Holographic and Related Technologies for Medical Simulation

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Abstract. Holographic technologies allow for direct three-dimensional (3D) imaging without the need for special glasses or headwear. Holographic imaging ranges from static (i.e., unchanging) toward dynamic (i.e., changing) presentations. Since dynamic holographic products are in their developmental infancy, this study utilized static holographic images to predict future needs and preferences for dynamic holography. Using a single anatomical model, five static holograms were created for subjective evaluation from respondents. Four major research questions addressed the aim of this study, to determine the impact of color, hogel size, polygon density, and directional resolution on user preferences and perceived image quality of holograms within the medical field.

Data collection took place at Orlando Regional Medical Center, a part of Orlando Health from November 2017–February 2018. A total of 32 medical educators and providers viewed the static holograms, answering a series of questions related to each hologram. Overall perceptions/preferences were reported. Trends suggest that participants preferred the color over monochrome hologram, even when both are of the same image quality. The highest polygon density, 3.3 M (3.3 million polygons) was rated as rendering significantly higher image quality than lower polygon densities. Furthermore, there is a potential interaction between hogel size (like a pixel) and directional resolution (angular rays in each hogel). This study provides useful technical recommendations for future development of static and dynamic holograms as a possible alternative to current 3D visualization mechanisms in the medical domain.

Keywords: Hologram · Three-dimensional (3D) visualization · Training

1 Introduction

The human body exists in three dimensions. It follows that technology should be able to display it as such. However, students often learn anatomy through two-dimensional (2D) pictures and must integrate these pictures into a three-dimensional (3D) mental model [1–3]. One drawback to using 2D images in anatomical education is that multiple pictures or diagrams (also known as “key views”) are needed to fully represent a 3D structure [2]. A second limitation of using 2D images is that they lack the depth

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cues needed to accurately and completely depict the spatial relationships among and within anatomical structures [4, 5].

Static holography can supplement digital technologies that are new to anatomical education classrooms, such as virtual and augmented reality systems. While virtual reality has recently garnered a considerable amount of attention, the technology is also not without its own disadvantages. Stereopsis, used in virtual reality headsets which allows for depth perception within the head-mounted display, presents a separate image to each eye and is the current standard for user-centered medical simulation [6–8]. While virtual and augmented reality systems can be effective tools for displaying 3D relationships, there are several negative usability effects on users with sustained use (e.g., visual fatigue and muscle fatigue in the neck), making alternative technologies for medical simulation more attractive [6, 7, 9].

A study by Rizzolo [10] describes specific benefits that holography can provide for medical curricula. These benefits include a clearer understanding of how 2D images can be reconstructed into a depiction of a 3D structure and improved visualization of 3D structures and relationships. Additionally, static holograms are reusable, such that students can take turns viewing the images individually or in groups, and the plates can be stored away for future use [11].

This paper outlines an overview of holograms and their associated technical components such as color, contrast, hogel size, polygon density, and directional resolution. We also evaluate whether differences in color, hogel size, polygon density, and directional resolution affect a viewer's ability to identify anatomical structures. We expect these outcomes reported will guide developers to produce images at or above a level of minimal usability, therefore, providing a recommended path for further technical development of both static and dynamic holography.

1.1 Holographic Displays Described

Before a discussion can take place on the classification of holograms used in this research, it is important to describe a holographic display. Bruckheimer [12] defines holography as "a method for creating an exact visual representation of an object in three physical dimensions using light" (p. 1). Holographic displays exhibit a remarkable advantage over other types of 3D displays. They are autostereoscopic, meaning users can view the displayed images in three dimensions without glasses or other supplementary eyewear, and have multiple viewpoints [7, 13, 14]. However, autostereoscopy affords a more comfortable experience as compared to various other methods of 3D visualization, such as virtual reality headsets, even when an external light source is needed [7]. Autostereoscopy may also decrease the potential for motion-related sickness [15].

In addition to being autostereoscopic, holographic displays can present several depth cues that 2D images cannot. Some of these depth cues are due to changes in how an image looks from different viewing angles and are referred to as parallax. When the effect of parallax is present, objects that are closer to the viewer move more quickly than objects that are further from the viewer [16]. Movement or motion parallax refers to the phenomenon that contributes to the perception of slightly different images when the viewer changes his or her position [13]. It is the form of parallax that is most important for the static holographic images used in this research. Movement parallax happens over time and with motion, so the displayed image is viewed from multiple viewpoints and provides information about the relative distances of objects in a visual scene [13, 16].

A second noticeable depth cue that is an important feature in holographic imagery is occlusion. Occlusion is the visual effect experienced when an object is blocked from view by another. The degree of occlusion changes when parts of the image come into view as the viewer changes position [7, 8, 13]. For instance, a building that appears to be blocking a tree is perceived as being in front of the trees. From another angle, the tree may be blocking the building and would then appear as being in front of the building. This cue becomes more pronounced as objects are displayed at increasingly larger distances apart [8].

In some types of holographic displays, a point light source (e.g., a flashlight) is needed to recreate the perception of the 3D image that was first generated during the printing process [17, 18]. In such displays, ambient light largely impedes the capability of viewing the printed image. Changing the location and/or angle of the direct light source when viewing a hologram can also affect both occlusion and motion parallax, depending on the type of hologram that is being viewed. In this way, motion parallax and occlusion operate together to produce multiple viewpoints of the same visual scene and can even help improve performance during interactive tasks involving reaching in depth [16].

1.2 Features of Holograms

There are several technical aspects of a static hologram that can be manipulated including color, contrast, hogel size, polygon density, and directional resolution. Generally, each of these static holography features can inform the development of dynamic hologram displays. Using the holograms created by Zebra Imaging Inc. (now known as HoloTech Switzerland AG) we can directly evaluate the usability of a 3D display system by adjusting several technological aspects while simultaneously allowing for various depth cues to be observable within the display.

Color. Monochrome refers to images that are printed in varying in shades of green rather than grey. Monochrome prints are best for models that lack texture, a limitation for medical imaging purposes where texture is of considerable importance [1, 18]. The coloring is manipulated during the image generation process, prior to printing. In either case, color and monochrome holographic images are displayed on a black background to distinguish the image from the empty space surrounding it.

Polygon Density. Polygon density is also altered entirely during the digital image generation process. The layout of polygons in a representation of a 3D image is sometimes referred to as a mesh [19]. Printed hologram images may contain millions (notated as M) of polygons, dependent on the count chosen during image generation. A higher polygon density generally corresponds to a sharper image but requires more processing power and is limited by the capabilities of the computer program used during image generation, the physical printing process, and the material holograms are printed on [18]. Additionally, missing or “sparkling” black hogels may appear in a holographic print if polygons become too large (i.e., low polygon density) and interfere with the hogel pitch.

Hogel Size. Hogel size refers to the dimensions of the holographic elements that comprise the image. Hogels are the holographic equivalent or version of pixels [20, 21]. The holograms are set to contain hogel sizes in millimeters (mm) or fractional parts of millimeters (e.g., 0.50 mm). Decreasing hogel size significantly impacts the cost required to generate and print a holographic image [22].

Directional Resolution. Directional resolution in static holography signifies the number of angular rays present in each hogel and does not exist for 2D displays [23]. In other words, it is the range of viewing angles from which hogel may be seen [23, 24]. For instance, the directional resolution of 128 × 128 has a total of 16,384 angular rays per hogel. It is important to determine if directional resolution influences user preferences and perceived image quality, as it measures the extent to which parallax is present in the displayed image [23].

1.3 Use of Static Holograms to Inform Dynamic Hologram Technology

Static holograms are studied in this research effort because they can be studied directly, whereas dynamic holographic displays are not as prevalent in use and lack in technical maturity. By implementing static holograms in the present experiment, we gain a higher understanding of the features that should be prioritized when evolving a realistic and useful dynamic holographic display for users. Following this, developers can focus on advancing the most important features, while maintaining a conservative expense and resource approach to the areas of holography that are not as important to users. For example, if it is found that the directional resolution of an image is critical in accurately perceiving an image, whereas color does not affect image perception, developers can allocate more resources into further improving directional resolution and distribute less resources towards improving or implementing color capabilities. By studying the impact of different criteria on end-user preferences (i.e., healthcare professionals) and the visualization materials they use, we seek to gain a higher understanding of the baseline features needed to create realistic and useful static and/or dynamic holographic displays for healthcare training purposes.

2 Methodology

2.1 Participants

Study participants consisted of 32 volunteers and included nurses (31%), medical students (25%), nursing students (12.5%), Emergency Medical Technicians (12.5%), medical residents (6%), physicians (6%), one nurse practitioner (3%) and one medical assistant (3%). Fifty-six percent of participants were females (n = 18), 43% worked in the emergency department, and the average age across all participants was 32 years. All participants had either normal or corrected-to-normal vision and none of the participants noted color vision deficiency (i.e., color blindness). Experience levels ranged from 1 to 20 years, with an average of 6.28 years. When asked about previous training experiences, participants indicated that they were primarily exposed to cadavers, deceased animals, simulations, and lectures, while 3D movies, virtual reality, and computer software were not commonly used during their anatomy training.

2.2 Study Material: Holograms

The static holograms shown to participants during this study were generated by a multi-step process. First, a real-world model was obtained from the Combat Capabilities Development Command which features a simulated bilateral leg amputation (as seen in Fig. 1 left). This model was then scanned using the Eva Professional Handheld Scanner by Artec 3D. The resulting images were meshed in the Artec Studio 11 software program. Further image manipulation was conducted using the software program MAYA12 from Autodesk [25]. Finally, the computer images were converted into static holograms using a multi-step lamination process and printed onto photopolymer plates. Figure 2 (right) was generated digitally from the Multiple Amputation Trauma Trainer MATT^{TM} Simulator and translated across each of the 18 channels.

Fig. 1. (Left) Full MATT^{TM} Simulator with bilateral leg amputations; blurred for graphic content

In total, five holograms were created by Zebra Imaging Inc., each hologram exhibited full parallax, thus making the 3D image visible from every overhead viewing angle. Each channel (or side of the hologram containing a 3D image) displayed a single image. Four of the holographic plates (Holograms 1, 2, 4, and 5) displayed one image on all four possible channels. One holographic plate (Hologram 3) compared just two channels. In all, 18 total channels were evaluated for perceived image quality, usability, and usefulness.

By using multiple iterations of the same image, the researchers were able to evaluate user perceptions across the four technical features of interest (e.g., color, polygon density, hogel size, and directional resolution). Please refer to Fig. 3 for an overview of the specific features that varied in each hologram.

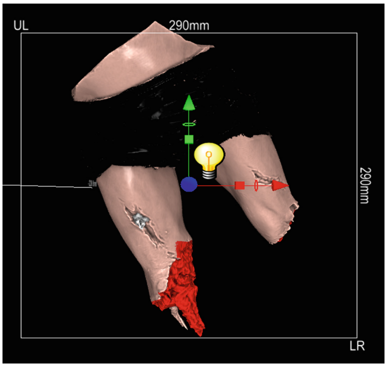

Fig. 2. (Right) Computer-generated 3D model of the MATT^{TM} Simulator with bilateral leg amputations

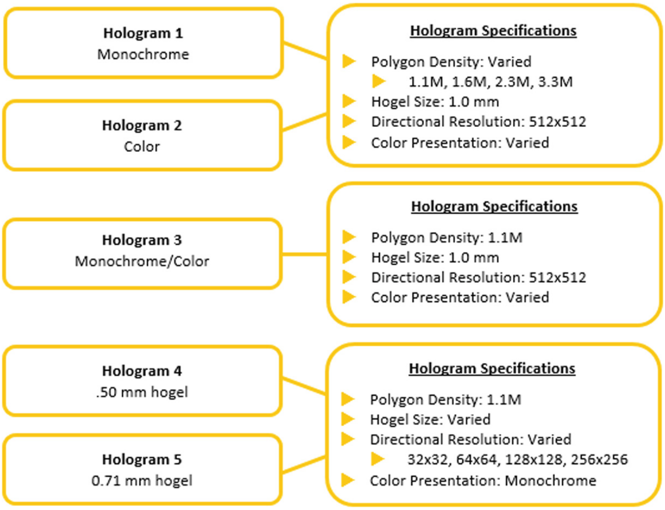

Fig. 3. Holograms overview

2.3 Research Questions

The five holograms were created by combining different levels of the four hologram features (i.e., color, polygon density, hogel size, directional resolution) in a way that allowed comparisons between different holograms to address the research questions (Table 1).

2.4 Study Procedures

All study materials were approved by the University of Central Florida's Institutional Review Board. After giving their consent for study participation, participants were

Table 1. Research questions summary

Questions	Hologram(s) compared
(A) **What is the optimal perceived image quality when polygon density is varied?** (Participant presented with holograms H1 and H2 in turn. Each of these holograms was rotated to show the adjacent channels that varied on polygon densities. Participant compared the image quality between adjacent channels)	(A1) **Monochrome** with **varying polygon density 1.1 M, 1.6 M, 2.3 M, 3.3 M** (H1) (A2) **Color** with **varying polygon density 1.1 M, 1.6 M, 2.3 M, 3.3 M** (H2)
(B) **Do users prefer color or monochrome presentation of holograms?** (Participant presented with H3, a hologram that was rotated to show its color and monochrome channels. Participant was asked which channel they preferred)	(B1) **Color vs monochrome** (H3)
(C) **What is the optimal perceived image quality when directional resolution is varied?** (Participant presented with holograms H4 and H5 in turn. Each of these holograms was rotated to show adjacent channels that varied on directional resolutions. Participant compared the image quality between adjacent channels)	(C1) Monochrome with **hogel size .50 mm**, and **varying directional resolutions 32 × 32, 64 × 64, 128 × 128, and 256 × 256** rays per hogel (H4) (C2) Monochrome with **hogel size .71 mm**, and **varying directional resolution 32 × 32, 64 × 64, 128 × 128, 256 × 256** rays per hogel (H5)
(D) **What is the optimal perceived image quality when hogel size is varied?** (Three holograms, H1, H4, and H5, that differed on hogel size were laid out from left to right before the participant. Participant compared the image quality of the holograms)	(D1) Monochrome with **hogel size 1.0 mm** (H1) placed on **Left** (D2) Monochrome with **hogel size .50 mm** (H4) placed in **Center** (D3) Monochrome **hogel size .71 mm** (H5) placed on **Right**

assigned unique participant identifiers which were created to ensure participant confidentiality and anonymity was protected (using https://www.randomizer.org). These IDs assisted with the hologram random sequencing order. Next, a demographics questionnaire and restrictions survey were administered. Based on answers to the restriction's questionnaire, the experimenter verified that there was no history of photosensitive seizures, color vision deficiency, or a physical or psychological sensitivity toward viewing anatomical images; two participants were dismissal from the study. Additionally, this study employed short questionnaires before, during, and after the hologram viewing task. All surveys were created through Qualtrics, a trusted third-party survey platform and administered via a tablet or paper copy.

During the study, a LED flashlight was handed to the participant for viewing and the room lights were turned off. A green light was used for monochrome holograms and white light was used for colored holograms [17, 26]. While standing, participants were instructed to hold the flashlight at ear level, aligned with their line of sight for optimal viewing. To facilitate the rotation and minimize potential damage to the surface, each hologram was placed on a rotating platform on the floor (except for holograms used for Research Question D), and a second experimenter rotated the platform when participants indicated they were ready to see the next image. (Note: interrater reliability was confirmed across experimenters to ensure conditions and rotation methods were consistent across participants.) Participants stood approximately eight inches away from the holograms. The participants were not allowed to view previous channels again, and each channel was only viewed for five - ten seconds to encourage participants to respond with their initial instincts.

Each participant randomly viewed all five holograms and were exposed to all the research questions listed in Table 1. For Research Questions A and C, participants were asked to indicate if they noticed a difference in image quality between adjacent channels following each of the four 90-degree rotations. The final comparison always compared the two most extreme differences (e.g., highest versus lowest polygon density or directional resolution). Question B asked about image quality regarding Hologram 3's two channels after a 180-degree rotation. Research Question D also asked about image quality in relation to the three holograms presented and participants were told to step laterally in front of each hologram they were viewing and made judgements about perceived image quality. For each comparison of adjacent channels, if the participant indicated a difference in image quality, they were asked if they perceived the quality had increased or decreased from the previous side (or from the previous hologram in the case of Research Question D). Additionally, respondents were asked if they could identify any anatomical structures (as seen in Figs. 1 and 2) in the holographic images and rate their ability to distinguish detail in the hologram, overall, between the choices of easy, moderate, and difficult.

3 Results

This study presents an evaluation of five static holograms with varying technical features, as explored through four major research questions. Evaluation included the impact changes to polygon density (Research Question A), color (Research Question B), directional resolution (Research Question C), and hogel size (Research Question D) had on perceptions of holographic image quality. Participants completed questionnaires before and after viewing the five holograms. Additionally, the questions answered by participants during hologram viewing provided insight on how the end user's perceptions of image quality are affected by the possible feature changes mentioned above. The results of this study are intended to guide future hologram technology features.

A within-subjects design was implemented, and research questions were assessed through a series of binomial tests. Chi-square tests were also conducted, when appropriate, and described in-text. An initial binomial test was conducted for each evaluation of a perceived image quality change during hologram viewing ("Do you see a difference in image quality: yes or no?"). This was performed to examine whether there was a significant difference in perceived image quality change from one hologram channel (or hologram, in the case of Research Question D) compared to the next. A second binomial test was conducted on responses regarding the direction of change (increase or decrease, if a change in image quality was perceived) to evaluate if one direction of change was perceived significantly more often than the other direction, for each evaluation. The binomial tests were run with the assumption (i.e., "expectation") that the proportions would be equivalent. Therefore, when comparing the two groups, it was expected to be 50-50. A significant result means one group responded significantly above chance.

All analyses were conducted using JASP v. 9 [27] and accompanying Bayes factors (BFs) are provided. Bayes factors provide an estimate of the likelihood of differences, such that BFs less than 1 provide evidence for the null hypothesis (i.e., no difference), while BFs 3 and larger provide anecdotal (1–3), substantial (3–10), or greater evidence (10+) for the alternative hypothesis [28]. When applicable, binomial tests are also reported to evaluate any potential of order effects that may exist from participants being exposed to the highest or lowest level of a factor (i.e., polygon density, color, directional resolution, or hogel size) first.

3.1 Research Question a on Polygon Density: What Is Optimal Perceived Image Quality When *Polygon Density* Is Varied?

To test Research Questions A1 and A2, the influence of polygon density changes on perceived image quality was evaluated within both a monochrome and a color hologram, respectively. As described in the Methodology section, both Holograms 1 and 2 used 1.0 mm hogel sizes and a directional resolution of 512 × 512 rays per hogel. Each hologram had four channels, with each channel containing one of the following four polygon densities: 1.0 M, 1.6 M, 2.3 M, and 3.3 M, where M = million. Since hologram rotation order was approximately counterbalanced (either the lowest to highest or the highest to lowest), responses by hologram channel viewing order are presented first to provide a sense of potential order effects. Next, the results of the binomial tests are presented.

Monochrome (Research Question A1). First, polygon density was considered within a monochrome hologram (Hologram 1). Order effects were evaluated by chi-square tests using the Yates correction due to small sample sizes. There were no significant order effects with respect to hologram channel viewing order (i.e., lowest or highest polygon density viewed first) in the monochrome hologram (all p's > .265; all BF's < 1.21). Binomial tests revealed a significantly larger number of participants than chance perceived differences in image quality between polygon densities 1.1 M and 1.6 M ($p = .050$; $BF = 2.02$), 1.6 M and 2.3 M ($p = .002$; $BF = 38.67$), and 3.3 M and 1.1 M ($p = .020$; $BF = 4.64$; see Table 2). Among the participants who did perceive a difference in image quality viewing the 1.1 M and 1.6 M channels, there was a significant difference in the proportion of participants who saw an "increase" in image quality $\chi^2(1) = 11.83$, $p < .001$, $BF = 1210.65$, especially when viewed from low to high. In this comparison, 100% of the participants reported the 1.6 M channel as yielding higher image quality, see Table 3.

Color (Research Question A2). Polygon density was also evaluated within a color hologram (Hologram 2). Order effects were again evaluated by chi-square tests using the Yates correction due to small sample sizes. There were no significant order effects

Table 2. Proportion of participants *perceiving a difference in image quality* between channels of different polygon densities in a monochrome hologram

Polygon density comparison	Hologram channel order	Proportion of participants	
		No difference	Difference
1.1 M vs. 1.6 M	Lowest first (n = 9)	0.11	0.89
	Highest first (n = 23)	0.39	0.61
	Total (n = 32)	**0.31***	**0.69***
1.6 M vs. 2.3 M	Lowest first (n = 9)	0.33	0.66
	Highest first (n = 23)	0.17	0.83
	Total (n = 32)	**0.22†**	**0.78†**
2.3 M vs. 3.3 M	Lowest first (n = 9)	0.44	0.56
	Highest first (n = 23)	0.48	0.52
	Total (n = 32)	**0.47**	**0.53**
3.3 M vs. 1.1 M	Lowest first (n = 9)	0.11	0.89
	Highest first (n = 23)	0.35	0.65
	Total (n = 32)	**0.39‡**	**0.61‡**

Note. Typographical symbols superscripts denote significant differences in perception of image quality change.

Table 3. Proportion of participants *perceiving an increase or decrease in image quality* between channels of different polygon densities in a monochrome hologram

Polygon density comparison	Hologram channel order	Proportion of participants	
		1.1 M better	1.6 M better
1.1 M vs. 1.6 M**	Lowest first (n = 8)	0	1
	Highest first (n = 14)	0.86	0.14
	Total (n = 22)	**0.55**	**0.45**
		1.6 M better	2.3 M better
1.6 M vs. 2.3 M	Lowest first (n = 6)	0.33	0.67
	Highest first (n = 19)	0.79	0.21
	Total (n = 23)	**0.68**	**0.32**
		2.3 M better	3.3 M better
2.3 M vs. 3.3 M	Lowest first (n = 5)	0.60	0.40
	Highest first (n = 12)	0.67	0.33
	Total (n = 17)	**0.65**	**0.35**
		3.3 M better	1.1 M better
3.3 M vs. 1.1 M	Lowest first (n = 8)	0.50	0.50
	Highest first (n = 15)	0.40	0.60
	Total (n = 23)	**0.43**	**0.57**

**Denotes that an order effect was observed for this comparison.

in the proportion of participants perceiving a difference in image quality in any of the four evaluations between the two viewing orders (all *p*'s > .204; all *BF*'s < 1.42). However, there was a significant difference in the proportion of participants who saw a directional "increase" in image quality $\chi^2(1) = 16.97$, $p < .001$, $BF = 35530$. Specifically, when viewed from low to high, 100% of participants reported the 1.6 M channel to be an increase in image quality over the 1.1 M channel. Conversely, when viewed from high to low, 100% of participants reported the 1.1 M channel to be an increase in image quality over the 1.6 M channel (see Table 5). The remaining three comparisons (e.g., 1.6 M vs. 2.3 M) showed no significant order effects (all *p*'s > 0.080; all *BF*'s < 4.87).

Table 4. Proportion of participants *perceiving a difference in image quality* between channels of different polygon densities in a color hologram

Polygon density comparison	Hologram order	Proportion of participants	
		No difference	Difference
1.1 M vs. 1.6 M	Lowest first (*n* = 18)	0.28	0.72
	Highest first (*n* = 14)	0.43	0.57
	Total (*n* = 32)	**0.34**	**0.66**
1.6 M vs. 2.3 M	Lowest first (*n* = 18)	0.22	0.78
	Highest first (*n* = 14)	0.50	0.50
	Total (*n* = 32)	**0.34**	**0.66**
2.3 M vs. 3.3 M	Lowest first (*n* = 18)	0.28	0.72
	Highest first (*n* = 14)	0.29	0.71
	Total (*n* = 32)	**0.28***	**0.72***
3.3 M vs. 1.1 M	Lowest first (*n* = 18)	0.28	0.72
	Highest first (*n* = 14)	0.21	0.79
	Total (*n* = 32)	**0.25†**	**0.75†**

Note. Typographical symbols superscripts denote significant differences in perception of image quality change.

Binomial tests revealed a significantly larger number of participants than chance perceived differences in image quality between polygon densities of 2.3 M and 3.3 M ($p = .020$; $BF = 4.64$), and between 3.3 M and 1.1 M ($p = .007$; $BF = 12.37$; see Table 4). Within participants who did perceive a difference in image quality, there was a significantly higher proportion of participants who rated the 3.3 M channel (75%) as higher in image quality than the 1.1 M channel ($p = .023$; $BF = 4.99$; see Table 5).

3.2 Research Question B on Color: Do Users Prefer Color or Monochrome Presentation of Holograms?

As detailed in the methodology, Hologram 3 contained two opposing channels showing the same image: one in color and one in monochrome. This hologram used 1.1 M polygon density, 1.0 mm hogel size, and a directional resolution of 512 × 512 rays per

Table 5. Proportion of participants *Perceiving an Increase or Decrease in Image Quality* between channels of different polygon densities in a color hologram

Polygon density comparison	Hologram order	Proportion of participants	
		1.1 M better	1.6 M better
1.1 M vs. 1.6 M**	Lowest First (*n* = 13)	0	1
	Highest First (*n* = 8)	1	0
	Total (*n* = 21)	**0.38**	**0.62**
		1.6 M better	2.3 M better
1.6 M vs. 2.3 M	Lowest First (*n* = 14)	0.21	0.79
	Highest First (*n* = 7)	0.71	0.29
	Total (*n* = 21)	**0.38**	**0.62**
		2.3 M better	3.3 M better
2.3 M vs. 3.3 M	Lowest First (*n* = 13)	0.31	0.69
	Highest First (*n* = 10)	0.30	0.70
	Total (*n* = 23)	**0.30**	**0.70**
		3.3 M better	1.1 M better
3.3 M vs. 1.1 M	Lowest First (*n* = 13)	0.62	0.38
	Highest First (*n* = 11)	0.91	0.09
	Total (*n* = 24)	**0.75‡**	**0.25‡**

Note. Typographical symbols superscripts denote significant differences in perception of image quality change.

**Denotes that an order effect was observed for this comparison.

hogel. Participants responded by stating whether they saw a difference in image quality between the two channels, the direction of the difference (increase or decrease), and any preference for one channel or the other. These responses were analyzed in the same way as the earlier analyses.

An analysis of order effects revealed that, regardless of whether the monochrome or color channel was viewed first, no order effects were present regarding a difference in perceived image quality ($p = 1.000$; $BF = 0.30$), direction of change ($p = .445$; $BF = 0.90$), or channel preference ($p = 1.000$; $BF = 0.41$).

Difference in Perceived Image Quality. Significantly more participants than chance (90.6%) reported seeing a difference in image quality between the color and monochrome channels, $p < .001$, $BF = 26240.03$.

Direction of Change. While most participants saw a difference in image quality between the two channels, there was no significant difference between the proportion of participants who saw either the color or monochrome channel as being of higher image quality than the other, $p = .711$, $BF = 0.26$. Thus, there was no consensus as to whether the color or monochrome channel was perceived to have higher image quality.

Channel Preference. When asked to provide the channel (i.e., color or monochrome) they preferred, more participants preferred the color hologram ($n = 19$) to the monochrome hologram (n = 11); however, this difference was not statistically significant (p = .200).

3.3 Research Question C on Directional Resolution: What Is Optimal Perceived Image Quality When Directional Resolution Is Varied?

Directional resolution was varied on two different four-channel holograms: one with a hogel size of 0.50 mm (Research Question C1; Hologram 4) and one with a hogel size of 0.71 mm (Research Question C2; Hologram 5). Both holograms were monochrome and used a 1.1 M polygon density. The four channels of directional resolution include 32 × 32, 64 × 64, 128 × 128, and 256 × 256 rays per hogel. Separate analyses were conducted for each set of comparisons within a hologram of a set hogel size.

Hogel Size 0.50 mm (Research Question C1). A set of analyses were conducted for comparisons of directional resolution on the hologram with hogel size 0.50 mm (Hologram 4). There were no order effects for a perceived difference in image quality dependent on which channel was viewed first (all p's > .591; all BF's < 0.55). For direction of change (i.e., an increase or decrease), a chi-square test revealed that there was a significant order effect for the comparison of 128 × 128 versus 256 × 256, $\chi^2(1) = 3.86$, p = .049, BF = 7.36, such that participants who viewed the highest resolution first were more likely to see 128 × 128 as an improvement over 256 × 256, whereas the opposite was more likely (i.e., 256 × 256 rays per hogel was seen as an increase in image quality over 128 × 128 rays per hogel) for participants who viewed the channels from lowest to highest resolution. No other order effects for direction of change were found (all p's > 0.479; all BF's < 0.95) for the other three comparisons (e.g., 32 × 32 vs. 64 × 64 rays per hogel).

There were significantly more participants who saw a difference between each pair of channels for all four comparisons than chance (all p's < .021; all BF's > 4.63; see Table 6). However, there was only a significant effect for the direction of change for the 256 × 256 versus 32 × 32 rays per hogel directional resolution comparison, with more participants responding 256 × 256 was better (n = 21) than 32 × 32 (n = 5), p = .002, BF = 37.79 (see Table 7). The other comparisons were not significantly different in terms of direction of change (all p's > 0.211; all BF's < 0.72), suggesting that there was no common perception of which resolution was higher in terms of image quality for intermediate steps in resolution.

Hogel Size 0.71 mm (Research Question C2). A corresponding set of analyses were conducted for comparisons of directional resolution on the hologram with hogel size 0.71 mm (Hologram 5). There was a significant order effect, with respect to hologram channel viewing order for the 32 × 32 vs 64 × 64 rays per hogel comparison, $\chi^2(1) = 10.24$, p = .001, BF = 380.09. In this case, significantly more people than chance perceived a difference in image quality between directional resolutions of 32 × 32 and 64 × 64 with a higher proportion of participants (n = 15/15) seeing a difference in image quality between the two resolutions when viewed from lowest to highest than when viewed highest to lowest (n = 7/17). There were no other significant

Table 6. Proportion of participants *perceiving a difference in image quality* between channels of different directional resolutions in a 0.50 mm hogel size hologram

Directional resolution comparison	Hologram order	Proportion of participants	
		No difference	Difference
32 × 32 vs. 64 × 64	Lowest first (*n* = 11)	0.36	0.64
	Highest first (*n* = 21)	0.24	0.76
	Total (*n* = 32)	**0.28***	**0.72***
64 × 64 vs. 128 × 128	Lowest first (*n* = 11)	0.18	0.82
	Highest first (*n* = 21)	0.33	0.67
	Total (*n* = 32)	**0.28†**	**0.72†**
128 × 128 vs. 256 × 256	Lowest first (*n* = 11)	0.36	0.64
	Highest first (*n* = 21)	0.24	0.76
	Total (*n* = 32)	**0.28‡**	**0.72‡**
256 × 256 vs. 32 × 32	Lowest first (*n* = 11)	0.09	0.91
	Highest first (*n* = 21)	0.24	0.76
	Total (*n* = 32)	**0.19§**	**0.81§**

Note. Typographical symbols superscripts denote significant differences in perception of image quality change.

order effects for the other three differences in image quality comparisons (e.g., 64 × 64 vs. 128 × 128; all *p*'s > .305; all *BF*'s < 0.93). There was also a significant order effect for the 32 × 32 vs 64 × 64 direction of change comparison, $\chi^2(1) = 4.99$, $p = .026$, $BF = 13.90$, with considerably more participants who viewed the channels in order from lowest to highest seeing the 64 × 64 rays per hogel image as higher quality than the 32 × 32 ($n = 13/15$), compared to participants who viewed the channels from highest to lowest ($n = 2/7$). No other significant order effects for direction of change judgments were found (all *p*'s > .477; all *BF*'s < 0.78).

There were significant differences in the proportion of participants who saw a difference in image quality between all sets of comparisons (all *p*'s < .051; all *BF*'s > 2.01), with most people noticing a difference in image quality in each case (see Table 8).

Specifically, there were significant differences in the proportion of participants who saw the 128x128 channel as higher image quality than the 64 × 64 channel, $p = .023$, $BF = 4.99$, and between the 256 × 256 and 32 × 32 channels, $p = .002$, $BF = 59.38$, with a higher proportion of responses indicating an increase in image quality for the higher resolution channel in each case (see Table 9).

3.4 Research Question D on Hogel Size: What Is Optimal Perceived Image Quality When *Hogel Size* Is Varied?

As detailed in the Methodology, the effect of hogel size on perceived image quality was evaluated by comparing three channels of varying hogel sizes across three separate

Table 7. Proportion of participants *perceiving an increase or decrease in image quality* between channels of different directional resolutions in a 0.50 mm hogel size hologram

Directional resolution comparison	Hologram order	Proportion of participants	
		32 × 32 better	64 × 64 better
32 × 32 vs. 64 × 64	Lowest first (n = 7)	0.43	0.57
	Highest first (n = 16)	0.69	0.31
	Total (n = 23)	**0.61**	**0.39**
		64 × 64 better	128 × 128 better
64 × 64 vs. 128 × 128	Lowest first (n = 9)	0.33	0.67
	Highest first (n = 14)	0.36	0.64
	Total (n = 23)	**0.35**	**0.65**
		128 × 128 better	256 × 256 better
128 × 128 vs. 256 × 256**	Lowest first (n = 7)	0.71	0.29
	Highest first (n = 16)	0.19	0.81
	Total (n = 23)	**0.35**	**0.65**
		256 × 256 better	32 × 32 better
256 × 256 vs. 32 × 32	Lowest first (n = 10)	0.80	0.20
	Highest first (n = 16)	0.81	0.19
	Total (n = 26)	**0.81‖**	**0.19‖**

Note. Typographical symbols superscripts denote significant differences in perception of image quality change.

**Denotes that an order effect was observed for this comparison.

holograms all monochrome and 1.1 M polygon density (only one channel per hologram was shown). Hogel size ranged from 0.50 mm (Hologram 4), to 0.71 mm (Hologram 5), to 1.0 mm (Hologram 1). Due to hologram processing limitations, directional resolution also varied, with 512 × 512 rays per hogel only on the 1.0 mm hogel size hologram, and 256 × 256 rays per hogel on the 0.50 mm and 0.71 mm holograms. For all three comparisons (0.50 mm vs. 0.71 mm, 0.71 mm vs 1.0 mm, and 0.5 mm vs 1.0 mm), most participants perceived a difference in image quality (all p's < .001; all BF's > 26240.00). There was no significant difference in the proportion of participants who saw either 1.0 mm or 0.5 mm holograms as higher quality than the other, $p = .856$, $BF = 0.24$. However, a majority of participants perceived the 0.71 mm hologram as higher quality than the 0.50 mm hologram ($p < .001$; $BF = 753.47$) as well as the 0.71 mm hologram as higher quality than the 1.0 mm hologram ($p = .050$; $BF = 2.02$).

Table 8. Proportion of participants *perceiving a difference in image quality* between channels of different directional resolutions in a 0.71 mm hogel size hologram

Directional resolution comparison	Hologram order	Proportion of participants	
		No difference	Difference
32 × 32 vs. 64 × 64**	Lowest First (*n* = 15)	0.00	1.00
	Highest First (n = 17)	0.59	0.41
	Total (*n* = 32)	**0.31***	**0.69***
64 × 64 vs. 128 × 128	Lowest First (*n* = 15)	0.13	0.87
	Highest First (*n* = 27)	0.35	0.65
	Total (*n* = 32)	**0.25†**	**0.75†**
128 × 128 vs. 256 × 256	Lowest First (*n* = 15)	0.20	0.80
	Highest First (*n* = 17)	0.18	0.82
	Total (*n* = 32)	**0.19‡**	**0.81‡**
256 × 256 vs. 32 × 32	Lowest First (*n* = 15)	0.20	0.80
	Highest First (*n* = 17)	0.12	0.88
	Total (*n* = 32)	**0.16§**	**0.84§**

Note. Typographical symbols superscripts denote significant differences in perception of image quality change.

**Denotes that an order effect was observe for this comparison.

4 Discussion

Key takeaways from the results are included, along with a summary of technical parameters (Table 10) concluding the following trends:

1. When evaluating a variety of polygon densities (1.1 M to 3.3 M) 3.3 M polygon density was rated as significantly higher image quality than the lowest extreme polygon density (1.1 M) for color holograms, with no clear direction of polygon density impact within monochrome holograms.
2. Color presentations did not show higher perceptions of image quality over monochrome presentations, but participants did indicate directly that they preferred color over monochrome holographic images.
3. When addressing direction resolution, 256 × 256 rays per hogel directional resolution with either 0.71 mm or 0.50 mm hogel size was noted as being of significantly higher image quality than directional resolutions of 32 × 32 rays per hogel. Within the 0.71 mm hogel hologram, 128 × 128 rays per hogel was rated as significantly higher in image quality than 64 × 64, with a similar trend observed for the 0.50 mm hogel hologram.
4. When assessing hogel size, a hogel size of 0.71 mm was rated as being of significantly higher quality over hogel sizes of 0.50 mm and 1.0 mm. However, hogel size may interact with the directional resolution.

It should be noted that each technical parameter comes with factors such as cost, performance expectation, and user preference. This study is about placing the correct

Table 9. Proportion of participants *perceiving an increase or decrease in image quality* between channels of different directional resolutions in a 0.71 mm hogel size hologram

Directional resolution comparison	Hologram Order	Proportion of participants	
		32 × 32 better	64 × 64 better
32 × 32 vs. 64 × 64**	Lowest first (*n* = 15)	0.13	0.87
	Highest first (*n* = 7)	0.71	0.29
	Total (*n* = 22)	**0.32**	**0.68**
		64 × 64 better	128 × 128 better
64 × 64 vs. 128 × 128	Lowest first (*n* = 13)	0.09	0.91
	Highest first (*n* = 11)	0.36	0.64
	Total (*n* = 24)	**0.25‖**	**0.75‖**
		128 × 128 better	256 × 256 better
128 × 128 vs. 256 × 256	Lowest first (*n* = 12)	0.42	0.58
	Highest first (*n* = 14)	0.21	0.79
	Total (*n* = 26)	**0.31**	**0.69**
		256 × 256 better	32 × 32 better
256 × 256 vs. 32 × 32	Lowest first (*n* = 12)	0.83	0.17
	Highest first (*n* = 15)	0.80	0.20
	Total (*n* = 27)	**0.82¶**	**0.18¶**

Note. Typographical symbols superscripts denote significant differences in perception of image quality change.

**Denotes that an order effect was observed for this comparison

Table 10. Summary of suggested technical parameters

Polygon density (1.1 M, 1.6 M, 2.3 M, 3.3 M)	Color vs. Monochrome	Directional resolution (32 × 32, 64 × 64, 128 × 128, 256 × 256, 512 × 512)	Hogel size (0.5 mm, 0.71 mm, 1.0 mm)
3.3 M	Color preferred, but monochrome may be sufficient	128 × 128, or 256 × 256 (512 × 512 possible with color holograms)	0.71 mm

usage of technology in combination with other factors. Additionally, some of these factors may interact with each other in ways that negatively affect user preferences. Therefore, the suggestions in Table 10 are subject to change based on the interaction effects and user population for future studies.

5 Limitations and Challenges

A limitation of the study is the relatively small sample size. With an increased sample size, counterbalancing would have been more equal across hologram viewing orders. Additionally, the researchers were limited on the amount of time that could be dedicated for each data collection session (i.e., 15 min per participant) which prevented more in-depth questions to be explored with participants and further comparisons between channels (e.g., 64 × 64 vs 256 × 256 rays per hogel). Finally, the study did not account for individual differences in acuity and quality of vision in participants, including differences in depth perception. These may have accounted for why some participants saw increases in image quality when others saw decreases for the same comparisons.

Many of the comparisons, specifically for hogel size and resolution changes, were evaluated using monochrome holograms. Future studies could evaluate if study results generalized to color holograms.

The comparison between the three hogel sizes had a difference in the directional resolution. Due to hologram processing limitations, directional resolution varied, with 512 × 512 rays per hogel only on the 1.0 mm hogel size hologram, and 256 × 256 rays per hogel on the 0.50 mm and 0.71 mm holograms. This created a challenge to analyze the results equally across the hogel variations. We were able to extrapolate outcomes from other hologram comparisons but cannot confirm the precision of the results. While it is not possible to print a single hologram with channels varying in hogel size (thereby keeping directional resolution constant within just one hologram), additional holograms with equal directional resolutions would have been preferred.

Finally, the holograms were produced by Zebra Imaging Inc., which is no longer in business. The first set of holograms produced by Zebra Imaging Inc. were substandard to our initial requirements. A second set of prints was ordered to correct the issues between the directional resolution channels. Future studies will need to employ the use of holograms from a different company since it is unclear if holograms with the same parameters printed by other companies would be different.

6 Conclusions and Future Work

A systematic approach is used to determine the ability of users to detect differences in static holograms based on initial reactions to viewing and comparing several 3D images. These evaluations are pertinent to the design of future autostereoscopic static and dynamic hologram displays. The methodology described herein provides an easy-to-execute approach to quickly ascertain the image characteristics users find most important and inform the development community of those characteristics. Theoretical implications will contribute to understanding the limitations of the human visual system to detect differences in new forms of visual media. Applications of the results will help to inform guidelines for development of the next generation of holographic displays and how tradeoffs among various display factors affect usability of the holograms.

Future work should continue to address the interaction of technical factors such as the combination of polygon density of 3.3 M, color versus monochrome, direction resolution of 128 × 128 versus 256 × 256 versus 512 × 512 rays per hogel (for color), and hogels of 0.50 mm versus 0.71 mm, as well as the implications on user preference and cost. Furthermore, a comparison of these factors across different fields of study or domains will allow a more comprehensive and generalizable evaluation of the effect of varying technical factors.

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