Exploring the Influence of Object Shapes and Colors on Depth Perception in Virtual Reality for Minimally Invasive Neurosurgical Training

Alessandro Iop
aiop@kth.se
KTH Royal Institute of Technology
Stockholm, Sweden

Olga Viberg
oviberg@kth.se
KTH Royal Institute of Technology
Stockholm, Sweden

Kristi Francis
Vilhelm Norström
David Mattias Persson
Linus Wallin
KTH Royal Institute of Technology
Stockholm, Sweden

Mario Romero
marior@kth.se
KTH Royal Institute of Technology
Stockholm, Sweden

Andrii Matviienko
andriim@kth.se
KTH Royal Institute of Technology
Stockholm, Sweden

ABSTRACT

Minimally invasive neurosurgery (MIS) involves inserting a medical instrument, e.g., a catheter, through a small incision to target an area inside the patient's body. Training surgeons to perform MIS is challenging since the surgical site is not directly visible from their perspective. In this paper, we conducted two pilot studies focused on object shapes and colors to collect preliminary results on their influence on depth perception for MIS in Virtual Reality. In the first study (N = 8), participants inserted a virtual catheter into objects of different shapes. In the second study (N = 5), they observed the insertion of a virtual catheter into objects of different colors and backgrounds under different lighting conditions. We found that participants' precision decreased with distance and was lower with the skull shape than with a cube. Moreover, depth perception was higher with blue backgrounds under better lighting conditions.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**; **Mixed / augmented reality**.

KEYWORDS

virtual reality, depth perception, minimally invasive neurosurgery

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1 INTRODUCTION

Minimally Invasive Surgery (MIS) is an operational approach commonly employed to perform localized procedures on a patient through small incisions. The goal is to reduce the risk of infection, and thus the length of hospital stay, and speed up the full recovery of the patient [14]. In cranial neurosurgery, MIS is usually adopted to treat conditions such as tumors, cystic brain lesions, and aneurysms [26]. However, training surgeons to perform MIS is challenging since they do not see inside the patient's cranium during the surgery, and the procedure has to be performed based on muscle memory rather than visual feedback [22]. Virtual Reality (VR) has shown a potential to accommodate training conditions due to its immersion into a digital 3D environment [5, 27]. Thus, training in a highly accurate VR simulation, where the surgeon can see inside the cranium, could provide a safe practice environment without patient complications. Nevertheless, there is evidence that the perceived depth in VR is underestimated compared to the real world [24, 28], which could negatively impact applications where very precise depth perception is needed. Yet, the influence of objects, shapes, and colors on depth perception in VR is underexplored and is the focus of this paper.

Previous work on VR training, e.g., in medical [10], transport [17], and military [29] contexts, is a useful substitute for normal training, especially considering the lower costs and, in some cases, risks of the training [35]. In the case of MIS procedures, the challenge with using VR is creating a highly realistic perception of virtual objects, specifically regarding depth perception. For example, participants often underestimate the actual distance to around 74% of the modeled distance [28]. Since cranial MIS typically requires sub-millimeter precision [26], depth perception is crucial to avoid damaging surrounding tissues. Researchers have shown that low and high-fidelity shapes of differing complexity with different luminance and colors affect depth perception in handheld mobile AR [8]. However, it is still unclear how exactly object shapes and colors influence depth perception for MIS in VR.

In this paper, we conducted two pilot studies focused on object shapes and colors to collect preliminary results on their influence

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on depth perception for MIS in VR. In the first study (N = 8), participants had to insert a virtual catheter at a particular depth for shapes of different levels of fidelity. In the second study (N = 5), participants had to passively observe the insertion of a virtual catheter into virtual objects of different colors and background colors under different lighting conditions. We found that participants' precision in selecting a target was lower with the skull shape than with a cube, and their precision decreased with the distance to a target. Moreover, depth perception was not affected by object colors. Still, it was higher with blue backgrounds than yellow, and high saturation and lightness conditions led to higher precision than low ones. With this work, we contribute an empirical evaluation of object shapes and colors on depth perception in Virtual Reality for minimally invasive neurosurgical training.

2 RELATED WORK

2.1 Minimally Invasive Neurosurgery and Virtual Reality Training

In modern neurosurgical practices, minimally invasive approaches are often adopted to target a small localized region in the patient's body, minimize damage to surrounding tissues and blood loss, and facilitate post-operative recovery from the surgery [26]. MIS is used to treat a wide range of disorders, including tumors, cystic brain lesions, and aneurysms [26]. However, despite the positive aspects of MIS, the technology used poses a few problems, which include a limited view of internal organs due to the usage of a monoscopic camera, limited haptic feedback due to the long surgical instruments attached to tubes, and challenging hand-eye coordination due to the tool moving around a pivot point [4]. Traditional training practices in the field mainly involve practicing on animal or human cadavers before performing surgeries directly on live patients [11]. Given the scarce and costly opportunities to carry out these training activities and the lack of well-established performance assessment criteria for MIS simulations [12], Virtual Reality (VR) can provide supplemental training opportunities for resident neurosurgeons due to its immersion into a digital 3D environment [5, 27].

One of the main advantages of using Virtual Reality (VR) for training is having a first-person perspective [32] of the environment and natural locomotion that facilitates a simulation experience more representative of reality than traditional desktop computer simulations [20]. Training using VR has been used for more than 20 years for task-specific applications where the first-person perspective and realistic interaction are central for the transfer of the knowledge acquired to real-life situations [20, 32, 35]. Although medical VR training has long been used, applications have generally been task- and area-specific, requiring anatomically-correct simulations [20]. One of the essential parts of surgical training is depth perception since even a small mistake could be detrimental when applied to real-world surgeries. Moreover, VR allows for highly accurate simulations where normal training is limited due to extensive cost and risk [11, 23]. However, existing VR training environments still have limitations that affect depth perception, which is vital for surgical procedures. Therefore, in our work, we explore in detail how depth perception [2] is affected by the shapes and colors of virtual objects.

2.2 Depth Perception in Virtual Reality

Multiple studies examined depth perception in VR [3, 16, 18, 21, 24, 25, 28, 30] by measuring the estimated *egocentric distances*, i.e., the perceived distance from the subject to an object. The results from these studies indicate that estimated egocentric distances in virtual environments are underestimated compared to real-world depth estimations. Another review of articles on egocentric distance perception in VR concluded that users underestimate distances to objects when they are located directly in front of them and overestimate distances when objects are located more than 30° to either the left or right [24, 28]. Another study also confirmed an underestimation for distances between 40 and 500 cm [3]. While earlier research has not fully accounted for the underestimation, the hardware used seems to contribute to the perceived depth perception [15], where newer models of VR headsets made the participants perform better. High-cost devices have been shown to yield more realistic distance perception in VR compared to low-cost devices, but distance is still overestimated regardless of the device used [7].

Previous research has explored the effects of distances on depth perception and investigated the effects of shapes and colors. As for perception of shapes, a study from 2020 [8] compared low- and high-fidelity shapes of differing complexity with different luminances and colors and found that the shape and fidelity of virtual 3D objects interact with color and luminance to affect depth perception in handheld mobile Augmented Reality. Their results indicate that colors and luminance affected simple high-fidelity objects more than complex ones. This suggests the necessity for more rigorously exploring these effects in task-specific applications, such as minimally invasive neurosurgical training in Virtual Reality. The work about shape and shadow influence in XR Displays by Adams et al. [1] suggests that an object's shape influences one's perception of ground contact. Still, the relationship between shape and surface contact perception is more complicated and requires further exploration. As for perception of color, a study on random-dot stereogram (RDS) – stereo pairs of images of random dots – has shown that the visual system is not able to perceive depth when there is only a difference in hue and that it is required to have differences in luminance for stereopsis [19]. Moreover, it was also shown that stereopsis was possible on isoluminant color RDS and concluded that not only the luminance channel contributed to depth perception, but also the chromatic channel [13]. Later research demonstrated that the stereo depth thresholds were substantially higher for objects modulated isoluminantly than for objects with modulated luminance [9]. Mixtures of luminance modulation and chromatic modulation have been shown to result in higher disparity thresholds. More recently, Chen et al. [6] examined color perception about stereoscopic vision but did not reach a clear contribution of color in stereoscopic vision by stating: "the contribution of color information to stereopsis is controversial, and whether the stereoscopic depth perception varies with chromaticity is ambiguous".

In summary, given the complexity of depth perception and how it is affected by shapes and colors in Virtual Reality, we systematically explored their effects on depth perception for minimally invasive neurosurgical training. In the following, we outline two controlled lab experiments, one focused on the influence of object shapes and another on the impact of colors.

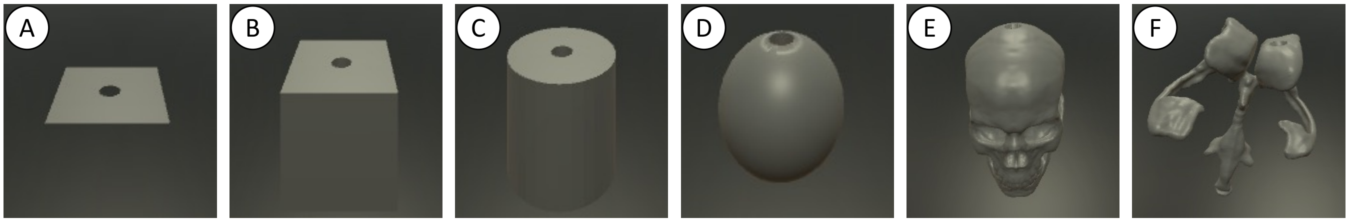

Figure 1: Shapes used in the first experiment: (a) plane, (b) cube, (c) cylinder, (d) sphere, (e) skull, (f) ventricles.

3 STUDY 1: EXPLORING THE INFLUENCE OF OBJECT SHAPES

In this study, we explored the influence of object shapes on depth perception in Virtual Reality surgical training. In a simulated surgical procedure, participants were tasked with inserting a virtual ventricular catheter into differently shaped objects at arbitrary depths. The research question for this study is: *How does the shape of an object impact depth perception in virtual reality surgical training?*

3.1 Participants

We recruited eight participants (4 M, 4 F) aged 22 to 38 ($M = 26.1, SD = 6.2$). To ensure participants had typical depth and color perception, we performed stereo-blindness[1] and color-blindness tests[2]. Due to possible complications, such as lens distortion and shifted viewing angle, when using VR headsets with glasses, only participants who did not use glasses were recruited. Participants did not receive compensation. Participants had no previous experience in neurosurgical practices.

3.2 Study Design, Task, and Procedure

The study was within-subjects, with two independent variables: (1) *shape* and (2) *depth*. The shape contained six levels of complexity: (1) plane, (2) cube, (3) cylinder, (4) sphere, (5) skull, and (6) ventricles (see Figure 1). The shapes covered six levels of abstraction, from a simple plane to a skull and ventricles. The distance to a target contained three levels: 0.5 cm, 1 cm, and 2cm. We created 18 conditions by combining all levels of shape and distance.

Each participant experienced each trial once while wearing a Meta Quest 2[3] VR headset. All shapes created in Unity 2021.3.3f1, were gray, opaque, and without any assigned texture. For each condition, the participant's task was to insert a virtual catheter into an opening in a shape until a certain level of depth (0.5, 1, and 2 cm) and to press a button on the controller to confirm it. With this, we measured the target offset, i.e., the Euclidean distance between the recorded trial and the procedurally determined ground truth. The shapes were fixed in mid-air, and participants had no other spatial points of reference. Since this study was made in the context of surgical procedures and the perceived depth is different depending on the distance from the observer [35], the participants were told to keep their heads still while looking down at the object at roughly an arm's length to simulate normal surgical conditions and to ensure that movement was not a contributing factor to depth perception. The duration of the experiment was 15 minutes.

3.3 Results

Given the non-parametric nature of the collected data, we applied the aligned rank transform for non-parametric factorial analyses [33]. For pairwise comparisons we used a Bonferroni p-value correction. Results from the present study are depicted in Figure 2.

We found that participants' precision in inserting the catheter was lower with the skull shape ($Md = 25mm, IQR = 15$) than with the cube ($Md = 16mm, IQR = 14$). However, no further differences were observed among other shapes: plane ($Md = 20mm, IQR = 20$), cylinder ($Md = 20mm, IQR = 16$), sphere ($Md = 18mm, IQR = 17$), and ventricles ($Md = 20mm, IQR = 14$). A statistically significant main effect confirmed this finding for the *shape* ($F(5, 35) = 3.09, p < 0.05, \eta^2 = 0.3$). The post-hoc analysis has shown a statistically significant difference between the skull and the cube ($p = 0.01$). However, the remaining pairwise comparisons were not statistically significant ($p > 0.05$).

We also found that participants' precision decreases with distance to target. Our results show that participants' offset was lower with the depth of 0.5 cm ($Md = 10mm, IQR = 6$) compared to 1 ($Md = 20mm, IQR = 7$) and 2 cm ($Md = 30mm, IQR = 13$). A statistically significant main effect confirmed this finding for the *depth* ($F(2, 14) = 95, p < 0.001, \eta^2 = 0.93$). The post-hoc analysis has shown a statistically significant difference between all depth levels ($p < 0.001$). However, we did not observe a statistically significant interaction effect between the shape and the depth ($F(10, 70) = 1.09, p > 0.05, \eta^2 = 0.13$).

4 STUDY 2: EXPLORING THE INFLUENCE OF OBJECT COLORS

In this study, we explored the influence of object colors on depth perception in Virtual Reality surgical training. In a simulated surgical procedure, participants were tasked with annotating the insertion point of a virtual ventricular catheter moving through a simple plane. Therefore, our research question for this study is: *How does the color of an object and background impact depth perception in virtual reality surgical training?*

4.1 Participants

We recruited five participants (three males, two females) aged between 21 and 25 years ($M = 21.6, SD = 0.9$). Similarly to the previous study, we performed stereo-blindness and color-blindness

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[1] https://www.mediacollege.com/3d/depth-perception/test.html
[2] https://www.colorblindnesstest.org/
[3] Meta Quest 2, Reality Labs, Menlo Park, CA, USA.

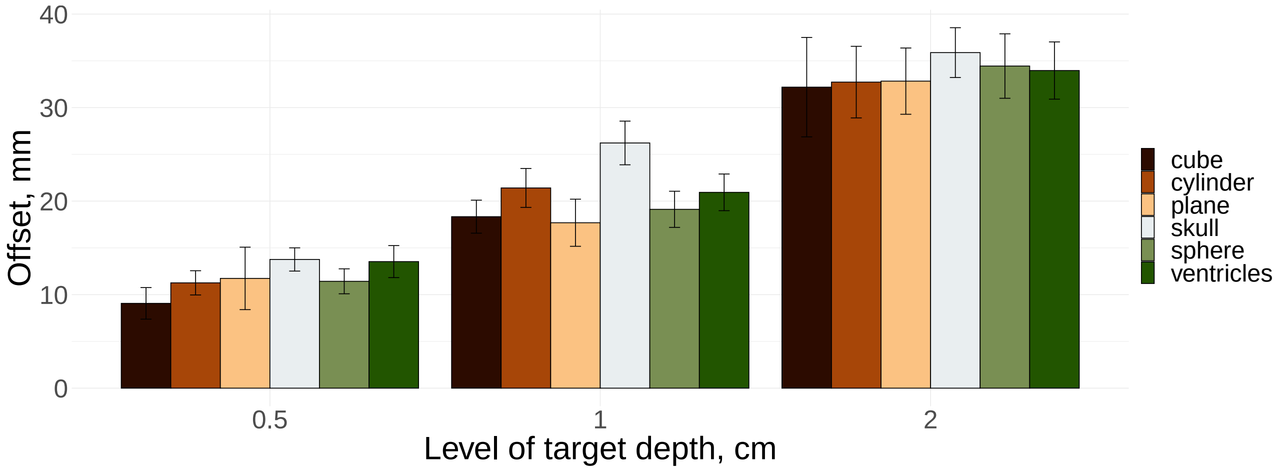

Figure 2: Overview of target offsets over six types of shapes (cube, cylinder, plane, skull, sphere, and ventricles) for three levels of target depth (0.5, 1, and 2 cm).

tests to ensure participants had typical depth and color perception. Participants had no previous experience in neurosurgical practices.

4.2 Study Design, Task, and Procedure

The study was designed to be within-subject with three independent variables: (1) *color of the background*, (2) *color of the plane*, and (3) *lighting conditions*. The color of the background and the plane varied between four distinct RGB hues: (1) blue [0,0,255], (2) green [0,255,0], (3) red [255,0,0], and (4) yellow [255,255,0]. These hues were selected as they have been shown to affect depth perception [6]. The colors of the background and plane were not combined in this study, i.e., when the background color was considered, the color of the plane was kept neutral white and vice versa.

Four different combinations of saturation (S) and luminosity (L) were also considered in the study. Between high (H - 100%) and low (L - 50%) values, the four levels of lighting conditions were: HS/HL, HS/LL, LS/HL, and LS/LL. In total, each participant underwent 32 trials (see Figure 3): 16 for the background color (2 color saturation * 2 color luminosity * 4 background colors) and 16 for the plane color (2 color saturation * 2 color luminosity * 4 plane colors).

We developed the virtual environment presented in the experiment using Unity 2021.3.11f1 and used the Meta Quest 2 HMD. During the experiment, participants were shown an animation of a catheter going through a hole in a plane; their task was to press a button when they perceived the catheter to be at the same height as the hole in the plane. They could also replay the animation as many times as needed by interacting with a virtual button in the virtual environment. Similarly to the first study, we measured the Euclidean distance from where the user pressed the button to the point of the entrance to assess the offset. In alignment with the first study, participants were located at an arm's length from the plane in the virtual environment. They were asked to keep still while undergoing the experiment. The total duration of the experiment was about 30 minutes.

4.3 Results

Given the non-parametric nature of the collected data, we applied the aligned rank transform for non-parametric factorial analyses [33]. For pairwise comparisons, we used a Bonferroni p-value correction. Results from the present study are depicted in Figure 4.

4.3.1 *Plane Color.*

We observed that offset was similar for all plane colors (blue: $Md = 2.9mm, IQR = 4$, red: $Md = 1.7mm, IQR = 2.9$, green: $Md = 2mm, IQR = 3$, yellow: $Md = 1.8mm, IQR = 4$) and lighting conditions (HS/HL: $Md = 1.8mm, IQR = 2$, HS/LL: $Md = 2mm, IQR = 3$, LS/HL: $Md = 2mm, IQR = 4$, LS/LL: $Md = 2mm, IQR = 4$). We did not observe statistically significant effects for the colors ($F(3,12) = 2.5, p > 0.05, \eta^2 = 0.39$) and lighting conditions ($F(3,12) = 0.34, p > 0.05, \eta^2 = 0.07$) . Lastly, we did not observe a statistically significant interaction effect for colors and the lighting conditions ($F(9,36) = 0.23, p > 0.05, \eta^2 = 0.05$).

4.3.2 *Background Color.*

We observed that offset was higher for yellow backgrounds than for blue ones, and we did not find any differences among other colors (blue: $Md = 0.6mm, IQR = 3$, red: $Md = 2.2mm, IQR = 3$, green: $Md = 1.7mm, IQR = 2$, yellow: $Md = 2.5mm, IQR = 3$). Moreover, lighting conditions of HS/HL led to higher precision than LS/LL (HS/HL: $Md = 0.9mm, IQR = 2$, HS/LL: $Md = 1.9mm, IQR = 3$, LS/HL: $Md = 2mm, IQR = 2$, LS/LL: $Md = 2mm, IQR = 3$). These findings were supported by statistically significant main effects for the colors ($F(3,12) = 4.6, p < 0.05, \eta^2 = 0.53$) and lighting conditions ($F(3,12) = 4.02, p < 0.05, \eta^2 = 0.5$). The pairwise comparisons have shown that there was a statistically significant difference between blue and yellow background color ($p < 0.05$) and between HS/HL and LS/LL lighting conditions ($p < 0.05$). The remaining pairwise comparisons were not statistically significant. Lastly, we did not observe a statistically significant interaction effect for colors and the lighting conditions ($F(9,36) = 1.48, p > 0.05, \eta^2 = 0.27$).

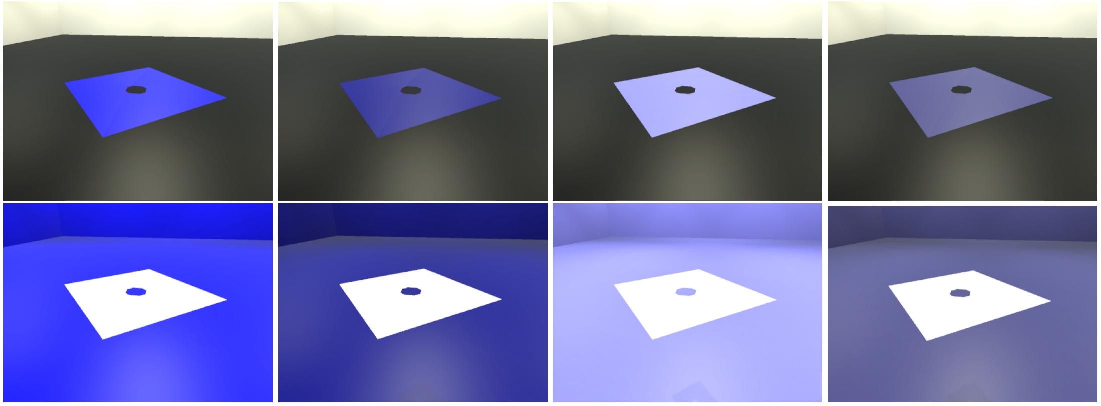

Figure 3: Lighting conditions used in the second experiment: plane (top row), background (bottom row). From left to right: HS/HL, HS/LL, LS/HL, LS/LL.

5 DISCUSSION AND FUTURE WORK

The results of the two studies suggest that, overall, participants tended to overestimate the depth of the insertion point for the catheter from an egocentric perspective. In other words, the distance between test subjects and the point of interest in space was deemed greater than it is. However, as described in the previous sections, no significant effects were observed for any independent variables considered in the second study (i.e., color attributes). Notably, our results contrast with previous research results, which reported a tendency towards underestimating the perceived egocentric depth in virtual environments [3, 7, 28, 30]. Conducting the experiments with a greater pool of subjects may yield a more significant impact on the pre-attentive visual features considered on the estimated depth of the catheter insertion point, either to corroborate or to contradict past findings. Despite significant evidence of underestimation reported in two studies [3, 28], more recent work has also shown that high-end VR devices enable higher accuracy [7]. Our findings can further support these claims, as the devices used in our studies are less than four years old at the time of writing.

Concerning the object's shape presented in the virtual environment, we showed that the precision in estimating depth tended to be higher for the cube than for the skull. This suggests that virtual objects with less detail may be more effective in supporting surgical simulations where the tool's insertion depth is important, compared to a photo-realistic depiction of the surgical scenario. On top of this, we showed that estimate precision decreases the farther the subject is from the area of interest - i.e., the insertion point. This implies that a region of interest that appears to be closer to the subject's perspective will be more easily estimated correctly. To corroborate the conclusion, the estimation accuracy tends to be higher for smaller distances, as can be inferred from the IQR calculated. In scenarios where placing an object closer to the user is impossible, increasing its size may enable the same improvement. Overall, we can only infer conclusions based on the relative differences between shapes experienced in a virtual environment, not the difference with real-world experience. Future research may address this comparison to provide additional evidence of VR's impact on depth perception.

Concerning the colors of the objects presented in the virtual environment, while no significant effects were observed for any of the color attributes in the plane, surprisingly, both hue and lighting conditions impacted depth perception when applied to the background color. In particular, blue backgrounds yielded less precise estimates than yellow ones, and high saturation/high lightness conditions yielded more precise estimates than low saturation/low lightness ones. Such impact of background properties on depth estimation suggests that the appearance of the surrounding environment may play a significant role in the perception of features of interest in the objects in the foreground. Future work exploring the interaction between color attributes and the distance between subject and object of interest may further support this conclusion. Notably, results from this study show greater accuracy and precision in participants' performance compared to those from the first study, meaning that their estimation of egocentric depth tended to be better. Although a conclusive comparison between the two studies cannot be made, results related to the plane shape used in the first one can suggest the presence of a significant difference between actively performing the catheter insertion and observing it from an outsider's perspective. In the former case, participants might have had to mind the catheter's position and orientation. At the same time, in the latter, they could focus their attention on a single coordinate of movement. Further research comparing these two scenarios could reveal additional insights that may be impactful in designing a meaningful surgical training experience.

As for the implications of these findings in the context of MIS and the applicability of VR as a training tool for such procedures, we have shown that it is crucial to consider the shapes and colors when designing training procedures with students. MIS typically involves performing surgeries through small incisions without a direct view of the surgical site, which requires high accuracy and precision. Therefore, visual features can be leveraged in immersive simulation scenarios to guide the learner's attention towards a point or region of interest in space [34]. At the same time, they can convey meaningful additional information, potentially useful

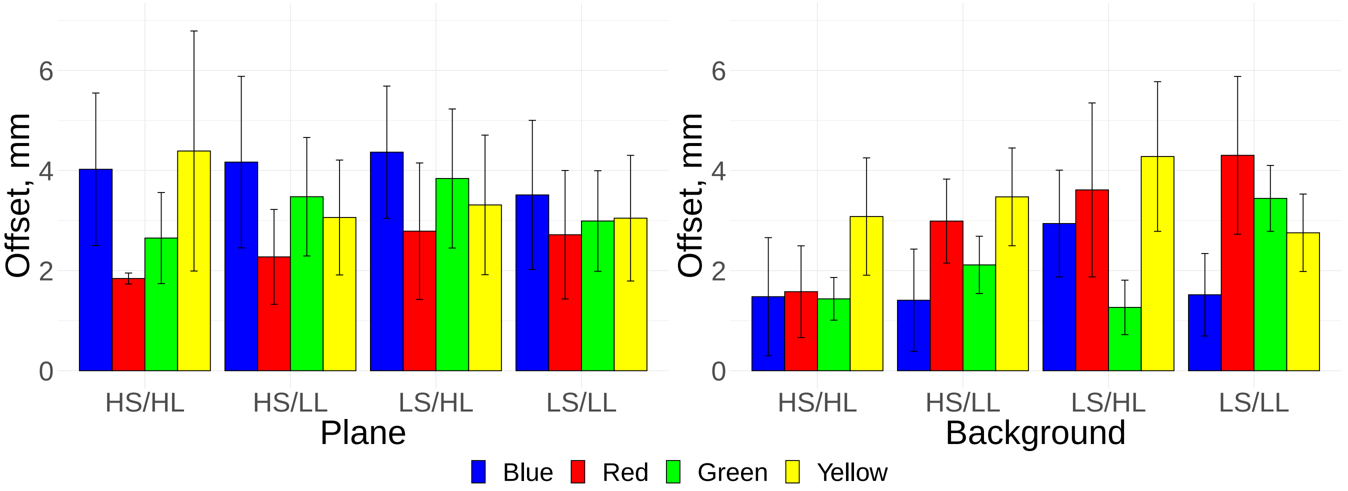

Figure 4: Overview of the target offset for plane (left) and background (right) colors for different levels of lighting conditions: HS/HL, HS/LL, LS/HL, LS/LL. HS - High Saturation, LS - Low Saturation, HL - High Luminosity, LL - Low Luminosity.

in acquiring and transferring procedural knowledge related to the surgical practice [31]. These conclusions may be extended to other high-precision tasks and practices, both within and outside the surgery domain. Despite a tendency toward overestimating egocentric depth perception in the scenario considered in our studies, features such as object shape and color attributes can be predictably controlled to yield estimations closer to the desired target. Future work on other features, both static, such as size, and dynamic, such as movement, as well as on the interaction of multiple features, may reveal further insights into the best design approach for educational practices in MIS.

6 CONCLUSION

To investigate the impact of pre-attentive visual features on depth perception in a virtual environment for minimally invasive surgery, we have conducted two studies focusing on object shapes and color, respectively. Our preliminary results indicate that participants' precision in selecting a target was lower with a more detailed skull shape than with a simpler cube, and their precision decreased with the distance to a target. Additionally, we found that depth perception was not affected by object color attributes such as hue, saturation, and lightness. Still, depth perception was more precise with blue backgrounds than yellow ones, and high saturation and lightness conditions led to higher precision than low ones.

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