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VR Color Picker: Three-Dimensional Color Selection Interfaces

JIEUN KIM[1], JAE-IN HWANG[1], AND JIEUN LEE[2]
[1]Center for Artificial Intelligence, Korea Institute of Science and Technology, Seoul 02792, South Korea
[2]Division of Computer Engineering, Hansung University, Seoul 02876, South Korea

Corresponding author: Jieun Lee (jieunlee@hansung.ac.kr)

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ABSTRACT In this paper, we propose a 3D color picker for virtual reality (VR) systems. Using the proposed color picker, the RGB and HSV color spaces are displayed in 3D shape, and a color can be selected through a one-step interaction by pointing at a location inside the color space with a 3D pointing device. This process is very simple compared with the multistep color selection interactions required for existing VR color pickers. Since the interior of the color space is not visible, we also propose three types of user interfaces that show the interior of the color space. These interfaces either cut out a portion of the color space, show cross-sections of the color space, or show discrete samples placed in the color space. We conducted user experiments on the color selection time, color selection accuracy, and usability and proved the usefulness and effectiveness of the proposed VR color picker.

INDEX TERMS Color, human–computer interaction, user interfaces, virtual reality, visualization.

I. INTRODUCTION

A color picker, which is a tool for selecting a color, is an essential tool for art and design. VR painting applications have recently gained popularity [1]–[7]. These applications provide various tools and effects so that users can freely draw or paint in the 3D space in VR. Although a 3D interaction with a 3D workspace is possible in a virtual environment, most VR painting applications use a 2D color picker based on the HSV color model. Usually, when a 2D color picker is implemented, a 2D pointing widget is utilized to set the hue and saturation and a 1D pointing widget is utilized to set the value (brightness). Alternatively, a 2D pointing widget is utilized to set the saturation and value and a 1D pointing widget is utilized to set the hue. The advantage of the existing 2D color picker is that it is familiar to many users who have been working with color pickers within a desktop environment; however, it has the disadvantage that several alternative interactions between the two widgets are required.

In VR, shapes can be displayed in 3D, and users can point to a 3D position; therefore, a better color picker can be designed that essentially reflects these observations. The RGB and HSV color models are commonly used for color selection, and their color spaces have shapes of a cube and a cone, respectively, in a 3D Cartesian space. An arbitrary color corresponds to a point in the color space. In VR, if the color space is displayed in 3D and a user points to a position in the color space using a 3D pointing interface, a color can be selected through a one-step interaction, which results in high efficiency. This process is very simple and easy to use compared to the multistep interaction required when using the 2D color picker introduced in the aforementioned VR painting applications. However, if the user specifies a color inside a color space, the color selection can be difficult because the interior of the color space is not visible. In this paper, we introduce a VR 3D color picker with new user interfaces that enable effective color selection while looking inside the color space (see Fig. 1). All interfaces that we propose are geometrically simple, robust and easy to understand. The first two interfaces are continuous color pickers, where either a subspace is cut out of the color space or cross-sections of the color space are shown. The third interface is a discrete color picker, in which color samples are placed in the color space. Because distinguishing colors using human vision is limited,

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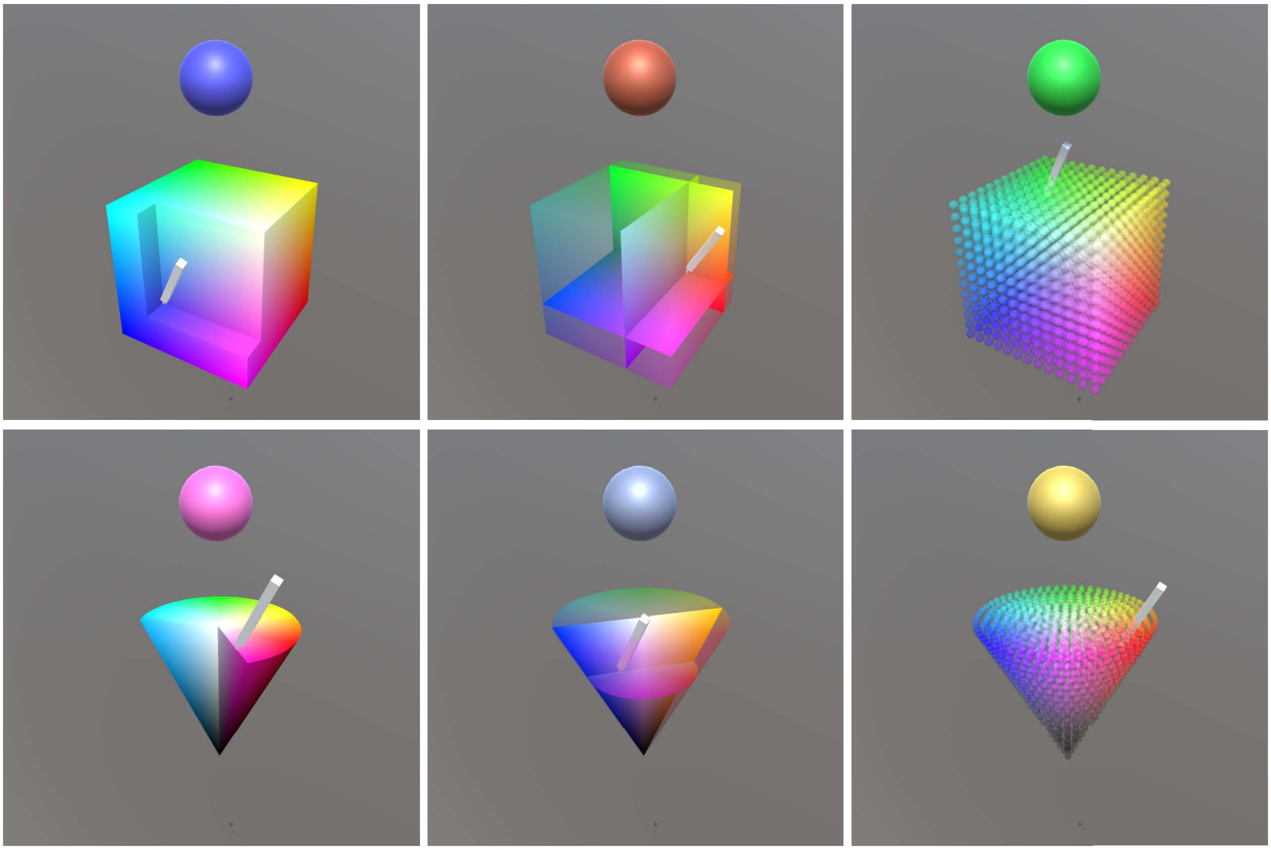


FIGURE 1. The VR color picker. Three user interfaces are proposed for the RGB and HSV color models.

providing a sufficient number of discrete colors instead of selecting one color from a continuous color space may be a good choice. Most existing VR color pickers use the color set provided by the system or the color set selected by the user in the form of a palette, which is displayed in a 2D area. A certain amount of time is required to search for a color from the color samples arranged in the 2D palette, and the search time significantly increases as the number of samples increases. Therefore, color grouping and color ordering are important to reduce the search time, and it is implied that it is difficult to automate color placement in a 2D palette when changing color samples. In this study, we propose placing color samples at a unique position in the 3D color space. Because the user can understand the principle of color change in the 3D color space, it is expected that they will quickly find the desired color when using the 3D discrete color picker.

The contributions of this study are as follows.

- Proposal of a new VR color picker using the 3D color space.
- Proposal of user interfaces that show the interior of the 3D color space.
- Proposal of a VR discrete color picker that places color samples in the 3D color space.
- Performance comparison between existing VR 2D color pickers and the proposed VR 3D color picker.

The remainder of this paper is organized as follows. In Section II, the work related to this research is introduced. In Section III, a VR 3D color picker and three user interfaces are proposed. In Section IV, the performance of the proposed color picker is compared with that of the existing VR color picker. Finally, in Section V, the study is concluded and future research is discussed.

II. RELATED WORK

A. COLOR AND COLOR MODELS

There are three types of cone cells in our eyes, and they response to different wavelengths. Specifically, these cones respond most sensitively to wavelengths of approximately 430 nm, 530 nm, and 570 nm, and humans recognize colors from the light intensities of these wavelengths. This is the Young-Helmholtz theory [8], which is also known as trichromatic theory of color vision. The wavelengths of 570 nm, 530 nm, and 430 nm are close to red, green, and blue, respectively. The "Commission Internationale de l'éclairage" (CIE) created the CIE 1931 XYZ color space and CIE 1931 RGB color space based on this theory [9], [10]. In the RGB color model, the color is represented as a combination of red, green, and blue light intensities.

The difficulty in using the RGB color model is that an arbitrary color must be decomposed into red, green, and blue intensities. Smith [11] presented an alternative color model for the RGB color model based on the perceptual variables of hue, saturation, and value (or brightness). He also derived an algorithm for transforming the RGB and HSV color models. The HSV color model is now widely used, and a similar color model HSL (hue, saturation, and lightness) is also commonly used. For the RGB and HSV color models, the perceptual difference between a pair of colors is not uniform with the distance between the two colors within the color space. An attempt was made to achieve perceptual uniformity for the CIE L*u*v* and CIE L*a*b* color models [12], and they were adopted by CIE in 1976. A color picker is a tool for selecting colors, and the RGB and HSV color models are commonly used for color pickers in digital devices. The VR color picker developed in this study also focuses on the RGB and HSV color models.

Shuwarz *et al.* [13] performed color-matching performance experiments on five color models: the RGB, Opponent, YIQ, LAB, and HSV color models. They compared the color selection time and color selection accuracy. The experiment showed that a fast color selection time but low accuracy was achieved using the RGB color model, and the slowest color selection time but relatively high accuracy was achieved using the HSV color model. They also found that user learning occurs as a result of repeated use of the Opponent, YIQ, LAB, and HSV color models but not the RGB color model.

Douglas and Kirkpatrick [14] designed a low-level interface that only shows the value of color attributes and a high-level interface that shows the effect of changes in color attributes. They performed color matching experiments on the RGB and HSV color models and compared the selection time and accuracy. The experimental results showed that the visual feedback and design of the interface may be more important factors for improving the usability of color selection than the specific color model used.

B. COLOR PICKERS IN DESKTOP APPLICATIONS

A color picker is necessary for various art and design applications and image and text editors running on a desktop computer. The color picker provides a range of interfaces so that users can easily and conveniently set colors. The color pickers commonly used in desktop environments are introduced in this section. Most color pickers in this category are represented in a 2D space and are based on the HSV or HSL color model. When the HSV color picker is displayed in 2D, a 2D + 1D picking interface is usually adopted. In other words, changes in the hue and saturation are displayed in a rectangular or circular frame for 2D selection, and changes in the brightness are displayed in a slider for 1D adjustment. Alternatively, changes in the saturation and brightness are displayed in a rectangular frame for 2D selection, and changes in the hue are displayed in a slider for 1D adjustment. In addition, there is a color palette in which the user can set preferred colors and code input text boxes where the user can input the desired color as HSV or RGB codes.

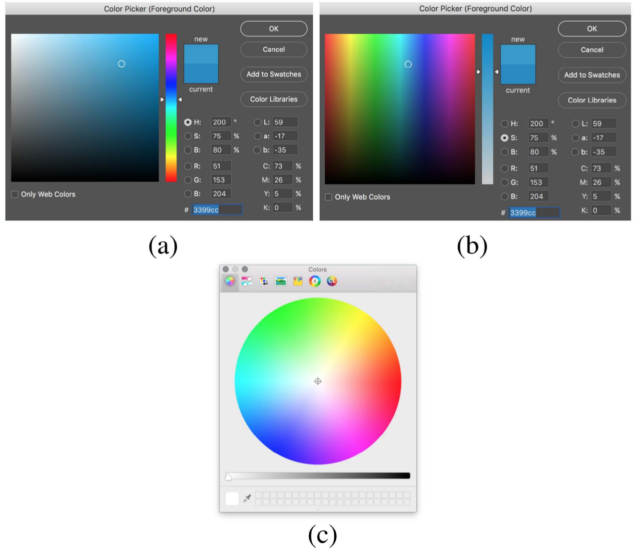


FIGURE 2. Desktop HSV color pickers. (a) and (b) in Adobe Photoshop, and (c) in Mac OS X. Images (a) and (b) from https://www.slrlounge.com/photoshop-tips-how-to-use-the-color-picker-tool/.

Fig. 2 (a) and Fig. 2 (b) show the HSV color picker in Adobe Photoshop. As shown in Fig. 2 (a), the user can set the saturation and brightness within the rectangular frame and set 5the hue on the slider; as shown in Fig. 2 (b), the user can set the hue and brightness within the rectangular frame and set the saturation on the slider. The color picker in Microsoft Windows Paint has almost the same layout. The color palette exists on the left side of the application, and on the right side, there is a 2D rectangular frame for selecting the hue and saturation and a 1D slider for adjusting the brightness. Fig. 2 (c) shows the color picker in the Mac OS X. This color picker has a color wheel for adjusting the hue and saturation and a value slider for adjusting the brightness. A 2D RGB color picker usually consists of three 1D sliders that are used to adjust the intensities of red, green, and blue or consists of three text boxes, where numeric values are entered.

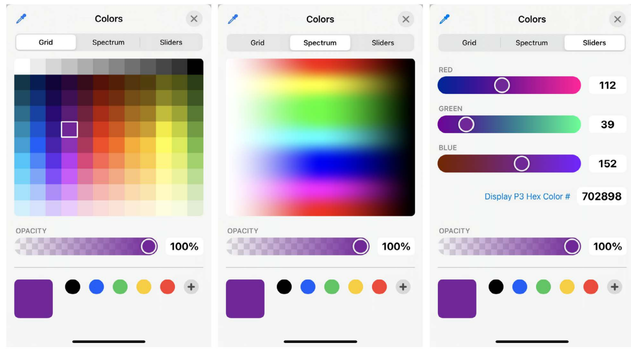
Wu and Takatsuka [15] proposed a color picker in which a user can select a color from a color space visualized as a 3D shape. Although a 3D color space is used, it is not possible to point directly into the color space because there is no 3D pointing device in the desktop environment. Instead, the user is allowed to set a cross-section that passes through the color space, and the user selects a color on the 2D cross-section using a 2D pointing device, that is, a mouse. The user also sets a color-interpolation path and selects the desired color from the interpolated color band. This color picker introduced the 3D color space, and it is possible to see the colors inside the color space by setting a cross-section; however, this color picker interface is complicated and the user interaction with the interface requires several steps, such as cross-section setting, interpolation path setting, and color selection from the color band.

Various studies have been conducted on color picker interfaces to support advanced and professional functionalities, such as color mixing, harmonious color suggestion, and palette recording. The most recent research articles on color pickers and color palettes fall into this category. Meier *et al.* [16] introduced various functions, such as composing a palette with artwork as a reference, providing a gradient color by mixing swatches, and recommending harmonious colors, and subsequent studies were inspired from this work. Wijffelaars *et al.* [17] designed a perceptually uniform palette using the CIE L*u*v* color model and intuitive parameters, such as hue, saturation, contrast, and hue range. The presented palette allows the user to specify colors with perceptual properties, such as perceptual order, equal perceptual distance, and equal importance. Jalal *et al.* [18] presented an interactive palette for color sampling, relationship exploration, color composites for mixing, color decomposition with other elements, and interactive recording to allow the reuse of previous color selections. Shugrina *et al.* [19] were inspired by how professional artists used palettes. They proposed a color palette interface that selected and blended colors to create gradients and gamuts. An infinite use history is saved when using this palette, so previously selected colors can be reused or edited, and repainting can be performed through the color editing history. Shugrina *et al.* [20] provided an interface for creating color themes by directly manipulating the color swatches. A user can create and arrange swatches and combine them with smooth step-based gradients and tricolor blends using smooth touch or mouse inputs. We propose the core concept of a 3D color picker in VR for our research; the advanced functions presented in this paragraph are not included. Advanced functions for VR 3D color pickers are expected to be proposed in the future.

C. COLOR PICKERS IN TOUCH SYSTEMS

Fig. 3 shows the color picker for iOS 14.7.1. This color picker is designed using three methods, and the user can choose one of these three methods. The first method is called the grid method, in which a color is selected from 120 tiles, whose brightness levels are sampled for achromatic and chromatic colors. In the second method, a 2D color space with white mixed to the left and black mixed to the right with a chromatic spectrum in the middle is provided. It is not possible to set the gray colors for this method. In the last method, which is called the slider method, the red, green, and blue intensities are adjusted or numeric values are entered. All three color pickers have a slider at the bottom to adjust the opacity and a palette to store the recently used colors.

Ebbinason and Kanna [21] used multi-touch to propose a color picker suitable for touch systems. The position of the color picker can be changed by moving the position of the first touch. The hue and saturation are set with the second touch, and the brightness is set by moving the color picker up and down while maintaining the first touch and releasing the second touch. It is possible to support the position independence of the color picker and provide quick feedback to the user. Compared with the previous model, the color selection time is reduced and the color selection accuracy is improved using this this model.



(a) (b) (c)

FIGURE 3. Color picker in iOS 14.7.1. This color picker is designed using three methods: (a) the grid method, (b) the spectrum method, and (c) the slider method.

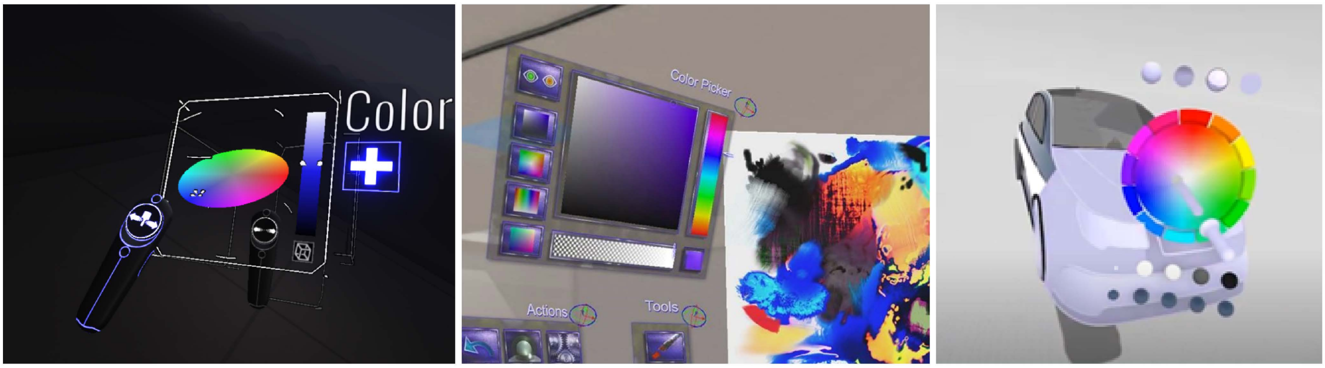
D. COLOR PICKERS IN VR SYSTEMS

In this section, the color pickers used in VR systems are introduced. Most VR painting applications [1]–[7] utilize the HSV 2D color picker that is traditionally used in the desktop environment in the VR 3D space.

In Google's Tilt Brush [3], which is a representative VR painting application, the traditional 2D HSV color picker is introduced into the virtual space. The user selects the hue and saturation by pointing to the color wheel and adjusts the brightness by moving the value slider (see Fig. 4 (a)).

The color picker in Cyber Paint [2] also utilizes a 2D user interface based on the HSV color model. A rectangular 2D frame and two 1D sliders are used for color selection. The user can change the rectangular frame to a hue-saturation space or a saturation-brightness space. When the slider is placed vertically to the right of the rectangular frame, its functionality changes according to the functionality mapped to the rectangular frame. That is, when the hue and saturation are mapped to the rectangular frame, the vertical slider is used to set the value. Alternatively, when the saturation and hue are mapped to the rectangular frame, the vertical slider is used to set the hue. The horizontal slider below the rectangular frame is used to set the fourth attribute of color, the opacity (see Fig. 4 (b)).

In Gravity Sketch [5], which is a commercial VR modeling software, a 3D color picker is introduced. Based on the HSV color model, the cross-sectional circle perpendicular to the value axis changes according to the pointer, and the color can be selected by specifying the hue and saturation on this cross-sectional circle. Small circles below the color picker display the most recently used color, and spheres above the color picker are used to change the shading method (see Fig. 4 (c)). As the cross-sectional circle moves back and forth, it becomes a type of 3D color picker. However, it is difficult to recognize this interface as a 3D interface because the user only sees the



(a) (b) (c)

FIGURE 4. VR Color pickers. (a) Tilt Brush [3] and (b) Cyber Paint [2] adopt a 2D HSV color picker, and (c) Gravity Sketch [5] adopts a partial 3D HSV color picker. Image (a) from https://arstechnica.com/gaming/2016/04/learning-how-to-vr-with-tilt-brush-htc-vives-killer-app/, image (b) from https://www.facebook.com/cyberpaintapp/, and image (c) captured the video from https://youtu.be/dx6OHFDC8rE.

cross-section at a moment and does not see the entire shape of the 3D color space. We use the 3D shape of the color space as it is and not only use the value to provide a cross-section but also use the hue and saturation to simultaneously provide cross-sections.

Several studies have implemented 3D color pickers in VR. In CavePainting by Keefe *et al.* [22], a 3D color picker was used in the form of a double hexagonal pyramid based on the HSL color model. Eight representative colors (red, green, blue, magenta, yellow, cyan, white, and black) are placed in the vertices of the pyramid. When the user moves the 3D pointer inside the color space (the pyramid), the color corresponding to the position is displayed on a sphere. Because the interior of the color space is empty, the user can immediately see the selected color. However, it is difficult to understand the color change within the color space since only eight representative colors are displayed. Our color picker displays a color space with a continuous color change, and the user can select a color by looking through the color space.

A VR color picker is posted on the blog of Leap Motion [23], a company that manufactures hand gesture recognition equipment. Based on the cube-shaped RGB color space, the edges of the cube are displayed in a gradient color. When a small cube-shaped prop moves inside the color space, its color changes according to its position. Because the edges of the cube show a continuous color change, this color picker provides slightly more information about the color change than CavePainting [22], but it is still difficult to identify the color changes inside the color space.

The study by Kim and Lee [24] suggested a 3D color picker that uses the 3D RGB color space and 3D HSV color space. They displayed the shape of the 3D color space, and the user can understand the principle of the color change through the color space surface. However, it is difficult to make fine adjustments close to the desired color since the interior of the color space is not visible. In this study, the surface of the color space is displayed so that the user can easily understand the principle of the color change. In addition, new interfaces that allow the user to see the inside of the color space are added to solve this problem.

Alex *et al.* [25] introduced a discrete color picker for VR. They compared the performance between the discrete color picker and continuous color picker when creating art in VR. The sample colors were grouped based on their similarity and placed in a 2D palette. A continuous color picker for comparison was constructed using the HSV color model. In the case of a discrete color picker, when a large number of colors are placed in a 2D palette, the user spends a significant amount of time searching for colors; therefore, they put effort into grouping and ordering the colors to reduce the color selection time. However, if the color samples are changed, a process of regrouping and arranging the colors is required; if the number of colors increases, grouping becomes more difficult. Therefore, it is not suitable for a system that automatically changes color samples. In our proposed discrete color picker, colors are automatically sampled and placed in their own positions in the 3D color space; therefore, no grouping and ordering process is required. In addition, the color change can be visually captured from the color space. Therefore, the user can quickly search for the desired color.

Just as a painter mixes colors on a palette or canvas in the real world, VR painting applications [26], [27] can be used to reproduce realistic color blending on a palette and canvas, which provides a more immersive user experience. If color blending is well implemented in VR, the role of the color picker is reduced.

III. INTERFACE DESIGN FOR A VR COLOR PICKER

In this section, we propose 3D color pickers for VR applications. The target color models are RGB and HSV, and the cube-shaped RGB color space and cone-shaped HSV color space are displayed in the virtual space. The user can intuitively determine the position of a color in the color space and can select a color using a 3D pointing device. In the case of a continuous color picker, we focus on devising user interfaces that show the inside of the color space. In the case of a

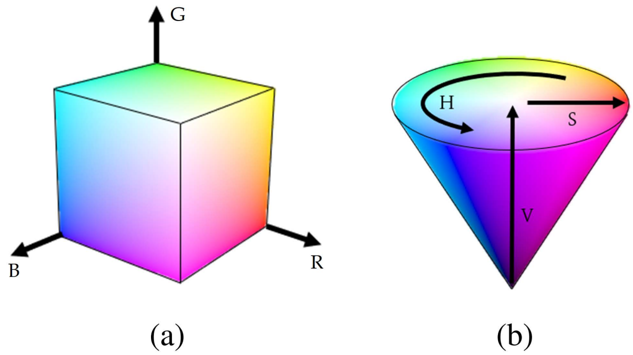


FIGURE 5. RGB and HSV color spaces. (a) The RGB color space has the shape of a cube, and (b) the HSV color space has the shape of a cone in the 3D Cartesian coordinate system.

discrete color picker, we focus on color space quantization for sampling colors.

A. TARGET COLOR MODELS

1) THE RED, GREEN, BLUE (RGB) COLOR MODEL

The RGB color model uses the intensities of red, green, and blue as three basic color properties. In other words, an arbitrary color is represented by the intensity values of red, green, and blue. When the intensity ranges from 0 to 1 and the color is written as an (r, g, b) tuple, (1, 0, 0) is red, (0, 1, 0) is green, (0, 0, 1) is blue, (0, 0, 0) is black, and (1, 1, 1) is white. If the (r, g, b) coordinates are considered (x, y, z) coordinates in a 3D Cartesian coordinate system, the RGB color space is contained inside the unit cube ranging from (0, 0, 0) to (1, 1, 1) (see Fig. 5 (a)). Any color given by (r, g, b) is located at a point in the cube. In VR, an arbitrary color can be specified by pointing to a 3D position inside a cube using a 3D pointing device, such as a handheld controller. By observing the color change on the surface of the color space, a user can approximately determine the position of the color to be selected. Colors close to the surface are easily identified, whereas the colors inside the cube are difficult to identify. For example, black lies at (0, 0, 0) and white lies at (1, 1, 1), and grays that change from black to white lie on the diagonal connecting (0, 0, 0) and (1, 1, 1). However, it is not easy to select these gray colors without prior knowledge of the RGB color space.

2) THE HUE, SATURATION, VALUE (HSV) COLOR MODEL

The HSV color model [11] uses hue, saturation, and value as the three basic properties of the color. The HSV color space is represented by the shape of a cone in 3D Cartesian coordinate space (see Fig. 5 (b)). Normally, the base circle of a cone is placed parallel to the x-z plane, and the vertical axis of the cone is placed parallel to the y-axis. The hue is represented as the angle of a cross-sectional circle ranging from 0° to 360°; red is placed at 0°, yellow at 60°, green at 120°, cyan at 180°, blue at 240°, and magenta at 300°. The value is the brightness of a color and varies along the vertical axis of the cone, with black being placed at the lowest position and white and pure colors at the highest position. Grays are placed on the vertical axis connecting white and black. The saturation is a color property that indicates the degree of color clarity. The higher the saturation is, the closer it is to a pure color, and the lower the saturation is, the more gray is mixed. Saturation is represented as the distance to the vertical axis of the cone. The closer it is to the vertical axis, the lower the saturation. As the HSV color model uses hue, saturation, and value, it is more perceptual to manipulate than the RGB color model, which uses red, green, and blue intensities. The user looks at the edge of the circle and selects the hue, moves to the vertical axis of the cone to decrease the saturation, and moves up and down to increase or decrease the brightness.

B. 3D COLOR PICKER INTERFACE CUTTING THE SUBSPACE OFF

When the color space is displayed opaquely, it is difficult to select a color because the interior of the color space cannot be seen. To show the color inside, we propose an interface that removes a portion of the color space based on the currently selected color position. As the portion of the color space is removed, the user can see the inside of the color space and make fine adjustments while looking in the vicinity of the current color.

1) RGB COLOR PICKER

As described in III-A1, the RGB color space displays colors by considering the red, green, and blue intensities (r, g, b) as spatial coordinates (x, y, z) and is contained in the unit cube. When the 3D pointer is positioned inside the color space, the cuboid subspace from the corner closest to the user to the pointer position is removed from the RGB color space. The cut-off boundary surface is reconstructed using three axial sections determined by the pointer position. The selected color is shown at the corner of the pointer position. As the user moves the pointer, the surface boundary is immediately updated (see Fig. 6).

2) HSV COLOR PICKER

The HSV color space is contained inside the cone, as previously described in III-A2. When a 3D pointer is placed inside the color space, the subspace above the value section and the subspace to the left of the hue section are removed. In the value section, the user can observe the color changes in the hue and saturation, and in the hue section, the user can observe the color changes in the saturation and value (see Fig. 7). The subspace corresponding to 120° is cut to the left of the hue section, and 120° was empirically determined to secure a sufficiently wide angle to comfortably view the interior. If the user uses a pointer with their left hand instead of their right hand, the right subspace of the hue section is removed. Fig. 7 shows the HSV color picker interface removing the subspace and the results of color picking.

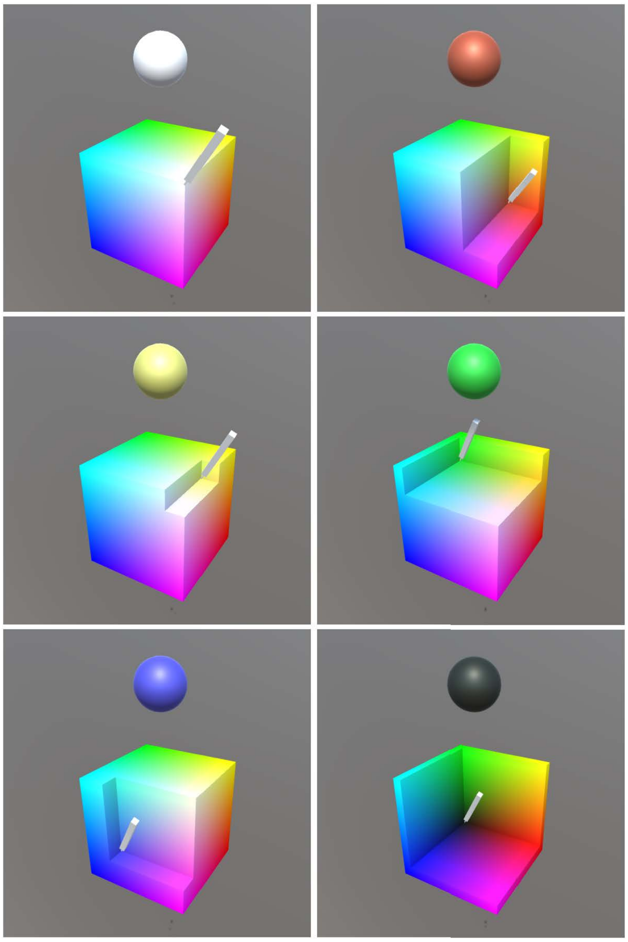


FIGURE 6. RGB color picker interface cutting the subspace off and the color picking results.

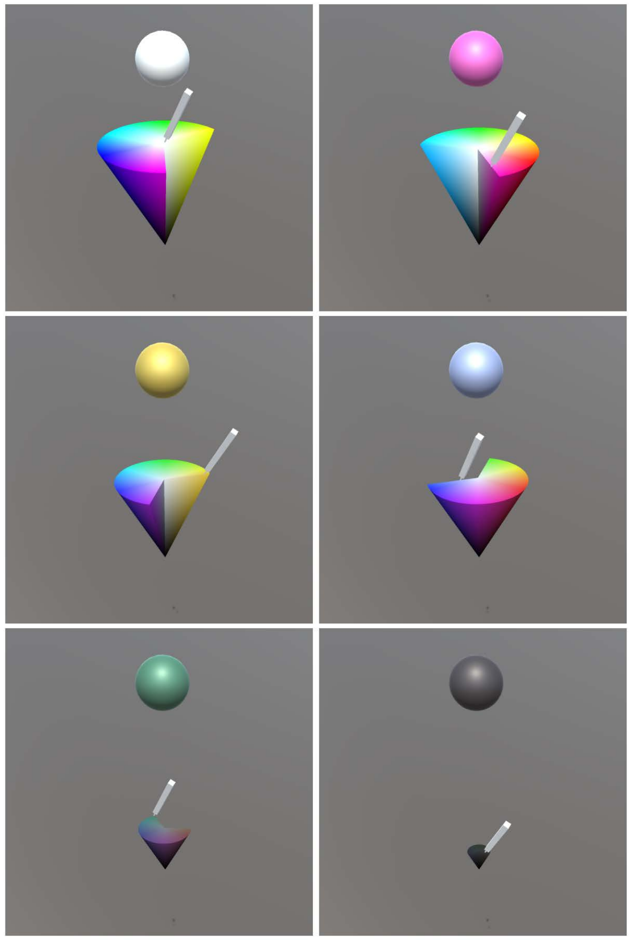


FIGURE 7. HSV color picker interface cutting the subspace off and the color picking results.

C. 3D COLOR PICKER INTERFACE SHOWING THE CROSS-SECTIONS

We propose another interface that shows colors inside the color space. When using this interface, the surface of the 3D color space is displayed semi-transparently and the cross-sections passing through the current 3D pointer position are opaquely displayed. The pointer position corresponds to the selected color, and the adjacent colors can be observed through the cross-sections. As the user moves the pointer within the color space, the cross-sections are updated immediately, helping to identify the currently selected color and surrounding colors.

1) RGB COLOR PICKER

We provide an interface that semi-transparently shows the surface of the RGB color space cube and shows opaquely rectangular cross-sections perpendicular to the x, y, and z axes based on the pointer position (x, y, z). Each cross-section contains a set of all colors when one property r, g, or b is fixed, and the other two properties are changed. The user sees the currently selected color at the intersection of the three cross-sections and makes fine adjustments by observing the colors shown on the cross-sections. Fig. 8 shows the cross-sections of the RGB color picker interface and the results of color picking.

2) HSV COLOR PICKER

In the HSV color space, we provide an interface that semi-transparently shows the surface of the color space cone and opaquely shows a cross-section perpendicular to the value axis and a cross-section containing the value axis based on the pointer position. Through the cross-section perpendicular to the value axis, the user observes all colors created by fixing the value and changing the hue and saturation. Through the cross-section containing the value axis, the user observes all colors created by fixing the hue and changing the saturation and value. The currently selected color lies on the intersection line of the two cross-sections. Fig. 9 shows the cross-sections of the HSV color picker interface and the results of color picking.

D. 3D DISCRETE COLOR PICKER

Considering the limitations of human vision in distinguishing colors and assuming that hundreds to thousands of colors are

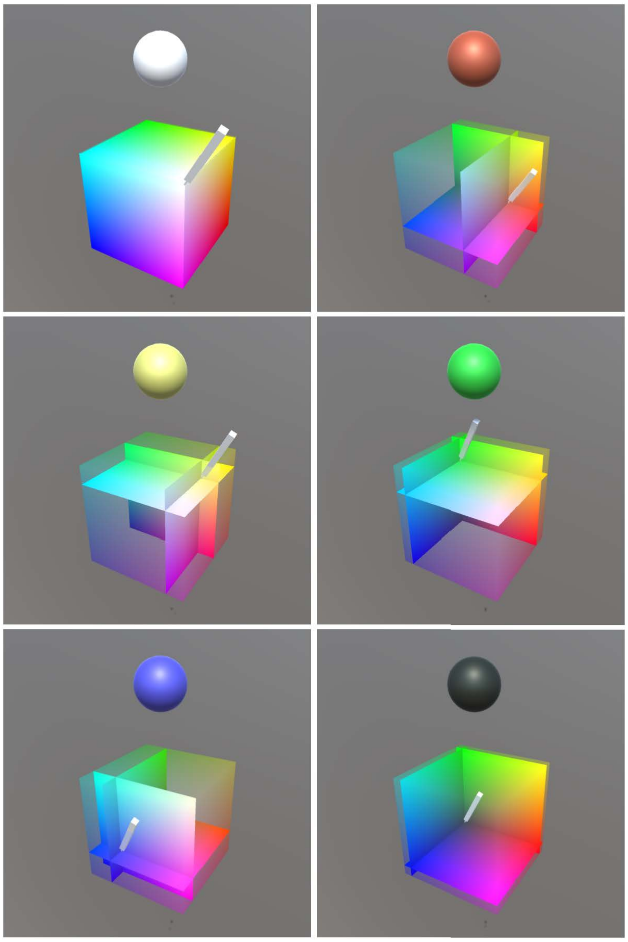


FIGURE 8. RGB color picker interface showing the cross-sections and the color picking results.

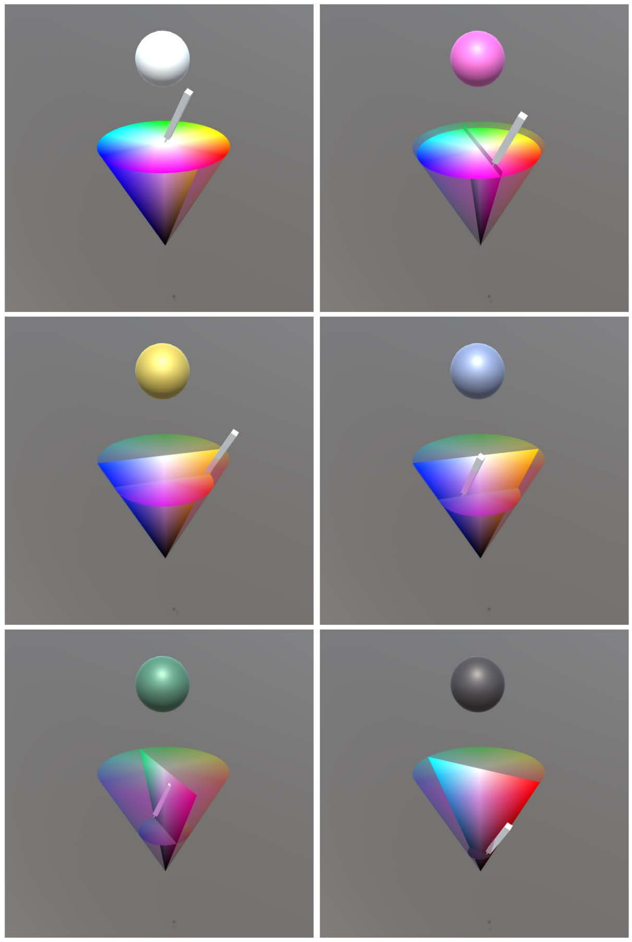


FIGURE 9. HSV color picker interface showing the cross-sections and the color picking results.

sufficient for general use, a discrete color picker may also be a good choice. The proposed discrete color picker quantizes the color space to sample colors and then displays the colors as small spheres at the corresponding positions in the 3D color space. The user can understand the color change in the color space and quickly reach the approximate position of the desired color. In addition, because colors are located at unique positions, there is no need to place, order, or group sample colors, unlike the method of arranging colors in a 2D palette.

1) RGB COLOR PICKER

Color samples were obtained by uniformly quantizing the red, green, and blue values. We used 13 levels ranging from 0 to 1 for red, green, and blue values. As a result, 2,197 color samples were obtained ($13^3 = 2197$). To sample typical colors such as red, green, blue, yellow, cyan, magenta, black, and white, the 0 and 1 values should be included in the value of the level. Small translucent spheres were drawn with the sampled colors at the location of the color inside the RGB color space. The size of the sphere should be sufficiently large so that the user can easily select the sphere and sufficiently small so that the user can see nearby spheres. When the pointer moves and touches a sphere, the sphere changes from translucent to opaque to clearly show the selected color. Fig. 10 shows the RGB discrete color picker and the results of color picking.

2) HSV COLOR PICKER

For the discrete HSV color picker, value samples are obtained by uniform quantization from 0 to 1, whereas hue and saturation samples are obtained by quantizing the distance from the vertical axis. If the saturation is uniformly sampled, the closer to the cone vertex, the smaller the color difference between the sample colors is, resulting in unnecessary sampling. This problem can be solved by quantizing the distance from the vertical axis of the cone instead of quantizing the saturation value itself. More saturation samples are generated at the base of the cone, and fewer saturation samples are generated at the vertex of the cone (see Fig. 11 (a)). The sampling rate for the hue is also proportional to the distance from the vertical axis. More hue samples are generated at the level with a larger radius of concentric circles, and fewer hue samples are generated at the level with a smaller radius of concentric circles (see Fig. 11 (b)).

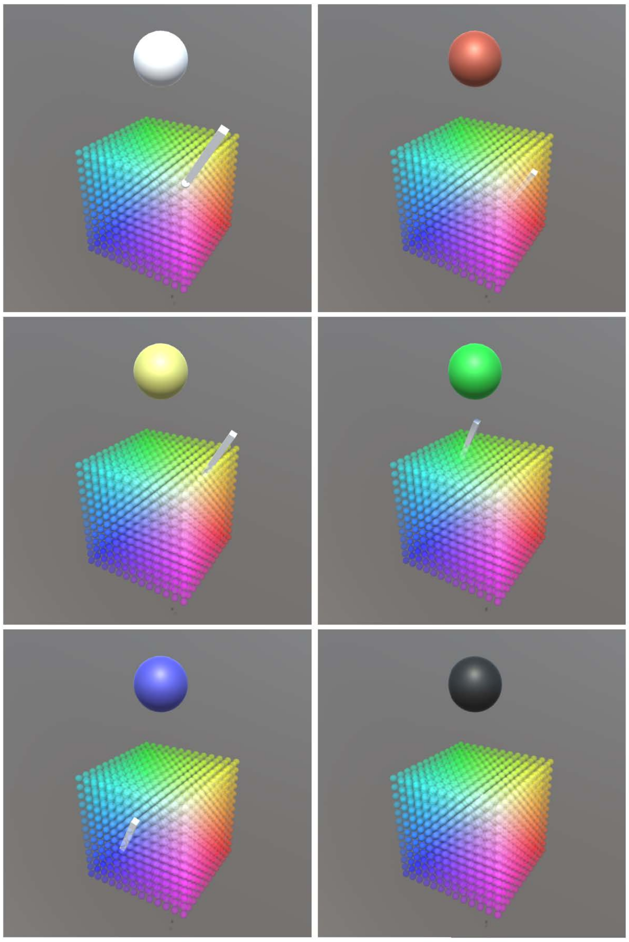


FIGURE 10. RGB discrete color picker and the color picking results.

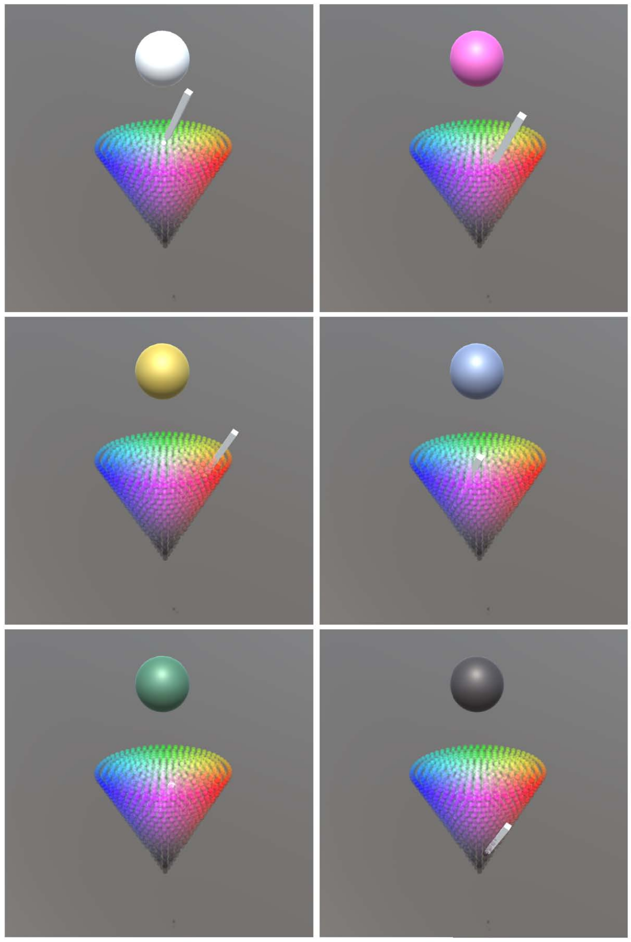


FIGURE 12. HSV discrete color picker and the color picking results.

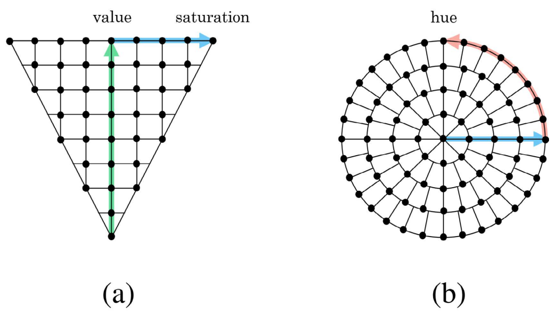


FIGURE 11. Quantization concept of the HSV color space for color sampling. (a) Saturation and value quantization and (b) hue and saturation quantization.

The proposed quantization method aims to make the color differences between the sample colors relatively similar. When obtaining discrete color samples, it is important that the perceptual color differences are uniform. Fig. 12 shows the HSV discrete color picker and the results of color picking. For the experiment, 1,756 samples were obtained through the quantization.

E. 2D HSV COLOR PICKER

The 2D HSV color picker is implemented for comparison with the proposed VR 3D color pickers, and it uses a conventional circular interface for setting the hue and saturation and a slider for setting the value. It has the same appearance as the color picker in Google Tilt Brush (see Fig. 4 (a)). Fig. 13 shows the 2D HSV color picker and the results of color picking.

IV. EXPERIMENTS

A. IMPLEMENTATION AND PARTICIPANTS

The color picker program was developed as C# code by integrating the Unity 3D Engine [28] 2020.3.13f1 and SteamVR plugin [29]. Participants used HTC Vive Pro [30] VR equipment, which consists of one headset and two handheld controllers that track the user's head and hands movements. Our color picker system was implemented in a room-scale VR, and the color picker appeared at a fixed location in the virtual space. The user moved freely, choosing a position and orientation convenient for observing and manipulating the color picker.

We used a Latin-squared experimental design with a balanced order, so multiple participants of the conditions are required. We recruited 35 people from a local university to compare 7 color pickers. There were 11 males and 24 females

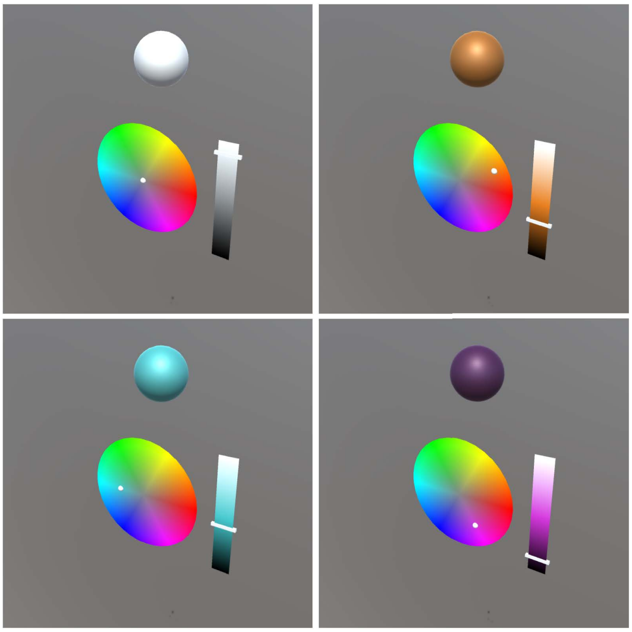


FIGURE 13. A conventional 2D HSV color picker implemented for comparative experiments and the color picking results.

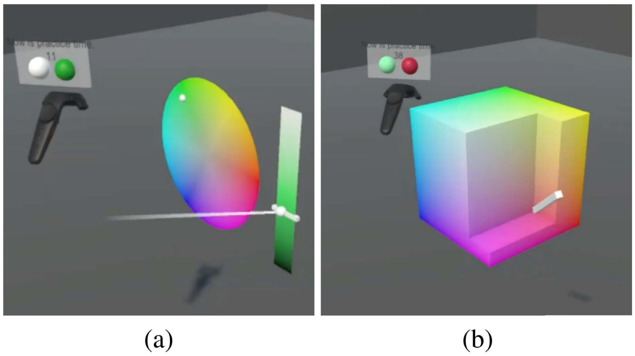


FIGURE 14. Scene of the experiments. (a) Color selection using the 2D HSV color picker, and (b) color selection using the 3D RGB color picker with the cut-off interface.

aged 20-36 years in the study. All participants reported normal hearing, normal vision, or vision corrected with glasses.

B. METHODS AND PROCEDURES

We adopted a within-subjects design, and participants experienced all of the following 7 conditions.

- Cut-off RGB: 3D RGB color picker, which uses the interface cutting the subspace off (Fig. 6)
- Cut-off HSV: 3D HSV color picker, which uses the interface cutting the subspace off (Fig. 7)
- Cross-section RGB: 3D RGB color picker, which uses the interface showing the cross-sections (Fig. 8)
- Cross-section HSV: 3D HSV color picker, which uses the interface showing the cross-sections (Fig. 9)
- Discrete RGB: 3D RGB color picker, which uses discrete color samples (Fig. 10)
- Discrete HSV: 3D HSV color picker, which uses discrete color samples (Fig. 12)
- 2D HSV: 2D HSV color picker, which is generally used (Fig. 13)

Participants started the experiment after watching a video containing explanations of the RGB and HSV color models and how to use the color pickers provided in this experiment. Participants were given 60 s to practice using each color picker prior to the experiment to learn how to navigate the color space and manipulate the color picker. The participants sufficiently explored the color space during the practice time to avoid difficulty using the color pickers. The seven color pickers used in the experiment were provided in a counterbalanced order so that the effect of acquaintance with the color space was not biased toward a specific color picker. Participants selected 10 colors for each given color picker, for a total of 70 color selections. Since there were 35 participants, the total number of color selections was 2,450.

At the start of the experiment, two spheres appeared on the participant's left controller. One was displayed with a randomly given color, and the other was changed to a color selected by the participant in real time. Participants were asked to select a color that was as similar to a given color as possible by using the color pickers (see Fig. 14). Once the color selection was completed, the completion time and color error for a given color were saved. The color selected using the HSV color pickers was converted to RGB value to measure the color error. We used the conversion formula presented in Smith's study [11].

For the usability evaluation of the proposed VR color picker, we conducted usability surveys for 35 participants after the experiment. The System Usability Scale (SUS) [31], Computer System Usability Questionnaire (CSUQ) [32], and Questionnaire for User Interface Satisfaction (QUIS) [33] are widely used to evaluate the usability of a system. We used the SUS questionnaire because it is simple and reliable for various sample sizes [34]. The SUS questionnaire was developed by John Brooke in 1986 and is used to measure a user's subjective perception of a system. This questionnaire consisted of 10 sentences about usability, and participants scored the degree of agreement with each sentence on a 5-level scale. The closer the SUS score obtained through the calculation formula is to 100, the higher the usability of the system.

C. MEASURES

- Completion time: The time taken for the participant to select a color using a color picker was measured. There was a time limit of 40 s. Therefore, no completion times exceeded 40 s.
- Color error: The difference between the RGB value of the color selected by the participant and the RGB value of the randomly given color was calculated using the square root sum.
- Usability: The usability of the color pickers was evaluated by using the SUS questionnaire.

TABLE 1. One-way ANOVA analysis of variance of the completion time.

Source	DF	SS	MS	F-value	P-value
Condition	6	2808	468.0	4.3	0.000254
Error	2443	265851	108.8		
Total	2449	268659			

TABLE 2. Grouping information of the completion time using Tukey's method and 95% confidence.

Condition	N	Mean	Grouping
Cut-off HSV	350	17.0	a
2D HSV	350	16.4	ab
Discrete RGB	350	16.0	abc
Cross-section RGB	350	15.6	abc
Cut-off RGB	350	14.5	bc
Cross-section HSV	350	14.3	bc
Discrete HSV	350	14.0	c

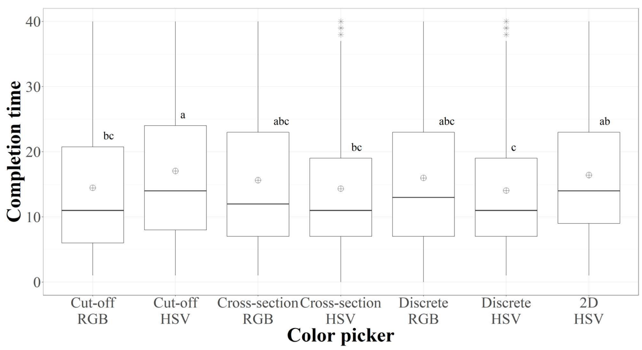


FIGURE 15. Completion time analysis of the adopted color pickers.

D. RESULT

Seven color pickers were analyzed using one-way ANOVA and Tukey's method. Six 3D color pickers (2D HSV was excluded) were analyzed using two-way ANOVA and Tukey's method for the difference in the color models and the difference in the interfaces. We adopted the commonly used significance level of 0.05, which means that if the p-value is less than 0.05, the experimental results are considered to be significantly different.

1) COMPLETION TIME

As a result of analyzing the difference in completion time for the seven color pickers using one-way ANOVA and Tukey's method, significantly different results were obtained with $p = 0.000254$ (see Table 1). Discrete HSV, cross-section HSV, and cut-off RGB, in which it took an average of 14 s to select a color, were significantly faster than cut-off HSV. Discrete HSV was significatly faster than 2D HSV and cut-off HSV. In comparison it took 16.4 s to select a color using 2D HSV (see Table 2 and Fig. 15).

Six 3D color pickers were analyzed using two-way ANOVA. The difference in the completion time of the two color models, RGB and HSV, was not significantly different, with a p-value of 0.645. In addition, the difference in the three interface types, cross-section, cut-off, and discrete, had a p-value of 0.297, confirming that there was no significant difference in their completion times (see Table 3, Fig. 16, and Fig. 17).

TABLE 3. Two-way ANOVA analysis of variance for the completion time.

Source	DF	SS	MS	F-value	P-value
RGB/HSV	1	23	23.5	0.212	0.645
Cut-off/Cross-section /Discrete	2	270	134.8	1.216	0.297
RGB/HSV * Cut-off/Cross-section /Discrete	2	2098	1048.9	9.462	8.11e-05
Error	2094	232115	110.8		
Total	2099	234506			

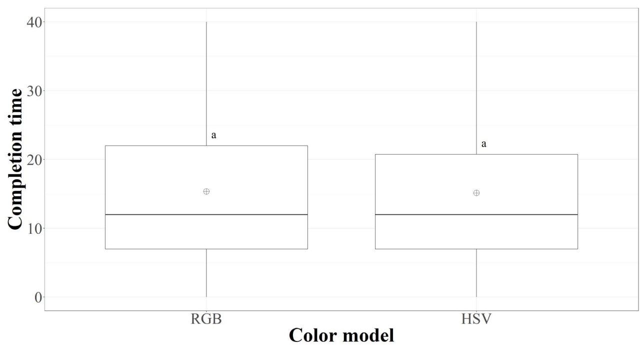


FIGURE 16. Completion time comparison of the adopted color models.

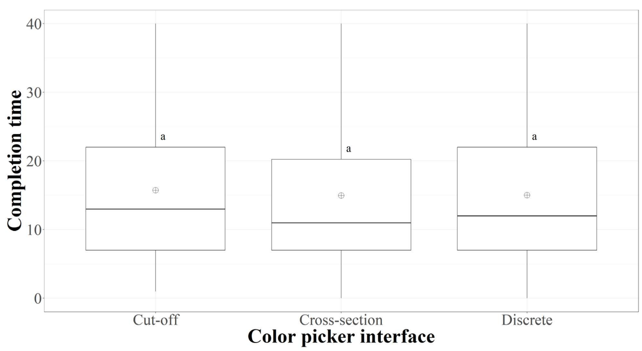


FIGURE 17. Completion time comparison of the adopted color picking interfaces.

2) COLOR ERROR

As a result of color error analysis, the p-value was 4.7e-10, and significantly different results were obtained (see Table 4). The average value of color error was the smallest in 2D HSV (0.132), but there was no significant difference with cut-off RGB and cross-section RGB. Compared to 2D HSV, discrete RGB, cut-off HSV, discrete HSV, and cross-section HSV had significantly larger color errors (see Table 5 and Fig. 18).

The results of color errors of six 3D color pickers (2D HSV was excluded) were analyzed using two-way ANOVA. The color error of the two color models, RGB and HSV, showed a significant difference with a p-value of 0.0233 (see Table 6). In other words, it is predicted that the color selection accuracy of the RGB color model is higher than that of the HSV

TABLE 4. One-way ANOVA analysis of variance for the color error.

Source	DF	SS	MS	F-value	P-value
Condition	6	0.587	0.09777	9.258	4.7e-10
Error	2443	25.799	0.01056		
Total	2449	26.386			

TABLE 5. Grouping information of the color error using Tukey's method and 95% confidence.

Condition	N	Mean	Grouping
Discrete RGB	350	0.177	a
Cut-off HSV	350	0.176	ab
Discrete HSV	350	0.173	ab
Cross-section HSV	350	0.162	abc
Cross-section RGB	350	0.154	bcd
Cut-off RGB	350	0.150	cd
2D HSV	350	0.132	d

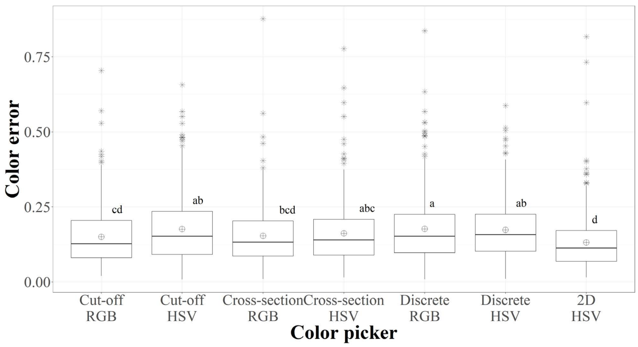


FIGURE 18. Color error analysis of the adopted color pickers.

TABLE 6. Two-way ANOVA analysis of variance for the color error.

Source	DF	SS	MS	F-value	P-value
RGB/HSV	1	0.056	0.05568	5.152	0.0233
Cut-off/Cross-section /Discrete	2	0.110	0.05506	5.094	0.00621
RGB/HSV * Cut-off/Cross-section/Discrete	2	0.079	0.03928	3.634	0.02659
Error	2094	22.634	0.01081		
Total	2099	22.879			

TABLE 7. Grouping information of the color error for the color models using Tukey's method and 95% confidence.

Condition	N	Mean	Grouping
HSV	1050	0.171	a
RGB	1050	0.160	b

color model (see Table 7 and Fig. 19). The three interface types, cross-section, cut-off, and discrete, had a significant difference with a p-value of 0.00621 (see Table 6). In other words, it is predicted that the color selection accuracy of the cross-section interface is higher than that of the discrete interface (see Table 8 and Fig. 20).

3) USABILITY

The SUS questionnaire was answered by 35 participants and the SUS scores of the 35 responses were calculated and

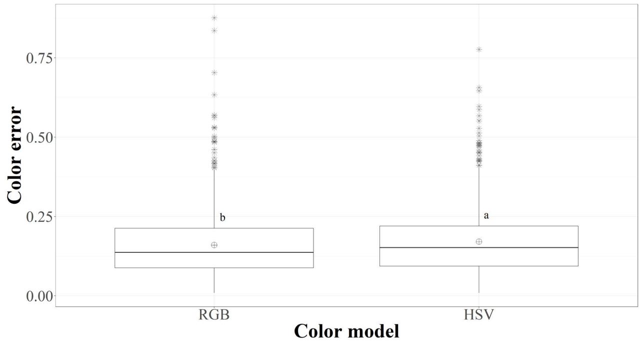


FIGURE 19. Color error comparison of the adopted color models.

TABLE 8. Grouping information of the color error for the the interfaces using Tukey's method and 95% confidence.

Condition	N	Mean	Grouping
Discrete	700	0.175	a
Cut-off	700	0.163	ab
Cross-section	700	0.158	b

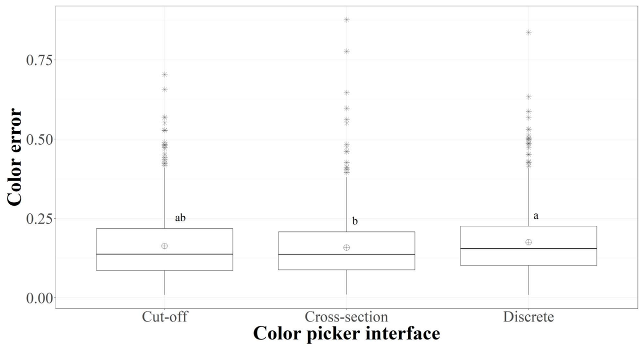


FIGURE 20. Color error comparison of the adopted color picking interfaces.

TABLE 9. One-way ANOVA analysis of variance of the SUS score.

Source	DF	SS	MS	F-value	P-value
Condition	6	12701	2116.8	4.452	0.000273
Error	238	113159	475.5		
Total	244	125860			

TABLE 10. Grouping information of the SUS score using Tukey's method and 95% confidence.

Condition	N	Mean	Grouping
2D HSV	35	74.1	a
Cut-off RGB	35	62.9	ab
Cross-section HSV	35	56.6	b
Cross-section RGB	35	55.4	b
Discrete HSV	35	54.9	b
Cut-off HSV	35	52.4	b
Discrete RGB	35	52.4	b

analyzed by one-way ANOVA and Tukey's method. 2D HSV and cut-off RGB had higher average values for usability compared to other color pickers with a p-value of 0.000273 (see Table 9, Table 10, and Fig. 21).

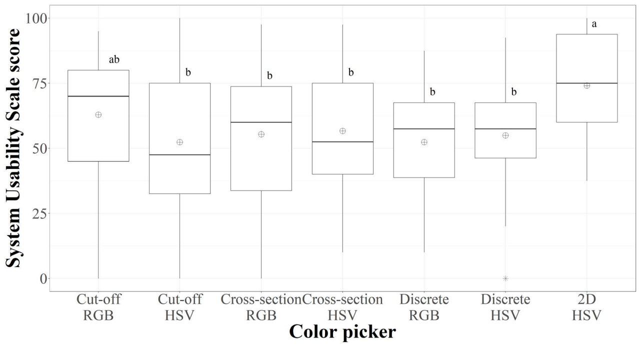


FIGURE 21. SUS score analysis of the adopted color pickers.

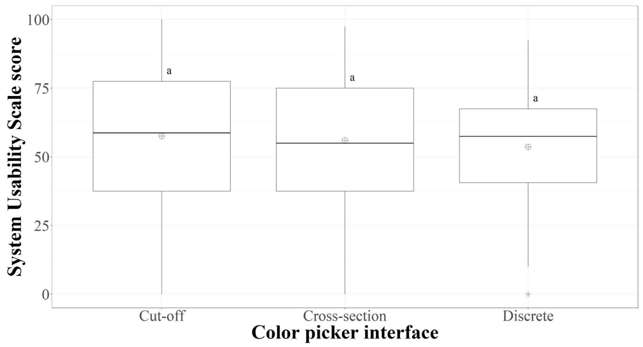


FIGURE 23. SUS score comparison of the adopted color picking interfaces.

TABLE 11. Two-way ANOVA analysis of variance for the SUS score.

Source	DF	SS	MS	F-value	P-value
RGB/HSV	1	257	257.4	0.529	0.468
Cut-off/Cross-section /Discrete	2	557	278.3	0.572	0.565
RGB/HSV * Cut-off/Cross-section /Discrete	2	1817	908.3	1.866	0.157
Error	204	99282	486.7		
Total	209	101913			

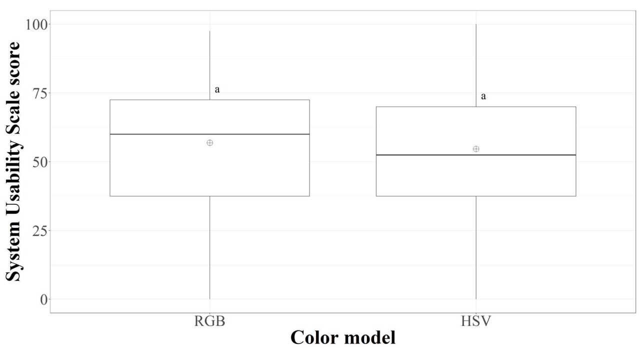


FIGURE 22. SUS score comparison of the adopted color models.

Six 3D color pickers were analyzed using two-way ANOVA. The difference in SUS scores between the RGB and HSV color models had a p-value of 0.468, which was not significantly different for usability. In addition, the difference in the three interface types, cross-section, cut-off, and discrete, also had a p-value of 0.565, confirming that there was no significant difference in usability (see Table 11, Fig. 22, and Fig. 23).

4) PRIOR EXPERIENCE AND COMMENTS

After the SUS survey, 35 participants were asked whether they had experienced VR and had prior knowledge of the 3D color space, and were allowed to freely comment on the seven color pickers. 21 participants (60.0%) had experience with VR before this experiment, and 14 participants (40.0%) had no experience with VR. 17 participants (48.6%) answered that they knew the 3D structure of the color space before the experiment, and 18 participants (51.4%) answered that they did not know the 3D structure of the color space.

Comments on the seven color pickers were not mandatory, and only a few participants left comments. Regarding the 2D HSV color picker, there were comments that it was familiar and easy to use (p14, p17, p20, p28, p30, p32, p33, p34, p35), comments that accurate color selection was difficult (p6, p9, p26), and comments that it was cumbersome to separately adjust the color wheel and brightness slider (p10, p11, p21, p25, p28).

There were many conflicting comments about the 3D color pickers. For example, there were comments that it was easy to use and it was difficult to use at the same time, and comments that the selected color looked good and it was difficult to see the color at the same time. There were large individual differences in usability and satisfaction with the 3D color pickers.

Regarding the cross-section RGB color picker, there were comments that it was difficult to use (p3, p9), comments that it was good to see all the colors (p7, p34), a comment that it was intuitive and easy (p14), a comment that prior knowledge about the color model was required (p14), a comment that it was the most usable method (p14), a comment that the moving cross-sections were not very helpful (p20), a comment that it was not possible to know exactly what color to select (p21), a comment that the translucent surface of the color space was inconspicuous and unnecessary (p23), a comment that it was easy to change color (p26), comments that it was not convenient to see all three cross-sections and they moved the pointer by feeling (p20, p35), a comment it took time to select dark colors (p26), a comment that the color could be precisely selected (p30), and a comment that it was convenient (p34).

Regarding the cross-section HSV color picker, there were comments that color selection was difficult in the small space near the vertex of the cone (p1, p23, p28, p30, p32), comments that the cone shape was inconvenient and difficult to use (p10, p26, p34), comments that the cone shape was convenient to use (p11, p20), a comment that the value section interfered with color selection (p20), a comment that it was the fastest and easiest way to select a color (p24), and a comment that it was difficult to see the selected color (p34).

Regarding the cut-off RGB color picker, there were comments that it was not obscured at all and the color to select was clearly visible (p1, p4, p28, p30, p35), comments that it was the most intuitive and convenient (p11, p21, p25, p26, p30, p34), a comment that it was difficult to use (p3), a comment that it took a long time due to the lack of prior knowledge of the color space (p7), a comment that it was difficult to point accurately (p14), a comment that it was complicated to use (p15), a comment that it was not intuitive (p20), comments that dark color selection was difficult (p20, p32), and a comment that knowledge about the color space was necessary (p35).

Regarding the cut-off HSV color picker, there were comments that color selection was difficult in the small space near the vertex of the cone (p10, p21, p23, p26, p32), comments that the cone shape was inconvenient (p4, p12), a comment that the cone shape was convenient (p11), a comment that it was difficult to use without prior knowledge (p14), comments that it was inconvenient to move to see the removed surface (p20, p21, p35), a comment that the desired color was easily selected from the colors around the pointer (p20), a comment that the removal angle of 120° was too large (p26), and a comment that the desired color disappeared because the left of the hue section was removed (p30).

Regarding the discrete RGB color picker, there were comments that it was difficult to see and confusing because the color spheres were overlapped (p1, p4, p7, p20, p21, p23, p26, p28, p30), comments that the color selection was not accurate compared to the continuous color picker (p10, p11, p12, p28), comments that the system response was slow (p25, p35), a comment that it was the easiest to select a color (p9), comments that they could select a color by feeling (p12, p20), a comment that it was intuitive (p14), a comment that it was dizzying to use (p19), a comment that dark color selection was difficult (p33), and a comment that it was uncomfortable to use (p34). Compared to the continuous color picker, the discrete color picker selects the closest color among the predetermined color samples, so the accuracy of color selection is inevitably lowered. Also, compared to other color pickers, it renders a large number of translucent spheres, so the system is slow to respond.

Regarding the discrete HSV color picker, there were a comment that it took a long time to select a color because there were many color samples provided (p1), comments that it was difficult to see and confusing because the color spheres were overlapped (p4, p28, p35), comments that it was difficult to accurately select a color due to the lack of samples (p10, p11, p16, p28), a comment that it was difficult to see the inside (p30), comments that it was difficult to select a color near the vertex of the cone (p10, p21, p32), comments that the desired color was visible (p20, p21), comments that the discrete interface was inconvenient (p25, p26, p34), and a comment that a color was selected by feeling (p35).

In the request to leave free comments from an overall point of view, there were a comment that the RGB cube space was easier to use than the HSV cone space (p4), a comment that the continuous color picker was more convenient than the discrete color picker (p4), and a comment that it was a change of the color picker suitable for virtual reality (p21).

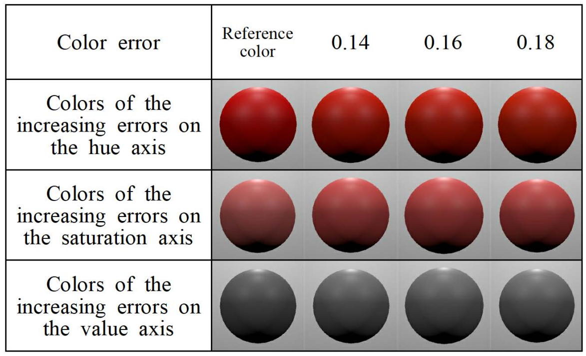


FIGURE 24. Color difference for the color error from 0.14 to 0.18.

E. DISCUSSION OF EXPERIMENTS

In this study, 35 participants made 2,450 color selections in VR to measure the color selection time and color selection accuracy of seven VR color pickers. For color selection time, we assumed that 3D color pickers would be faster given their one-step interaction, and 2D HSV color picker would take more time because of multistep interactions between the color wheel and slider are required. As a result of the experiment on color selection time, discrete HSV, cross-section HSV, and cut-off RGB color pickers had an average of 14 s to select a color, which was faster than the average of 16.4 s of 2D HSV color picker. In particular, discrete HSV color picker was significantly faster than 2D HSV color picker (see Table 2).

To compare the color selection accuracy of the color pickers, the color error between a color given at random and a color selected by the user was measured. The color errors of the seven color pickers were in the range of 0.132 to 0.177, as shown in Table 5. To show how much these numerical differences differ when viewed with the naked eye, Fig. 24 presents color differences according to the color errors in the range of 0.14 to 0.18 for the reference color. The first row in Fig. 24 shows the colors of the increasing errors on the hue axis from the highest saturation of red, and the second row shows the colors of the increasing errors on the saturation axis from the middle saturation of red. The third row shows the colors of the increasing errors on the value axis from the middle value of gray. Compared to the differences in the hue axis and the value axis, the difference in the saturation axis is slightly felt, but overall, it appears very similar. The color error of 2D HSV color picker was the smallest at 0.132, but according to analysis of variance, there was no significant difference. It was determined that 2D HSV, cut-off RGB, and cross-section RGB color pickers have similar color selection accuracy (see Table 5).

The results of two-way ANOVA and Tukey's method for the color selection error shows that the HSV color model has lower accuracy than the RGB color model (see Table 6 and Table 7). The cause of the difference between the HSV color model and the RGB color model can be inferred from the comments left by the participants. Several participants gave the comments that color selection was difficult near the vertex of the HSV cone. Near the vertex of the HSV cone, the color space becomes very small, and it would be difficult to move the pointer to select a color in this small space, resulting in high color selection error. Particularly in the cut-off HSV color picker, when the pointer navigates near the vertex, most of the color space is removed, leaving only a small volume, as shown in the last figure of Fig. 7. It would be difficult for the participant to select a color from this small volume. As shown in the last figure of Fig. 6, in the case of the cut-off RGB color picker, even if the subspace is removed by moving the pointer near black, the cut-off boundary surface for observing colors is rather large, so there would be no such difficulty. The method of removing the subspace of the cut-off HSV color picker should be changed to a new way. A cylinder shape can be substituted for a cone shape of the HSV color space, but ultimately it is better to use a perceptually uniform color space such as CIE L*u*v* or CIE L*a*b*.

The results of two-way ANOVA and Tukey's method for the color selection error shows that the discrete interface has lower accuracy than other interfaces (see Table 6 and Table 8). Several participants also gave the comments that the color selection was not accurate compared to the continuous color picker. However, the discrete color picker has to select a color from predetermined samples, and there is an irreducible error between a randomly given color and the selected sample. Taking this into account, the color errors of the discrete color pickers should be considered smaller than those listed in Table 5. Although setting color samples by uniformly quantizing the color space is suggested in this paper, it seems more practical to use traditional color collections used in the design field as color samples for the discrete color picker. These include FS 595, BS 381, RAL, ISCC-NBS, NCS, Pantone, and Munsell. In this case, our approach to placing color samples in unique locations in 3D would still be an advantage. Another negative comment about the discrete color picker is that the color spheres overlap, making it difficult to see the interior of the color space. It is expected that this problem can be improved by combining the discrete interface with the cut-off interface or with the cross-section interface.

For the usability evaluation, an SUS survey was conducted on the seven color pickers, and 2D HSV and cut-off RGB color pickers have higher usability than other color pickers. Except for the 2D HSV, the usability of the 3D color pickers was not significantly different. The difference in usability for color models and interfaces was also not significant.

When comprehensively evaluated in the three aspects of color selection time, color selection accuracy, and usability, the cut-off RGB color picker showed a similar level to the 2D HSV color picker. When quantitatively evaluated in color selection time and color selection accuracy, the cut-off RGB color picker and the cross-section RGB color picker showed similar levels to the 2D HSV color picker. This proves that it is feasible to substitute the 2D HSV color picker for a 3D form in VR.

V. CONCLUSION

In this study, we presented a full 3D color picker for VR. The color picker was designed by adopting the 3D shape of RGB and HSV color spaces, and the user selected a color by the simple interaction of placing a 3D pointer in the color space. To show colors inside the color space, we added three user interfaces: an interface cutting a portion of the color space off, an interface showing the cross-sections of the color space, and an interface placing discrete color samples of the color space. The 3D color picker and the 2D HSV color picker were compared through user experiments, and the 3D color picker that adopted the RGB color model and the interface cutting a portion of the color space was the best when comprehensively evaluating color selection time, color selection accuracy, and usability. The experimental result proves that the proposed 3D color picker can replace the conventional 2D color picker in VR. The 3D color picker is easy and enjoyable to use and consistent with 3D scenes and 3D interactions, so it is expected to be widely used in VR.

In the future, we will explore ways to combine the proposed 3D color picker interfaces to achieve more efficient user interaction, for example, the combination of the discrete interface, cross-section interface and cut-off interface. We plan to develop a discrete color picker using traditional color collections as color samples to pursue practicality. Finally, we plan to apply the 3D color picker to a perceptually uniform color model, CIE L*u*v* or CIE L*a*b*.

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JIEUN KIM received the B.S. degree in IT application system engineering and the M.S. degree in IT convergence engineering from Hansung University, Seoul, South Korea, in 2019 and 2021, respectively. Since 2021, she has been a Researcher with the Center for Artificial Intelligence, Korea Institute of Science and Technology (KIST), Seoul. Her research interests include virtual reality, human–computer interaction, and virtual humans.

JAE-IN HWANG received the B.S., M.S., and Ph.D. degrees in computer science and engineering from the Pohang University of Science and Technology, South Korea, in 1998, 2000, and 2007, respectively. He is currently an Associate Professor with the Korea Institute of Science and Technology (KIST), UST, Seoul, South Korea, and a Principal Research Scientist with the Center for Artificial Intelligence, KIST, Seoul. His research interests include virtual reality, augmented reality, and 3D user interaction.

JIEUN LEE received the B.S. degree in computer engineering from Ewha Womans University, Seoul, South Korea, in 1997, the M.S. degree in computer science and engineering from the Pohang University of Science and Technology, Pohang, South Korea, in 1999, and the Ph.D. degree in computer science and engineering from Seoul National University, Seoul, in 2007. From 1999 to 2002, she was a Researcher with the LG Corporate Institute of Technology, Seoul. She was an Associate Professor with the Department of Computer Engineering, Chosun University, Gwangju, South Korea, and she has been an Associate Professor with the Division of Computer Engineering, Hansung University, Seoul. Her research interests include computer graphics, geometric modeling and processing, human–computer interaction, and virtual reality.