. As already mentioned, MR devices are mainly divided into optical and video see-through HMDs, depending on whether actual images are viewed directly by the user or via a video input. We are interested in how the scale and color of different types of HMDs affect users' perception. No comprehensive work has been done in this connection.

Users' perception in VR/AR/MR environments. Given the availability of immersive environments using VR/AR/MR technologies, it has become possible for users to experience virtual objects as if

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they were real [11]. Therefore, many researchers have considered users' perception in using these technologies in order to evaluate the sense of presence and emotional response that they experience when interacting with virtual objects in VR/AR/MR environments [12]. There have been a few attempts to evaluate users' perception, which were conducted using questionnaires and by monitoring physiological signals, such as the heart rate and skin conductance [13, 14]. As a result of a representative research, Diaz et al. proposed depth perception in augmented reality as a function of the virtual object design. In their studies, they found that participants underestimated the depth and rendering of virtual objects, which influenced their perception of the objects' spatial position [15]. Additionally, Baumeister et al. investigated and showed results concerning the cognitive load imposed on users by MR devices, comparing different types of augmented reality displays (e.g., a projection-based spatial augmented reality, optical see-through HMD, and video see-through HMD). The results showed that spatial augmented reality helped to reduce cognitive load [16]. Our work was designed to further the research of two pioneering works by proposing an object-level comparison in terms of scale and color differences, comparing actual and virtual objects in relation to two forms of HMD.

MR consistency. Another related trend is the use of illumination and rendering techniques to make the appearance of virtual objects consistent and thus achieve a coherent AR [17]. Rohmer et al. proposed a photorealistic and high-quality AR framework, with compensated differential rendering and shadows, to illuminate virtual objects and make them consistent with real objects [18]. Additionally, Rhee et al. presented a novel immersive system that provided composite optimized 3D virtual objects with a lighting source, which allowed them to create a live 360-video and thus illuminate the virtual objects [19]. For our research, some of these concepts were borrowed, but they were modified for the purposes of our research on how to compensate for users' perception.

3. Experiment 1: Scale Perception

So far, we have described our motivation for investigating the effects of scale and color conflicts on users' perception in using heterogeneous MR devices and related works on MR devices, as well as users' perception in VR/AR/MR environments, in terms of MR consistency. In this section, we present our experiments and the results concerning the differences in users' perception in using different MR devices that are caused by the degree of scale (e.g., optical see-through HMD vs. video see-through HMD) in the defined experiment below.

3.1. Overview of Experimental Design

In the experiment, we compared a video see-through HMD and an optical see-through HMD, as MR devices, in terms of users' perception (e.g., their sense of scale in relation to virtual objects) (See Fig.3). In the experiment, to assess users' scale perception, participants were permitted to adjust the size of a virtual cubic puzzle and select the same size as the actual puzzle. Then, we compared different types of HMD in relation to users' scale perception. It should be noted that we assumed that users have different senses of scale, depending on the HMD used. Fig.4 shows the actual cubic puzzle used in the scale comparison experiment. It is 5.5 cm in size and has different colors on each side, with 6 colors in total.

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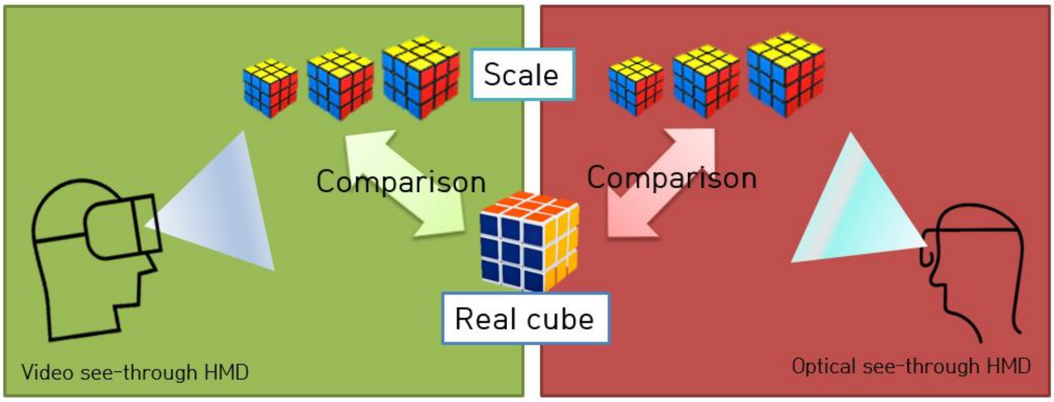

Figure 3. Scale perception in comparing a real cubic puzzle with a virtual one using a video see-through HMD and an optical see-through HMD. In the experiment, two cubes (each with a real and a virtual cube) appeared at the same time for comparison.

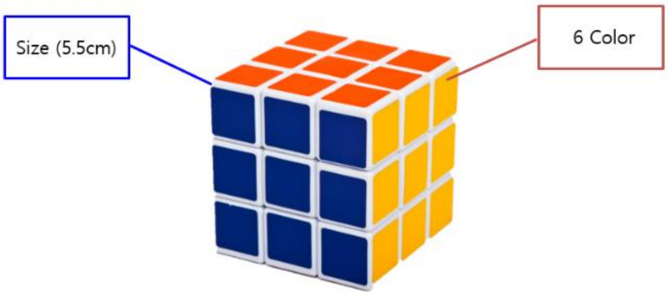

Figure 4. Real cubic puzzle provided as a basis for the scale comparison. It is 5.5 cm in size and has different colors on each side.

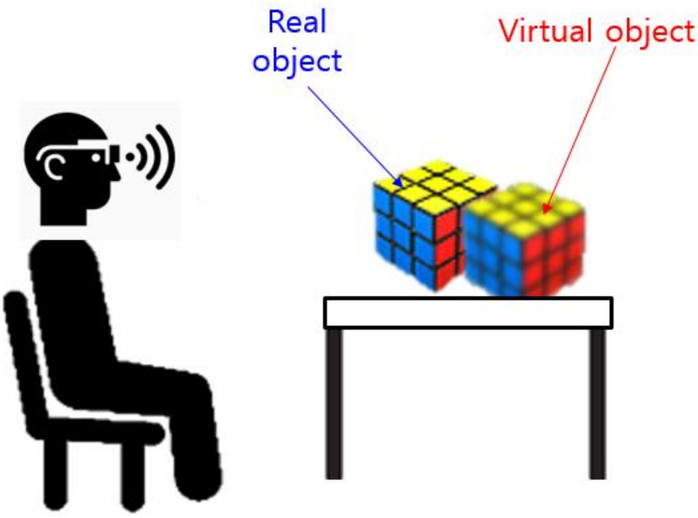

Figure 5. Experimental design. A participant compared the size of the virtual cube with the actual cube in the experiment.

Fig. 5 shows our system configuration for the experiment. A participant in our experiment was seated in a chair in front of a desk, then the subject wore a MR head-mounted display (HMD) to view the virtual cube and compare it with the real cube.

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The main factor was the scale value of the virtual cube, and two test conditions (video vs. optical) were employed. We also included the variable of the distance between the participant and the cube. Fig. 6 shows the two test conditions, including the video and optical see-through HMD. As already mentioned, the video see-through HMD has a dual-webcam module attached, which allows the user to visualize the virtual cube, and the optical see-through HMD, which allowed the user to integrate the virtual cube into reality, since the device is semi-transparent. In our experiment, we used a Microsoft HoloLens, for the optical see-through HMD, and an Oculus Rift and OVRVision stereo camera set for the video see-through HMD (See Fig.6).

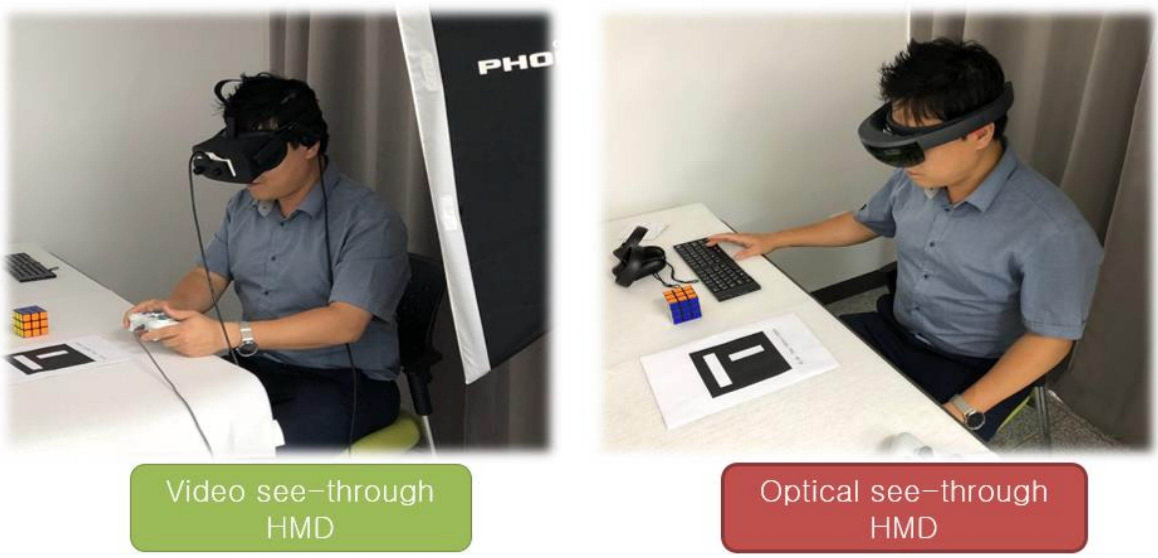

Figure 6. Video see-through HMD, with a dual-webcam module attached, which allows the user to visualize the virtual cube (left), and the optical see-through HMD, which allows the user to integrate the virtual cube into reality, since the device is semi-transparent in our experiment (right). Participants could see the virtual cubes placed on the fiducial MR marker.

3.2. Experimental setup for scale perception

As mentioned earlier in the overview of the experimental design, in order to evaluate users' scale perception in using heterogeneous MR devices, we compared the scale difference between two HMDs (video vs. optical see-through HMDs). To set up this experiment, after geometrically calibrating the FOV (Field of view) and distortion of the HMD, we installed an experimental environment that consisted of the HMD, a real object (e.g., an actual cube), and a fiducial MR marker for the registration of the virtual cube. As for the test conditions, a 3D virtual cube, with the same shape as the real cube, was constructed using Unity3D and appeared at the same time in a given MR environment.

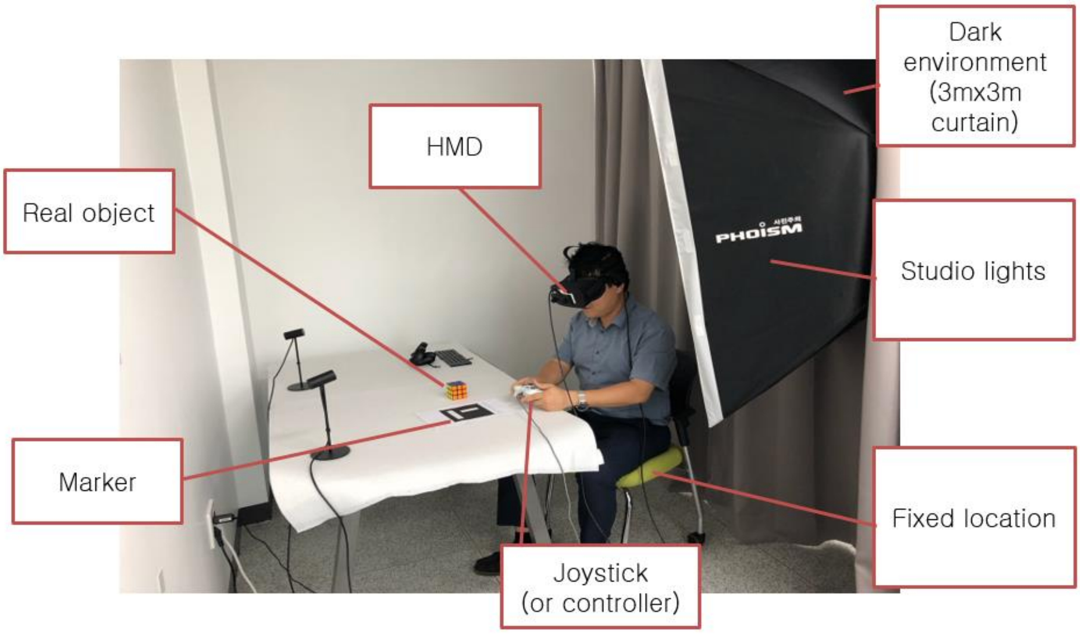

Figure 7. System setup in our experiment. The participant wearing the HMD sits in a chair and compares the size of the actual cube with that of the virtual one, and the participant can adjust the size of the virtual cube using a joystick (or controller).

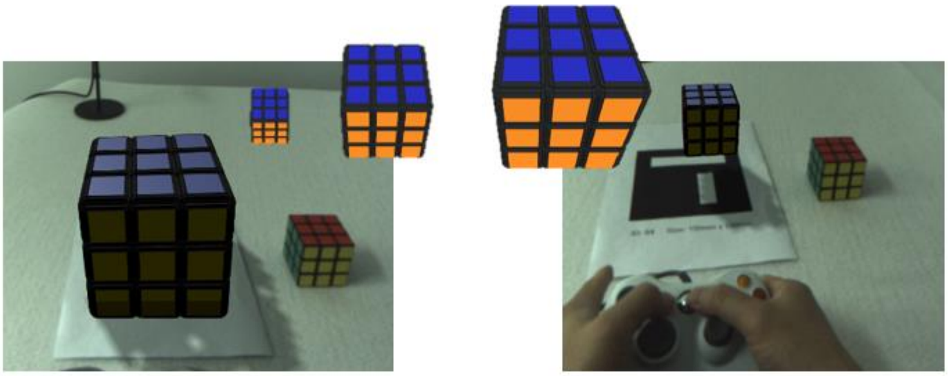

Figure 8. Experimental task of adjusting the scale parameter of the virtual cube in comparing it with the actual cube. In the experiment, the subject was asked to match the size of the actual cube. In the first frame, the virtual cube was presented as large (left). Participants were able to adjust the size with a joystick.

3.3. Experimental Task and Procedure

The experiment was carried out with 60 paid subjects, who were divided into two groups. Thirty subjects participated in the experiment under each of the two conditions, with a between-subject measurement. To assess the sense of scale, as an indicator of users' perception, the experiment was designed with two factors (i.e., the heterogeneous MR devices and distance between the object and the participant). We measured how participants perceived the scale of the virtual cube compared with that of the actual cube in the MR environment. Thus, during the experiment, the subject was asked to control and adjust the size of the virtual cube and try to match the size of the actual cube using a joystick (or controller) (See Fig.8).

After the experiment, the subjects were asked to submit their answers to a list of questions concerning their experience, which was conducted by having the subjects fill out a questionnaire.

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The question categories are as follows: "What were your criteria regarding size? (The total size of the real cube, the partial size of the real cube or the size of the fiducial marker)".

3.4. Results and Discussions

Before the experiment, we hypothesized that both the video and optical see-through HMD were assumed to have different scales, depending on their distance from polynomial regression forms. One-way ANOVA analysis was conducted for the three experimental test conditions, and the use of the video-based MR device (video see-through HMD, p-value = 0.1265, $p > 0.05$) and the optical-based MR device (optical see-through HMD, p-value = 0.3195, $p > 0.05$) was not affected by the distance factor (i.e., 10 cm, 40 cm, and 70 cm) between the participant and the virtual object.

However, in both HMD situations, we confirmed the result that virtual objects are underestimated, compared with actual objects. For example, people thought 6.04 cm was equal to the real cube, which was 5.5 cm (see the result of 10 cm, when wearing the video see-through HMD, in Fig. 9). Thus, as shown in previous studies, we found that people tend to perceive the virtual object as small. In previous research works, people tended to underestimate the virtual space [15].

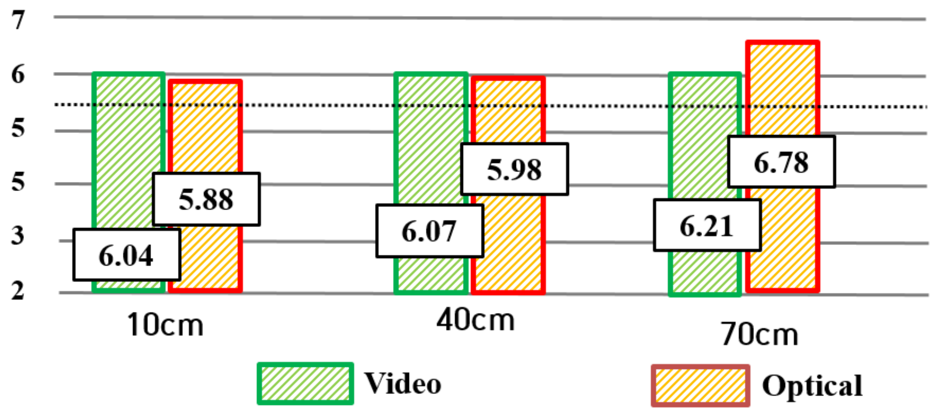

Figure 9. Results regarding scale perception. The subjects underestimated the virtual cube, compared to the real cube (5.5 cm), in using two MR devices (video and optical). Statistically significant differences between all distance conditions were not found ($p > 0.05$).

4. Experiment 2: Color Perception

In the second experiment, we investigated users' color perception in using different MR devices. Thus, we present the experiment and the result regarding users' perception of the degree of color in the defined experiment, shown below.

4.1. Overview of the Experimental Design

The experiment regarding color perception was similar to the scale evaluation. We compared the video see-through HMD and the optical see-through HMD in relation to users' perception in using different types of HMDs (e.g., their sense of color in relation to virtual objects) (See Fig.10). In the experiment, participants were asked to select the color that appeared to be most similar to that of the actual cube among a number of virtual cubes with different colors. We decided to carry out the experiment using the method of allowing users to choose similar colors, because adjusting for matching, as in the scale experiment, was too time-consuming. The real cube with different colors on the 6 sides, as shown in Fig. 4, was used in the experiment.

The factor was the color value of the virtual cube under two test conditions (video vs. optical), and Fig. 11 shows two test conditions, including the video and the optical see-through HMD.

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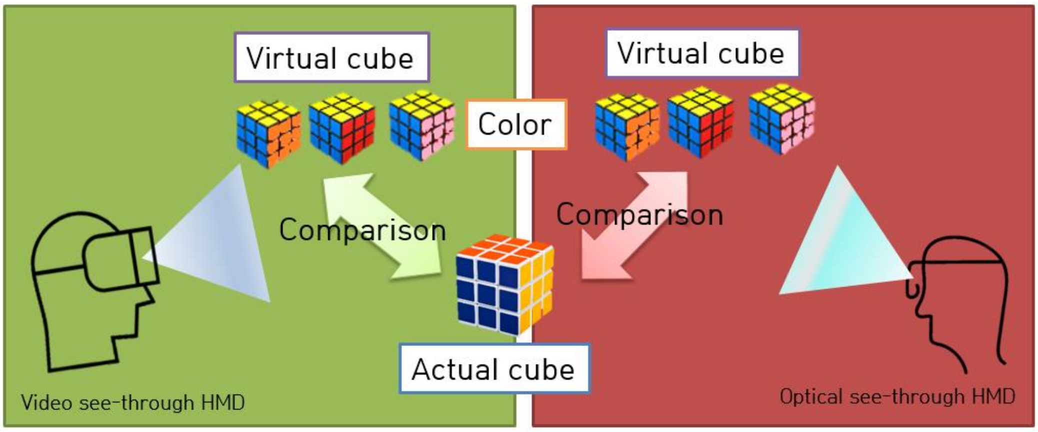

Figure 10. We investigated users' color perception in comparing a real cubic puzzle and a virtual one using the video see-through and the optical see-through HMD.

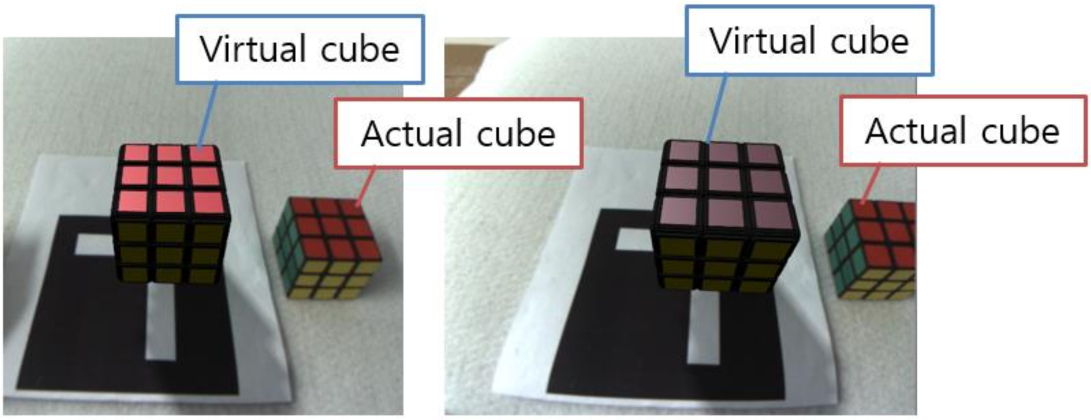

Figure 11. Experimental task of selecting a color parameter for the virtual cube, compared to the actual cube. In the experiment, the subject was asked to match the color of the actual cube.

4.2. Experimental setup for color perception

Unlike in the scale experiment, in the color experiment, we installed a curtain and two studio lights to ensure that the real and virtual environments had the same light conditions (See Fig.7). It should be noted that it is important that, when calculating the colors of the virtual object, ambient lighting is considered. Thus, we applied the same shadow to our virtual object as the real-life shadow using the same light conditions. For example, the shadow on the virtual cube was rendered the same as the shadow on the actual cube. Fig. 12 shows the light condition and the simulated shadow in the virtual environment. The shadow matched the actual shadow, which was the control variable. To measure the lighting condition of the real environment, we used a color meter and a light sensor module.

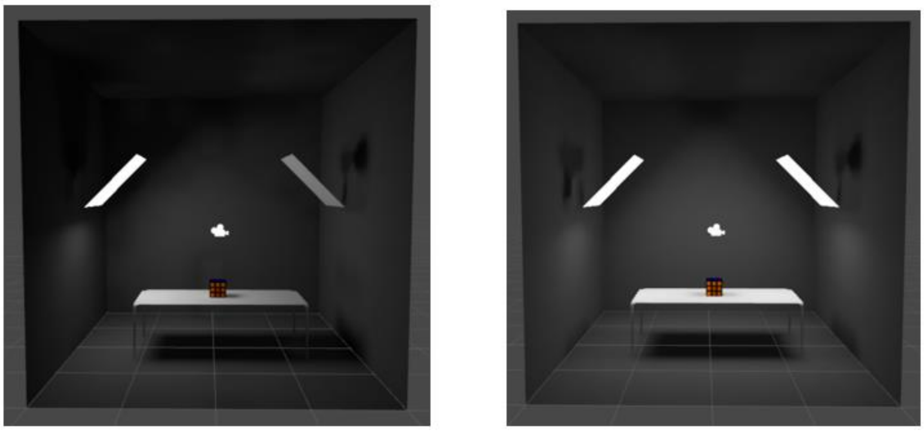

Figure 12. Light condition and the shadow in the virtual environment. The intensity of the virtual environment was set to be equal to the real space. The left figure shows a situation in which one of the studio lights is turned on, and the right figure shows a situation in which two lights are turned on.

Fig.13 shows the color values for the candidates in the experiment. Because the participants using the optical see-through and the video see-through HMD experienced different intensity values, we used the HSL (Hue, Saturation, Lightness) color model to set candidates (See Fig.13). Then, we selected 7 candidates in the color vector at a given intensity, depending on the HMD used (See Fig.13). Table 1 shows 7 color candidates, selected for each RGB (with a total of 21 colors), in the color experiment.

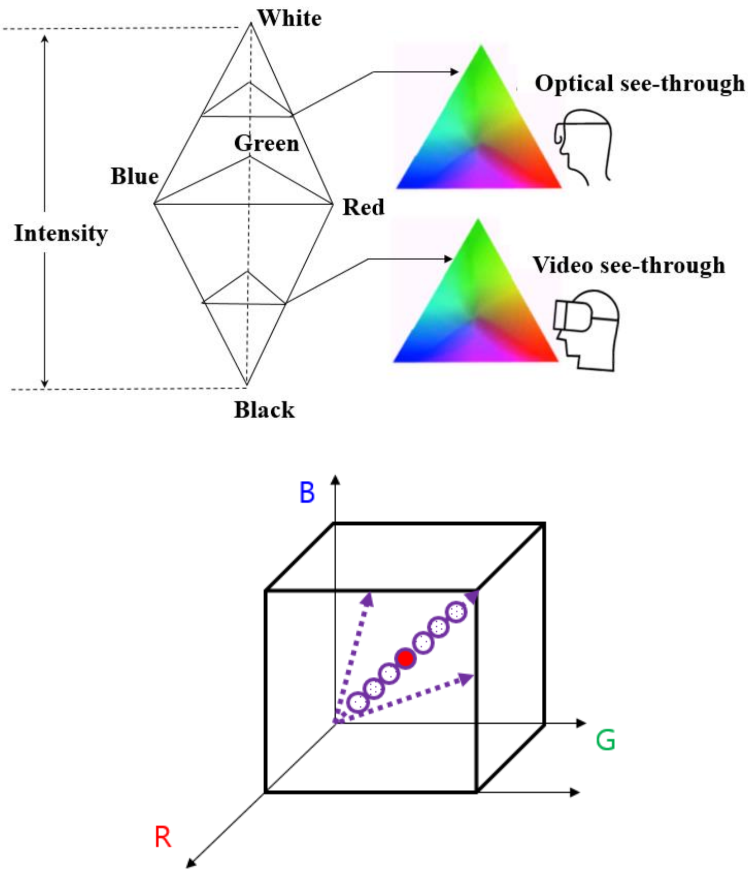

Figure 13. Experimental setup for selecting color values. In the experiment, we used the HSL color model, which includes color and lightness (top), and set it to 7 RGB levels (bottom).

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Table 1. Candidates for color perception. Participants were asked to select a color for the virtual cube that appeared to be the most similar color to the actual cube among color candidates.

	Red			Green			Blue		
Level	R	G	B	R	G	B	R	G	B
1	162	43	51	27	100	78	38	50	121
2	171	45	53	28	105	82	40	52	128
3	180	47	55	29	110	86	42	54	135
4	189	49	57	30	115	90	44	56	142
5	198	51	59	31	120	94	146	58	149
6	207	53	61	32	125	98	48	60	156
7	216	55	63	33	130	102	50	62	163

4.3. Experimental Task and Procedure

To assess users' perception in terms of color difference in using heterogeneous MR devices, we adapt the method used in the scale perception experiment. In the case of our scale perception, we measured how the participants perceived the scale of the virtual cube, compared with the actual cube, in the MR environment. The task in color perception was similar. Additionally, the experiment was conducted with 60 paid subjects, divided into two groups, with a between-subject measurement, as in the scale experiment.

During the experiment, participants tried to match the virtual cube and the actual cube in terms of color. The rest was performed in the same manner as the scale experiment.

4.4. Results and Discussions

Before the experiment, as in the scale perception, we hypothesized that both the video and optical see-through HMDs induce different color perceptions. The results showed that the experimental test conditions for the video-based MR device and the optical based MR device did not have a major effect on users' color perception of the virtual object. However, we confirmed the result that virtual objects are overestimated, compared with actual objects. For example, people thought red 211 of the virtual cube was equal to red 189 of the real cube (see the result of red, when wearing the video see-through HMD, in Fig. 14).

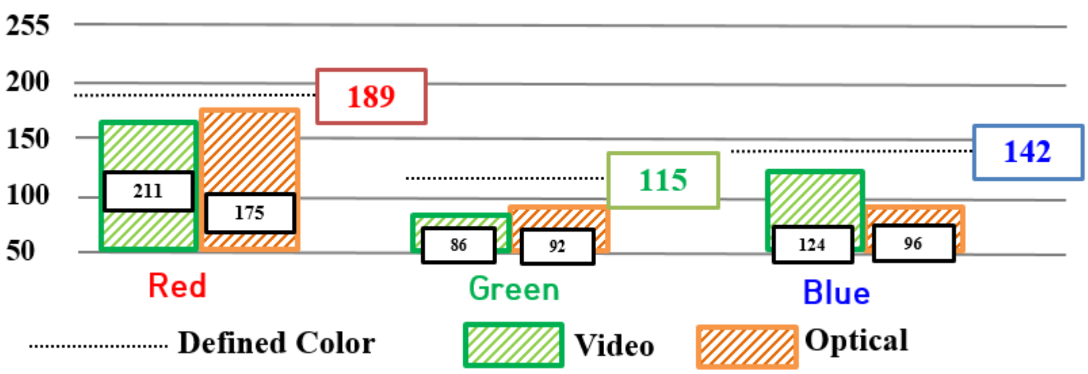

Figure 14. Results regarding color perception. The subjects overestimated color in using two MR devices (video and optical).

5. Conclusions and Future Works

In this paper, we presented the effects of scale and color perception in using heterogamous MR devices (optical vs. video see-through HMD) to improve MR experience and the design of future MR systems. We conducted two experiments (scale and color). The main result of our experiments was that participants tend to underestimate virtual objects in terms of scale, whereas our study found that subjects overestimated virtual objects in the MR environment in terms of color. From these findings, we found that if we adjust the size and color of a virtual object according to the characteristics of the HMD, people will be able to recognize the same virtual object, irrespective of the MR HMD used.

For future research, there are still many aspects of MatchMR that need improvement in terms of its practical applicability and perceptual factors. Specifically, it is necessary to study the chromatic characterization of the mixed reality system, which determines the color transformation between the device-dependent color space, such as RGB, and the device-independent color space, such as CIEXYZ or CIE Lab, and the differences in color gamut and dynamic range between different devices. Additionally, we will continue to explore various MR devices, including smartphones, in order to make them usable in the real world. We also plan to further extend our experiments using various parameters that affect users' perception, as shown in Fig. 2.

Author Contributions: Kwang-seong Shin performed the prototype implementation and usability experiments. Howon Kim designed the study in terms of conceptualizing and performed the analysis of the results, and Dongsik Jo analyzed the data and contributed to the writing of the paper.

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Conflicts of Interest: The authors declare no conflicts of interest.

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