PERCEPTUAL ALLOWANCES OF ANAMORPHIC INTERACTION CUES IN SPATIAL AUGMENTED REALITY

by

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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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STATEMENT OF CONTRIBUTIONS

Cheryl Lao is the main author of all chapters which were written under the supervision of Daniel Vogel and Craig Kaplan.

ABSTRACT

Spatial Augmented Reality (SAR) enables the projection of digital content directly on the physical environment without the use of wearable displays. In spaces where viewers are encouraged to explore different locations, perspective anamorphosis techniques can be used to guide them through the physical environment. We propose a design space for describing anamorphic SAR interaction cues based on the continuity of the image when projected onto the environment, and the need for movement in order to understand the cue. We conduct two perceptual studies using virtual reality (VR) to simulate a SAR environment, to explore how well viewers identify ocular points on various surface geometries. We also present a system approach and experiment design for a future study to compare participants' ability to find the ocular point in a VR setting versus a SAR setting. This work can enable designers to create anamorphic content that takes advantage of the geometry in their physical space.

ACKNOWLEDGMENTS

I want to say a huge THANK YOU to my advisors Dan Vogel and Craig Kaplan for always being so supportive throughout my degree! I don't know many other advisors who would let their students take 3 internships during a master's degree but Dan and Craig aren't your typical advisors. I really couldn't have done it without their constant support and shared interest in arts and crafts.

Those internships led to research that does not show up in my thesis, but I'm so glad I was able to have a breadth of experiences during my degree. I want to thank my mentors across all my internships: Paul Asente and Jose Echevarria at Adobe, Victor Zordan and Morgan McGuire at Roblox, and Thomas White at Meta for introducing me to all the exciting work that is happening in industry research labs.

While I wasn't away on internships, I was in Waterloo and dodging geese and going to the Clay and Glass Gallery. I'm going to miss the ~~St Paul's~~ United College Pals: Nikhita, Iara, and Matthew and our Ring Road walks! I'm also going to miss lunchtimes at St Jerome's with the lab crew.

Finally, I would like to thank Prof. Ville Mäkelä and Prof. Toshiya Hachisuka for reading my thesis and providing insightful feedback.

DEDICATION

This thesis is dedicated to my parents and my sister, who always help me see things from a different perspective.

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The author preparing to write her future master's thesis, circa 2001

INTRODUCTION

Anamorphosis is a technique for generating images that can only be understood from a specific point of view [9]. *Perspective Anamorphosis*, which is the focus of this work, relies on a linear transformation of the ideal viewing point of a piece of content [36]. The *anamorph*, or the piece of content that has been transformed, will appear distorted and possibly unrecognizable from viewpoints other than the ideal viewing location, also known as the *ocular point* [9]. *Catoptric*, or *mirror anamorphosis*, is another form of anamorphosis where curved mirrors are used to deform the image. In this work, we do not explore catoptric anamorphosis and refer to perspective anamorphosis simply as "anamorphosis".

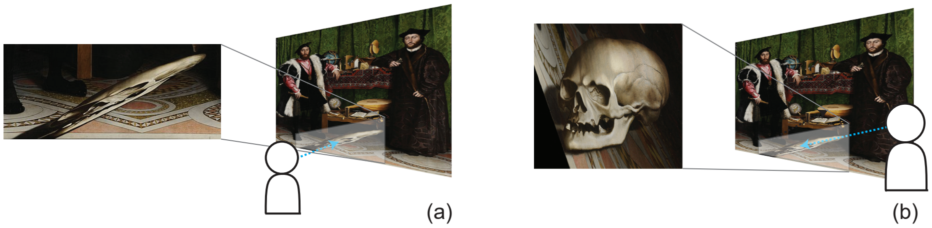


Figure 1.1: (a) The viewer facing the painting at a 90° angle (b) The viewer at the ocular point for the skull

An anamorph can guide a viewer to move to the ocular point in the space and serve as an interaction cue. The earliest known anamorphic drawing is Leonardo da Vinci's *Anamorphoses of a child's head, and an eye* which needs to be viewed from an oblique angle to be understood [41]. Another famous example of anamorphosis can be found in the painting *The Ambassadors* by Hans Holbein the Younger [44], where the viewer needs to move to a specific location relative to the painting in order to view a skull at the correct angle. While there is no explicit call for the viewer to move, the perspective distortion implies an optimal viewing angle and position for the viewer (Figure 1.1). Another example of using anamorphosis to encourage users to move can be found in the console game *Viewfinder* [39] which uses perspective matching as a game mechanism.

Spatial Augmented Reality (SAR), which is augmented reality facilitated by physical projectors, can be used to project dynamic content on existing geometry without the use of head-mounted displays or physical changes to the environment. A museum or gallery curator could intentionally distort a piece of projected content so that it is only understandable when a visitor is standing at a predetermined location in the space. This can serve as an interaction cue in a SAR experience. For example, if an exhibit has a specific vantage point where certain details of a sculpture are visible, a designer may wish to guide viewers to that point and display related information about the sculptural details that can only be read from that viewpoint. SAR enables dynamic updates of digital content in a physical space, which could be used to create viewpoint-specific renderings of anamorphic images or changes in the projected content depending on viewer locations. When creating SAR experiences, designers need to be mindful of the potential viewing angles of the content and the relationship between the projected content and the scene geometry. For example, if a designer projects an image onto a wall in a museum with texture from fossils embedded inside, the image will be distorted by the geometry of the fossils that protrude from the surface and the viewing angle. While perspective distortions are relatively simple to anticipate on flat surfaces, many SAR environments are made of complex geometry that make it difficult for designers to anticipate geometric distortions.

While there is existing work on interaction cues in augmented reality [10], and user interfaces in immersive cultural heritage settings [5], there is currently no work on anamorphic interaction cues where the geometry of the space and the viewing angle has a direct effect on the content being presented to the user. There is a need for guidelines that support designers in effectively integrating anamorphic techniques into the design of spatial experiences.

In this work, we focus on how perspective anamorphosis can be used to create interaction cues in 3D environments. Through a series of user studies that explore different angles and projection surfaces, we found that viewers are able to find the ocular point of a piece of projected content more accurately on surfaces with more complex geometry. This suggests that more complex geometry actually aids viewers in finding the ocular point, at the expense of incomprehensibility at a wider range of angles.

We propose a design space for describing anamorphic SAR content based on the continuity of the image when projected onto the environment, and the need for movement in order to understand the cue. We conduct two perceptual studies using Virtual Reality (VR) to simulate a SAR environment for logistical reasons and to enable a high degree of control over conditions. These enable us to explore how well viewers identify ocular points for viewing anamorphic projections on various surface geometries. We also present a system approach and experiment design for a future study to compare participants' ability to find the ocular point in a VR setting versus a SAR setting. The results from this experiment could reveal the potential for VR to serve as a valid prototyping and experimental tool for evaluating SAR experiences. The findings in this work can help guide designers of immersive experiences when creating anamorphic interaction cues.

2

BACKGROUND

In this chapter, we discuss past work relating to perspective anamorphosis, SAR, and how techniques from those areas can be applied to other immersive 3D technologies.

2.1 PERSPECTIVE ANAMORPHOSIS

Perspective anamorphosis is a technique that involves creating distorted content that can only be viewed correctly from a particular viewing location. In this work, we focus on distortions that occur as a result of projection angle and projection surface, but anamorphosis can come as the result of intentionally manipulating a 3D shape as well [36]. In the context of perspective anamorphosis using a projector in a space, the ocular point of a projected image should be the origin point of the projector that is displaying it. If the projector intrinsics and extrinsics are known, the source of the projected image can be manipulated to a virtual projector location that does not necessarily line up with the location of a physical projector. In this work, when we refer to the image originating from a certain projector location, we are referring to a *virtual* projector location which does not necessarily coincide with the location of a projector in physical space.

2.1.1 *The Psychology behind Anamorphosis*

Anamorphosis is a *metaphysical* experience where a viewer is able to perceive multiple versions of what they see, but does not attempt to reconcile them [25]. While the viewer can see the depth of the anamorphic image using their stereo vision, they can also interpret what they see as a flat image. Kennedy and Pirenne [21] called this the integration between "incompatible things: depth and flatnes". There is a certain degree of robustness to a perspective where a viewer is able to compensate for the distortion of an image due to movement when they perceive the image [25]. The visual interpretation of the anamorphic image dominates our perception, suppressing the interpretation of the environment it is in. An awareness of the surface is key to this compensation as the geometry of the surface changes the image that can be perceived by the viewer [15]. However, a viewer can be aware of the surface and not perform the compensation, which is how anamorphic images can be perceived [40]. Prior work has focused on measuring perception of images on flat planes at various angles and distances [33], but there is limited work on how this can be used to purposefully limit viewing angles on different geometry.

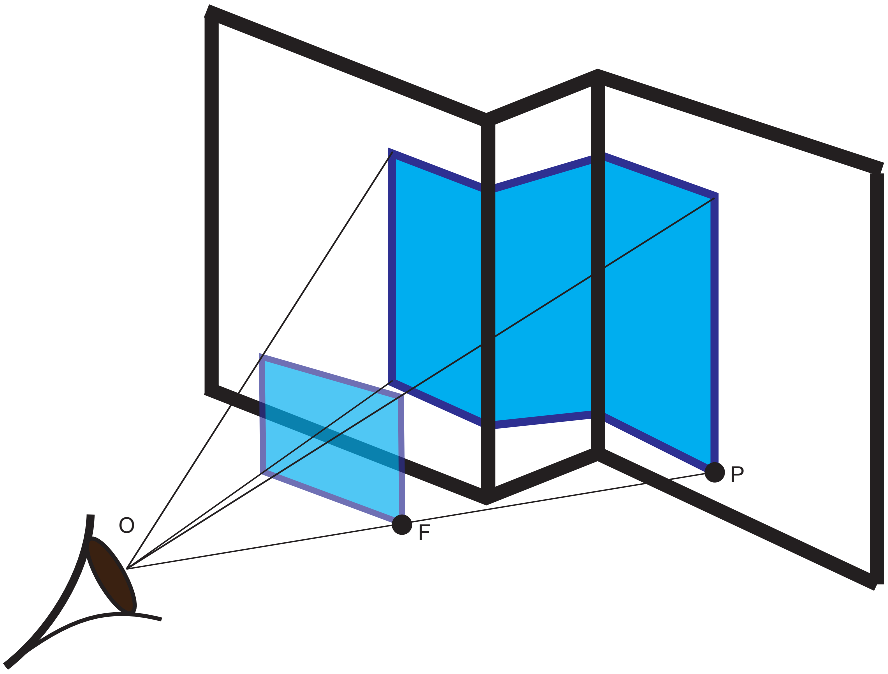


Figure 2.1: Point F represents a point on the view frustum and point P represents a point on the projected image. Point O represents the ocular point.

The perception of an image can depend on the content that is depicted. For example, human faces show high tolerance for distortion [11]. Perkins [33] focused on identifying whether line drawings of boxes represented rectangular or skewed boxes at 26 and 41 degrees from the image plane. They found that participants had a strong ability to compensate for oblique viewing angles and a small tendency to make their decision according to the foreshortened image.

Depth perception can depend on binocular and monocular cues. Monocular depth cues such as convergence, texture gradients, and familiar size combined with binocular cues such as accommodation help a viewer perceive depth and general object constancy in an image [34]. Gestalt psychology presents the idea that visual perception is guided by principles that cannot be predicted from modelling the scene with Euclidean geometry [21]. Gestalt psychology also introduces the idea of *generic* and *specific* viewpoints. Generic viewpoints are viewpoints where the visible elements and their spatial relationships are mostly maintained despite small changes in viewpoint, while specific viewpoints are viewpoints with spatial alignments that are easily broken with changes in perspective [1]. A designer would normally avoid the specific viewpoint to maximize information for the viewer, but in anamorphosis, the specific viewpoint is the ocular point where the anamorphic effect is visible. For example, in Figure 1.1b, the viewer is at a viewpoint where the anamorphic effect can be seen.

2.1.2 *Geometric Representations*

Perception is reliant on psychophysics, so there is no purely mathematical way to determine exactly how an anamorphic image will be perceived by a viewer. However, concepts from projective geometry can help us model the effects of changing the ocular point on the projected image. The *Principle of Radial Occlusion* empirically describes the relationship between a point and its *anamorphic equivalents* [2]. Two points look the same to an observer at point O if they are *collinear*, or lie on the same ray with an origin at O. As shown in Figure 2.1, for an observer at point O, the points on the image plane P can be seen as a flat image on the view frustum F because all of the points on plane P have an anamorphic equivalent on view frustum F. Modelling the observer's view simply as one point is an abstraction that ignores stereo vision, but this is useful for geometric representations of anamorphosis where we want to represent the viewer's location as one point.

Sanchez et al. [36] describe how anamorphic free-form deformations are affine transformations of points along the radial direction from the ocular point to a point on the projected image. This could be used to deform a projection on a surface of the geometry or the surface itself. *Homeomorphism* is a correspondence between two geometries where there is a one-to-one mapping that is continuous in both directions [12]. An image projected onto surfaces with no discontinuities in the generic view would be homeomorphic with the original image because it is being stretched by the projection surface but remain as one continuous image.

2.2 SPATIAL AUGMENTED REALITY (SAR)

View-dependent rendering in immersive environments has been explored in other work. However, no past work has focused on creating guidelines for SAR designers to purposefully take advantage of anamorphosis to encourage different behaviours in viewers.

2.2.1 *SAR Examples*

SAR differs from many other immersive technologies such as VR because it does not require viewers to wear or carry any equipment. CAVE systems are another example of a projector-based immersive technology when content is projected on to real-world surfaces and the viewer wears special glasses for viewing the projected 3D images [8]. However, CAVE systems are not "museum hardy" because the screens, trackers and glasses might be too fragile for use by the general public in an ongoing exhibit [8]. This is in contrast to SAR systems which could be set up in an environment with many visitors. Cruz-Neira et al. [7] outlined the eight depth cues that are available in the real world. These cues are: Occlusion, Perspective Projection, Binocular Disparity, Motion Parallax, Convergence, Accommodation, Atmospheric Effects, and

Lighting and Shadows. SAR can provide all of these depth cues except accommodation.

In past work by Schmidt et al. [38] on SAR usage in exhibits, projections on the floor guided viewers through an exhibit space and gave indications for the ideal viewpoints of an experience. These are explicit interaction cues that require tracking the user's location throughout the experience. Prior work by Benko et al. [4] explores how dyadic projections can be used to display perspective-correct content to two viewers facing one another. This system requires head tracking for both participants so that the projected content can be changed for each of them.

Other researchers have developed systems based on mobile SAR projectors that follow the viewer throughout the space [26, 43]. While this is guaranteed to produce perspective-correct images for the viewer, it is difficult to create large-scale shared experiences with multiple users and the display surface is limited to the reach of the projector. SAR with stationary projectors has been used to create experiences on a much larger scale, such as in projections onto buildings prior to construction [42]. Regardless of scale or degree of user position tracking, SAR offers a unique way to fully integrate digital content into the physical space.

2.2.2 *Design Considerations*

While SAR enables a users to interact with digital content in a physical space, it also has three limitations: (1) SAR content needs to be projected onto a physical surface and cannot create mid-air displays; (2) Projector brightness can limit its use in outdoor spaces; and (3) A geometric model of the environment needs to be known ahead of time or calculated dynamically [28].

Ens et al. [13] proposed the metaphor of *ethereal planes*, where 2D virtual windows are situated in 3D physical space. In SAR, the content is intrinsically linked to the physical space on which it is projected and virtual content could be seen as an ethereal window into the digital world. The perspective at which a viewer sees a 3D object can have an important effect on perception. In work by Sanchez et al. [37], Escher-like images are rendered using deformed 3D models, guided by perspective anamorphosis. Digital content projected onto a surface and the surface itself can both be anamorphic.

While SAR has physical limitations that are not present in augmented reality displays that can display mid-air content, the limitations can inspire unique experiences that integrate the physical geometry of a space into the experience.

2.3 SPATIAL USER INTERFACES

Spatial user interfaces allow a user to interact with digital content in 3D space. This is in contrast to traditional 2D user interfaces which limit interactions to a plane or discrete interactions with lower levels of immersion. A SAR user interface must be projected onto existing geometry in a given space, which makes it inherently spatial.

2.3.1 *Spatiality and Diegesis*

Fagerholt and Lorentzon [14] proposed a spatiality-diegesis continuum that can be used to describe the user interfaces in 3D game environments. The continuum spanned the axes of *diegesis* (diegetic/non-diegetic) and *spatiality* (spatial/non-spatial). We extend the ideas in their work to describe other immersive experiences with a narrative component in chapter 3.

DIEGETIC/NON-DIEGETIC Diegetic user interfaces are interfaces that are part of the in-game environment and can be perceived by the characters in the game. The term *diegesis* was first introduced by Aristotle and Plato to describe a narrative technique where a narrator tells the story [24]. In the context of immersive experiences, this means that a piece of user interface is part of the virtual world and can be perceived by the characters in the experience. For example, a signpost in a game that other characters in the game can read and interact with as well. In contrast, *non-diegetic* interfaces are not part of the narrative and are only perceived by the players of a game, for example, in the form of a heads-up display[20].

SPATIAL/NON-SPATIAL *Spatial* user interfaces are user interface elements that are in the 3D environment of the game, such as signposts in a open world game. *Non-spatial* user interfaces are not part of the 3D environment and may appear as pop-up indicators in the user's view. Both interface types can be diegetic or non-diegetic [14].

The anamorphic scenes that we examine represent a subset of spatial interfaces because of their reliance on the geometry of the projection surfaces. An anamorphic interaction cue implemented using SAR could be non-diegetic and be used solely as a guidance technique, or it could be diegetic and serve as part of the narrative of the experience.

2.3.2 *Across the Reality-Virtuality Continuum*

The reality-virtuality continuum describes the continuum between reality and complete virtual experiences [29]. SAR is closer to reality than VR, but spatial interfaces can exist in technologies across the continuum.

Dillman et al. [10] proposed a framework for classifying augmented reality interaction cues in video games. The framework included dimensions such as markedness, trigger, and purpose. *Markedness* denotes how much the cue stands out from its surroundings in the game envionment, *trigger* is the type of interaction that triggers the cue, and *purpose* is the reason that the cue exists in the game. These dimensions can similarly be applied to classify SAR interaction cues. Researchers have compared types of interfaces on the diegesis-spatiality continuum and found that diegetic and spatial interfaces were more immersive than other types of interfaces in VR first-person games[35].

All SAR content needs to be projected onto existing geometry. While this constraint does not exist for user interfaces presented in AR or VR, designers can still create anamorphic interaction cues in these environments. In fact, designers could embed anamorphic interaction cues that rely on the alignment of 3D objects to a specific viewpoint using VR as a prototyping tool for a SAR experience. Past work has explored using a VR authoring system to create multi-user AR experiences [6]. SAR interactions can also be recreated in VR scenes where the user is completely immersed in a virtual recreation of a physical space. For example, Mäkelä et al. [27] explored how public display research could be conducted in VR environments that simulate a physical space in real life. They found that using VR as a simulation for real-world experiments has some experimental validity and discussed how VR may enable higher levels of control over the environment at the cost of external validity. We further explore how researchers might compare performance between VR and SAR versions of the same task in chapter 7.

3

ANAMORPHIC INTERACTION CUE DESIGN SPACE

Anamorphic interaction cues are cues where anamorphosis is intentionally used in the design. The cues can be used to encourage users to move through an environment without explicitly prompting them to do so.

Within the diegesis-spatiality continuum [14], anamorphic interaction cues can be considered spatial interfaces. The intentional movement that can be encouraged by the designer of the interface can also serve as a diegetic cue that moves a narrative along. For example, a designer may wish to guide a museum visitor through a sequence of viewpoints around a dinosaur model to communicate how it evolved. We expand on the use of anamorphosis as a narrative tool in section 3.2. Interaction cues that are part of the narrative of the experience can be a part of hands-off interactive storytelling where the user maintains agency while being immersed in the experience [32].

We propose a design space for classifying anamorphic interaction cues using two dimensions: *continuity* and *the need for observer movement*. The location of the observer in relation to the ideal viewing angle of the user interface can affect the classification of a piece of anamorphic content in the design space. Smaller projection angles tend to create more distortion as a result of foreshortening. Unlike content presented on heads-up displays, the angle and position of the viewer relative to the content being displayed can drastically change the observer's ability to understand the content. Perceptual allowances must be considered when designing anamorphic interfaces. In the following chapters, we explore how viewing angle and the geometry of the projection surface affect observer understanding of stimuli.

Anamorphic interaction cues can be used to guide users through a physical space by applying perspective distortions that encourage a viewer to move to correct them. For example, an observer might see a distorted image where the ocular point appears to the left of their current location and feel encouraged to move to see the version of that image that is not distorted by moving towards the ocular point (Figure 3.1a). These interaction cues offer a way to nudge users towards an intended spatial experience without explicitly asking them to go to specific areas or follow paths.

3.1 DESIGN SPACE

Anamorphic interaction cues are implicit spatial cues that encourage observers to move through a space in order to understand the content. Our design space is a way to classify a piece of anamorphic content based on the level of continuity of the image when projected onto the projection surface and how much movement the cue requires an observer to go through in order to understand it (Figure 3.2).

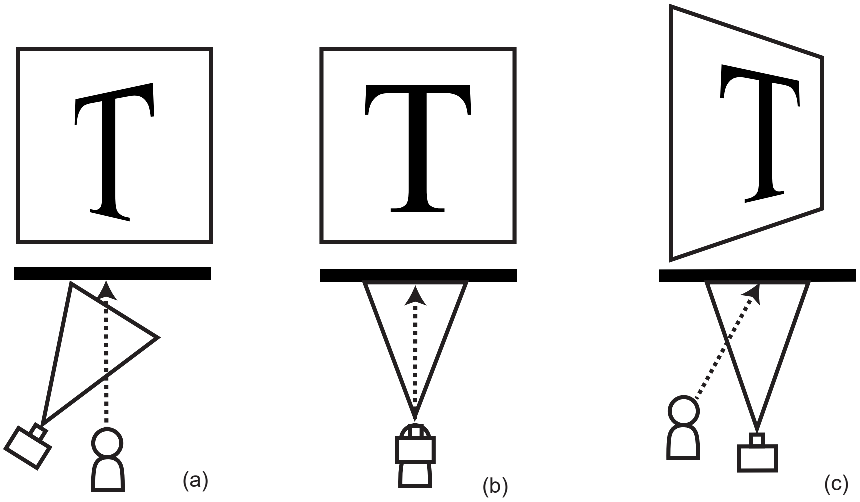


Figure 3.1: Changing projector placement versus changing observer placement. The top row of images with the letter T are the view of the observer. The bottom row of images are the corresponding top-down views of the scene: (a) The projector is at an oblique angle while the observer is facing the projection surface (b) The projector and the observer are both facing the plane at a 90° angle (c) The observer is at an oblique angle relative to the surface and the projector is at a 90° angle to the surface.

CONTINUITY The continuity axis ranges from *continuous* to *discontinuous* for the continuity of the projected image. We define *continuous* stimuli as images where the projection onto the surface is homeomorphic, or has a 1-to-1 pixel mapping, with the source image at most *generic viewpoints*. As a reminder, generic viewpoints are viewpoints where spatial relationships are mostly maintained despite small changes in viewpoint (Figure 3.2ABCD). *Discontinuous* stimuli are situations where discontinuities in the projected image appear at generic viewpoints (Figure 3.2EFG). This is a continuous axis with varying likelihood that an image will be broken up when projected onto the projection surface. For example, the image in Figure 5.1 shows how an image may be distorted to the viewer depending on the projection geometry and viewing angle. We explore various task types on continuous geometry in chapter 4 and discontinuous geometry in chapter 5.

NEED FOR MOVEMENT The Need for Movement axis describes how much the observer needs to move in order to understand the stimulus, which could be affected by viewing angle or the geometry of the projection surface. The *None* level (area A of Figure 3.2) describes interaction cues where the observer can already see and understand the stimulus without moving (Figure 3.3a). The *Suggested* level (areas B and E of Figure 3.2) is for interaction cues that contain some level of perspective distortion but are still understandable (Figure 3.3b). These are within the range of understanding of the specific viewpoint. The *Recommended* level (areas C and F of Figure 3.2) represents interaction cues that could be better understood if the observer were to move

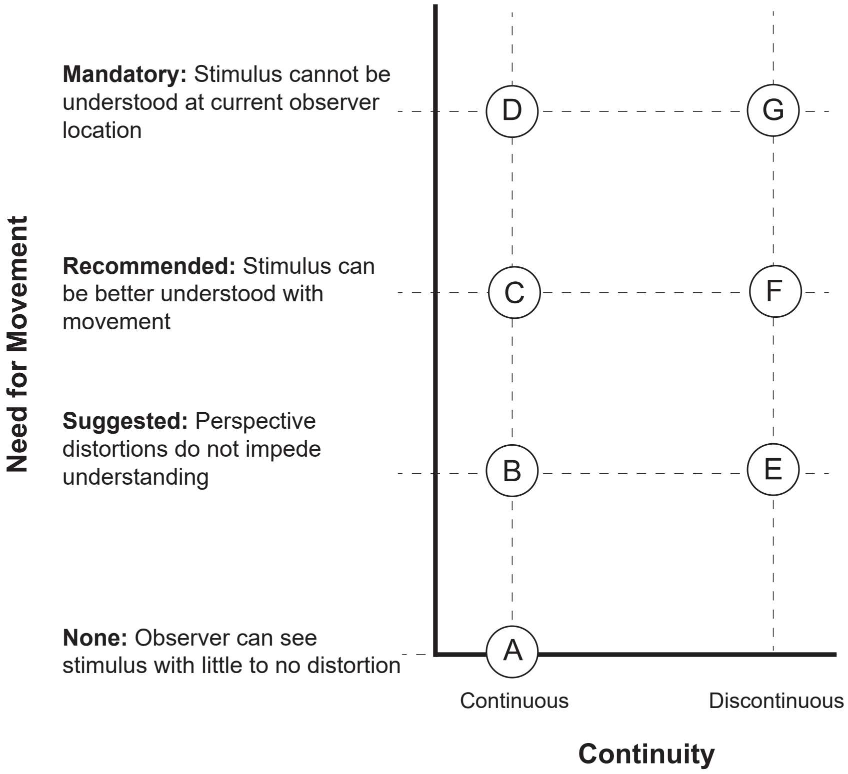


Figure 3.2: Movement-Continuity Design Space for Anamorphic Interaction Cues.

closer to the ocular point (Figure 3.3c). These interaction cues might have significant discontinuities or perspective warps at the observer's current viewpoint. The *Mandatory* level (areas D and G of Figure 3.2) represents interaction cues that cannot be understood unless the user moves closer to the ocular point (Figure 3.3d). This could be due to an extreme perspective distortion or occlusions from the geometry of the projection surface.

3D interactions can be classified into four main categories: navigation, system control, selection, and manipulation [22]. Our work explores how anamorphic interaction cues can be used for navigation, but the content of the anamorphic image can indicate actions from the other categories as well. In the next section, we introduce a design scenario where anamorphic interaction cues are used to guide viewers through a museum exhibit. We also present an experiment exploring continuous stimuli in chapter 4 and discontinuous stimuli in chapter 5.

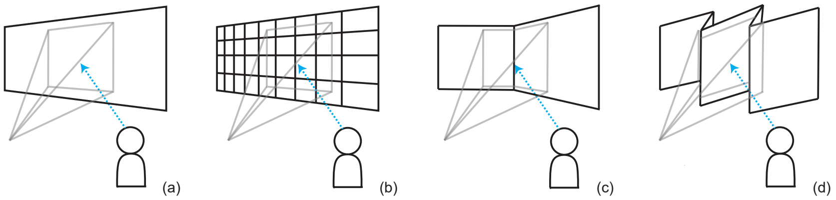


Figure 3.3: Surfaces with varying needs for movement: (a) No movement needed (b) Suggested movement because of small discontinuities in the image (c) Recommended movement because of perspective distortion (d) Mandatory movement because of occlusion

3.2 MUSEUM EXPERIENCE DESIGN SCENARIO

Museums and other cultural heritage sites offer ideal locations for the implementation of SAR interfaces. The architecture of the room is unlikely to change often, but the content within the space will change for various exhibits. It is often infeasible to offer every visitor a mixed reality headset, but anamorphic SAR interaction cues could be used to encourage observers to move through the exhibit without explicitly defining a route.

Imagine a scenario where a designer is tasked with using spatial augmented reality to guide visitors through an exhibit with pottery artifacts from various time periods. The staff want to design an experience that leads visitors through the different parts of the exhibit, without explicitly enforcing a specific path. This is where anamorphic interaction cues could be used to guide visitors along a route that follows the narrative of the exhibit.

NONE - CONTINUOUS The exhibit begins with the visitors facing a replica of the Venus of Dolní Věstonice, the oldest known ceramic artifact. The name of the exhibit is projected on the flat wall above the sculpture and can be easily read by the visitors as they enter (Figure 3.4a).

NONE - DISCONTINUOUS The name of the artifact and decorative elements from the site of its discovery in the Czech Republic are projected around the sculpture. A projection highlights the crack on the sculpture where it was assembled from two separate pieces recovered from the archaeological site. The highlighted location has an associated explanation projected on the wall behind the sculpture and connected by a line. Although the information is on different image planes, the visitors are able to see the aligned image from their initial viewing location (Figure 3.4b).

SUGGESTED - CONTINUOUS The next part of the exhibit takes the visitors to a scene in a cave in China where some of the earliest fragments of pots have been found. To lead the visitors into the space and give more information, the designer projects information onto a flat wall at an angle where the ocular point is further into the exhibit (Figure 3.4c).

SUGGESTED - DISCONTINUOUS This part of the exhibit has a recreation of the cave wall with many fragments from clay pots embedded into the surface. Information on the contents of the wall is projected onto the cave wall. The pottery fragments cause some discontinuities in the projected image, but the information is still mostly readable to the visitors. The visitors can choose to move closer to the ocular point to resolve some of the occlusions but they do not affect understanding (Figure 3.4d).

RECOMMENDED - CONTINUOUS The next area of the exhibit is on the invention of the pottery wheel in Mesopotamia. A model of a pottery wheel with clay on it sits at the centre of a semi-circular wall. The ocular point for the projection with information on the pottery wheel is at one side of the semicircle. The image is projected at an oblique angle to the surface and the curvature of the wall adds additional distortion. This indicates to the visitors that they need to go to the ocular point to undo the distortion (Figure 3.4e).

RECOMMENDED - DISCONTINUOUS One side of the pottery wheel is illuminated with the outline of a vase that is barely discernible to the visitors at their current locations because it is being projected at an angle onto the pottery wheel. The pieces of the outline join to make the complete outline as the visitors move closer to the ocular point. This encourages movement to a specific location (Figure 3.4f).

MANDATORY - CONTINUOUS The last part of the exhibit explores the industrial revolution and its effect on the pottery industry. Artifacts from a pottery factory in England are displayed along the edge of the room. To guide visitors to the end of the line of artifacts but also encourage exploration, the designer places the ocular point of a projection close to the wall at the end of the line of artifacts. This creates a long projection that is visible along the length of the wall but is unreadable until the visitor walks to the end of the line of objects (Figure 3.4g).

MANDATORY - DISCONTINUOUS The designer would like to end the exhibit with additional information on resources to learn more about each of the exhibits, but they want to hide this from the visitors until the very end. The designer decides to project this text onto a wall of pottery at the end of the exhibit so that visitors need to be standing at a specific location at the end to read the text. Outside of that location, the information is partially occluded. When the visitors stand at the ocular point at the exit and look back at the wall, they see that all the pieces coalesce into the parting message of the exhibit (Figure 3.4h).

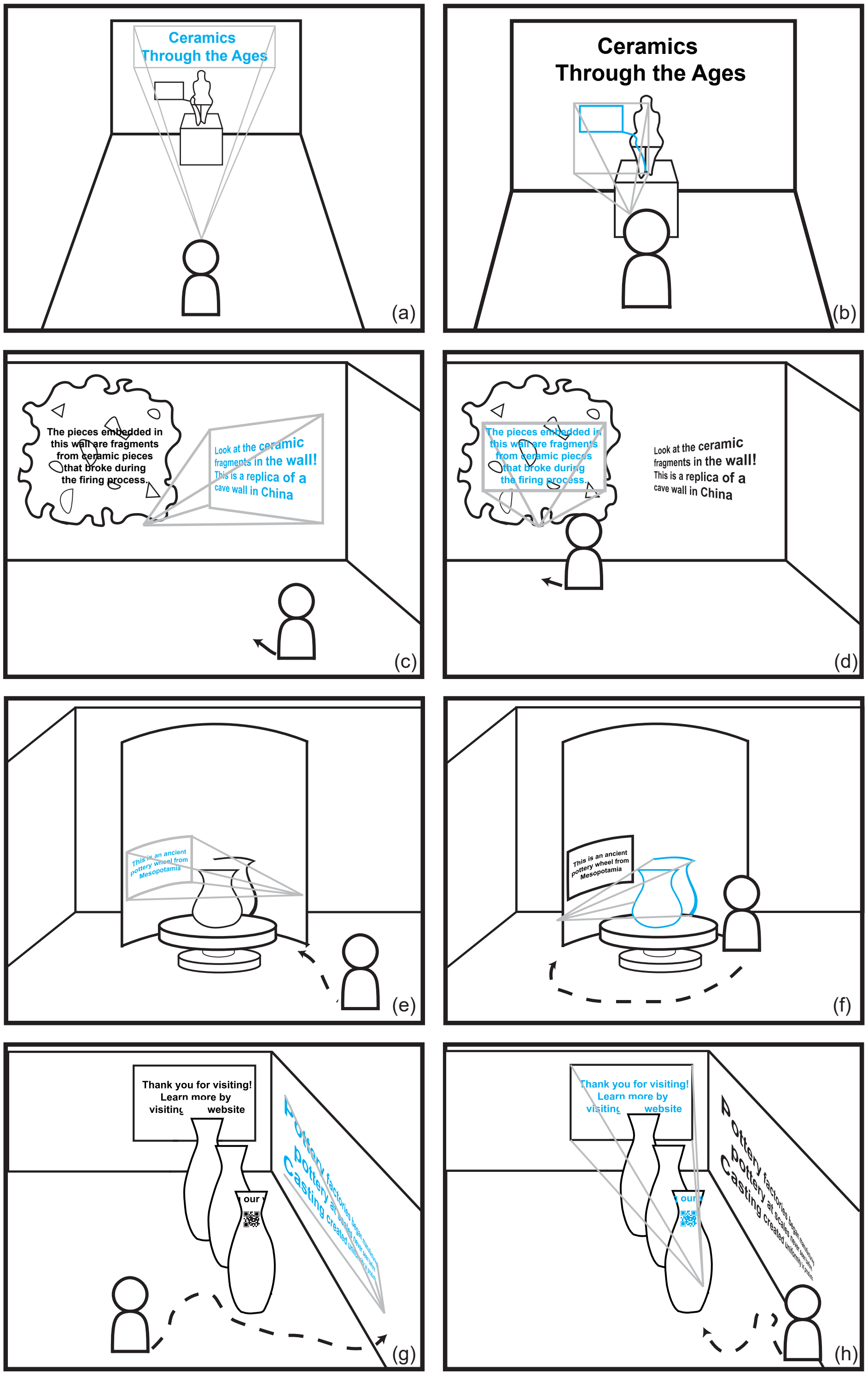


Figure 3.4: SAR museum design example: (a) No movement necessary - continuous stimuli (b) No movement necessary - discontinuous stimuli (c) Suggested movement - continuous stimuli (d) Suggested movement - discontinuous stimuli (e) Recommended movement - continuous stimuli (f) Recommended movement - discontinuous stimuli(g) Mandatory movement - continuous stimuli (h) Mandatory movement - discontinuous stimuli

4

EXPERIMENT 1: CONTINUOUS STIMULI

While past work has focused on showing the limits of perception at oblique angles on flat surfaces [31, 33] or evaluating the effectiveness of mounted SAR displays that align with the viewer's perspective [17], our work is centred around exploring the perceptual limitations of projecting content on various surfaces and angles, and how it affects viewer understanding of the content.

This chapter focuses on the effect of viewing angle and projection surface on user understanding of continuous anamorphic interaction cues. The continuity of the stimulus allows the viewer to follow the content without the need to overcome discontinuities.

The goal of this experiment was to evaluate the comprehensibility of anamorphic content with varying projection angles and on different continuous surfaces in a SAR environment. To achieve this goal, we assessed viewer perception through a series of visual acuity tests. These tests evaluated the participants' ability to understand a stimulus from various viewing angles where either the projected image or participant is placed at an oblique angle. The conditions in this study represent areas A, B, C, and D in our design space (Figure 3.2). We chose to simulate the SAR environment using VR for this experiment to gain more control over the experimental conditions.

4.1 SETUP

In this within-subjects study, participants entered a VR environment in which they were placed at different angles from an image projected onto a surface and asked to complete various tasks. The orders of the angle and tasks were randomized for each trial and the surface geometry order was counterbalanced between participants. The VR task was followed by a questionnaire and NASA TLX survey [16] to capture additional feedback on the individual tasks and projection surfaces from the participants.

4.1.1 *Participants*

We recruited 12 participants (10 male, 2 female; 4 18–24 years old, 6 25–34 years old, and 2 35–44 years old). All had binocular vision and use of both hands to participate in our study. Participants were recruited using online advertisements and word-of-mouth, and received $15 for successful completion of the one-hour study. Corrective eyewear was allowed in the study and did not impact the experience of the participants.

4.1.2 *Apparatus*

The experiment was run on an untethered Oculus Quest 2 with Oculus Touch controllers to allow participants to move freely within the bounds of the experiment space, which was approximately 3.5m × 2.5m × 4m. The virtual space available to the participant was approximately 16m × 9m × 4.5m (Figure 4.1). Participants were able to navigate the VR scene through a combination of physically walking through the space and virtual movement using the joystick on their left controller. The participant could move in the direction of the joystick movement at 1m/s by moving the joystick in the direction in which they wanted to move in the virtual space.

In each trial, the participant was placed 3m away from the centre of the stimulus at an angle that varied according to the trial. The projector was also placed 3m away from the centre of the stimulus at an angle specified by the trial. We sampled the location and rotation of the participant every half of a second to track their movement patterns.

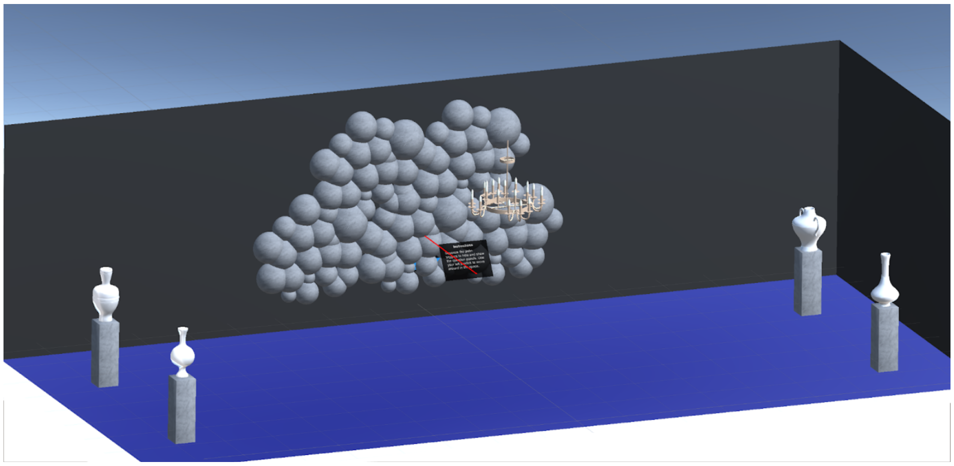


Figure 4.1: The VR scene with a textured wall. The red ray is the participant's raycast.

4.2 CONDITIONS

The trials were grouped by the surface where content was projected. For each surface, participants completed all of the tasks and each task was repeated over several trials at different configurations.

The trials were repeated in two projector-participant angle configurations: placing the projector at an oblique angle (Figure 3.1a) and placing the participant at an oblique angle (Figure 3.1c). Figure 4.2 shows how the participant is placed at angle θ and distance d from the centre of the stimulus. These variations were designed to compare how projection angles on different surfaces may distort the stimulus in ways that differ from perspective-only distortions.

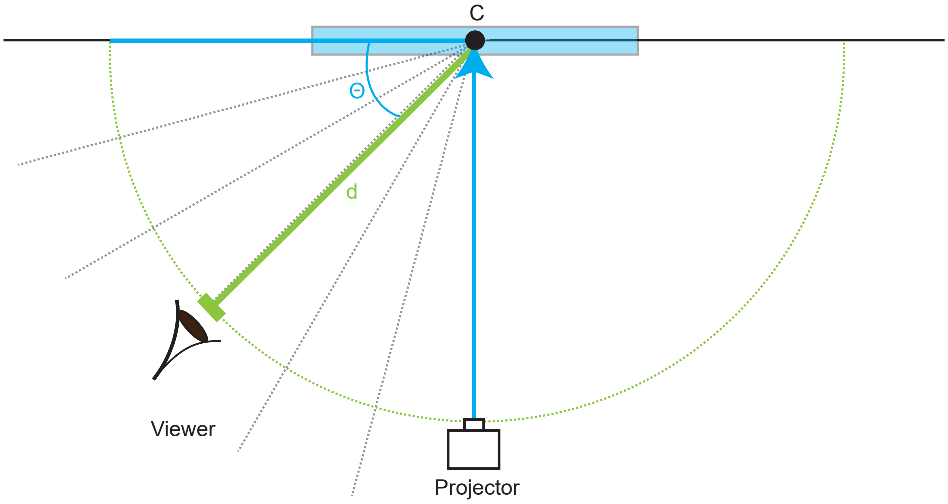


Figure 4.2: Angle measurements in relation to stimulus. d is the distance between the viewer and the centre of the stimulus, c. θ is the angle between the viewer and the viewing plane

4.2.1 *Tasks*

Each of the tasks in this experiment was designed to test a different aspect of understanding anamorphic content.

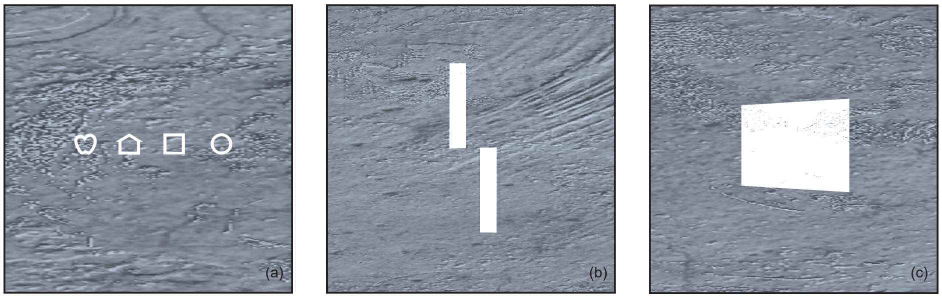


Figure 4.3: Tasks: (a) Symbol Recognition task with an apple, house, square and circle (b) Line Alignment task with misalignment (c) Perfect Square task where the projector is to the left of the observer

SYMBOL RECOGNITION TASK The Lea symbols test is a visual acuity test featuring four symbols that appear as circles when they are beyond the threshold for recognition [3]. We selected Lea symbols because they are similar to text in terms of symbol recognition, without the associated semantic implications of words. The symbols are designed to be difficult to distinguish from one another, but are all recognizable shapes that an observer would be able to identify without prior knowledge of the task.

In our test, we randomized the order of the four symbols (Figure 4.3a) and randomly selected three other symbol combinations to present to the participants as multiple choice options. The symbols were approximately 10cm X 10cm when viewed on the flat wall, but the size was distorted by varying the geometry and angle. The centre was always calibrated to be at the height of the participant. We instructed participants to identify all four symbols before selecting an option, but we did not specify that they need to move. They were asked to move only as much as they needed to in order to be confident in their answers. The participant used raycasting with their VR controller to select an option out of four on a panel in front of them. At generic viewpoints where some distortion is present, the Symbol Recognition Task would roughly correspond to Suggested Movement in area B in Figure 3.2.

LINE ALIGNMENT TASK The Vernier acuity test is used by vision researchers to measure an observer's ability to identify positional offsets between stimuli [19]. We modified the task so that instead of simply detecting misalignment between lines, participants were asked to control one of the lines using the joystick to align it to an existing reference projection above the line that they can move (Figure 4.3b). Most research on vernier acuity test performance has focused on using a flat surface, but some work has explored vernier acuity on stereodisparate objects, or objects at different depths [18].

We chose to use the line alignment task to test participants' ability to understand the relative positioning of UI elements at different angles. We hypothesize that the line alignment task is easier when the participant is at a viewpoint where they have a good view of the reference line, but movement is not necessary to complete the task. In our framework, this would correspond with recommended movement in area C in Figure 3.2.

PERFECT SQUARE TASK We designed the perfect square task to force participants to move through the space towards a predetermined viewpoint. Participants were presented with the projection of a white square at various angles and asked to move to the location where they see a perfect square, which is the ocular point (Figure 4.4). This would correspond to mandatory movement in area D in Figure 3.2.

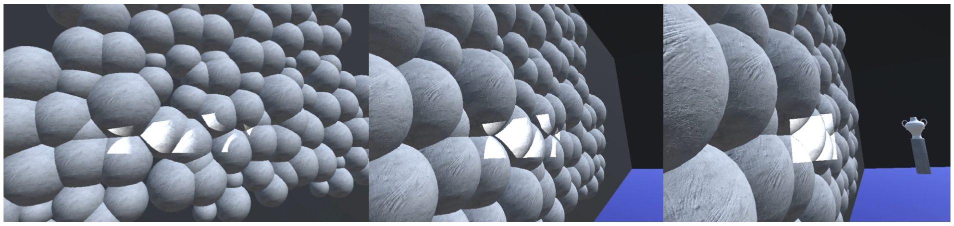


Figure 4.4: Perfect square task stimulus from various viewing angles

4.2.2 *Surfaces*

We repeated the tasks above with four surface conditions: Flat Wall, Concave Wall, Convex Wall, and Textured Wall. The walls were all approximately 2m wide. Our intention was to choose surfaces that would distort the projected image in various ways or require different movements from the participants.

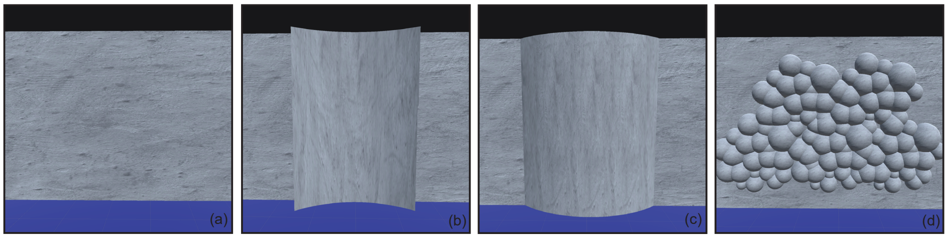


Figure 4.5: Surfaces: (a) Flat Wall (b) Concave Wall (c) Convex Wall (d) Textured Wall

FLAT WALL The Flat Wall (Figure 4.5a) serves as a control condition. The wall has a slight concrete texture but the geometry is flat. Content projected on this surface will be continuous regardless of angle and this corresponds to area A in Figure 3.2

CONCAVE WALL The Concave Wall (Figure 4.5b) introduces perspective warps along the curvature of the surface to images projected to the centre. The curve is approximately 70cm × 370cm, constructed from a cylinder with a radius of 3m. At most viewpoints that are not close to 0° to the wall, this corresponds to area B in Figure 3.2.

CONVEX WALL The Convex Wall (Figure 4.5c) introduces perspective warps along the curvature of the surface and can occlude images projected at oblique angles to the user when parts disappear off the horizon of the curve. . The curve is approximately 70cm × 370cm, constructed from a cylinder with a radius of 3m. Because of the possibility of occlusion at some angles, this corresponds to area C in Figure 3.2.

TEXTURED WALL The Textured Wall (Figure 4.5d) warps different parts of the image along the curves of the bubbles on its surface. Each sphere has a diameter between 30cm and 90cm and is packed to overlap slightly with adjacent spheres on the wall. There are some mild discontinuities that appear at generic viewpoints, which would place this surface closer to the discontinuous side of the design space. At oblique angles, the stimulus might be so distorted that the viewer is unable to understand it. This corresponds to area D in Figure 3.2.

4.3 PROCEDURE

The experimenter began by explaining each of the tasks to the participant and introducing them to the various controls on the Quest 2 device. Next, participants began completing tasks in the VR environment. Participants could choose to physically walk through the space or use the joystick movement at any time in the study. Participants were given the chance to take a break after each surface condition. After the VR tasks were completed, the participants were asked to fill out a post-study survey on the computer which had questions about the challenges that they faced in each of the SURFACE and TASK pairings along with a NASA-TLX survey [16].

4.4 DESIGN

This experiment had a within-subjects design with two primary independent variables: Projection SURFACE with 4 levels (FLAT, CONCAVE, CONVEX, TEXTURED); and ANGLE with 6 levels (15°, 30°, 45°, 60°, 75°, and 90°). Each of the ANGLE trials was repeated with 2 CONFIGURATION options that describe whether the participant or the projector was placed at an oblique angle while the other remained at 90° to the image plane (PROJECTOR and PARTICIPANT). The ANGLE repetition with 90° was only performed once because the CONFIGURATION is the same whether the participant or projector is at 90°.

The primary measures computed from logs are *Accuracy* and *Completion Time*. *Accuracy* is measured through participant performance in each of the three tasks. For the symbol recognition task, this was the number of correct answers to the symbol recognition questions. For the line alignment task, this was the distance between the ideal location of the aligned lines and the location selected by the participant. For the perfect square task, the accuracy was measured as the distance between the ocular point of the projection and the location of the participant when they confirm their answer.

Completion time is the amount of time between the beginning of the trial and when the participant submits their answer.

In summary: (4 SURFACES × 3 TASKS × 11 ANGLES/CONFIGURATIONS) = 132 data points per participant.

4.5 RESULTS

4.5.1 *Task Completion Time*

Task completion times increased as the angle became smaller whether the projector or the participant was placed at an oblique angle. The variance was more pronounced in the case where the participant was moved, but the general trend of increased task completion time with projection angle was consistent across conditions. The completion times for the symbol recognition task and the perfect square task increased considerably when the projector was placed at 15° away from the image plane.

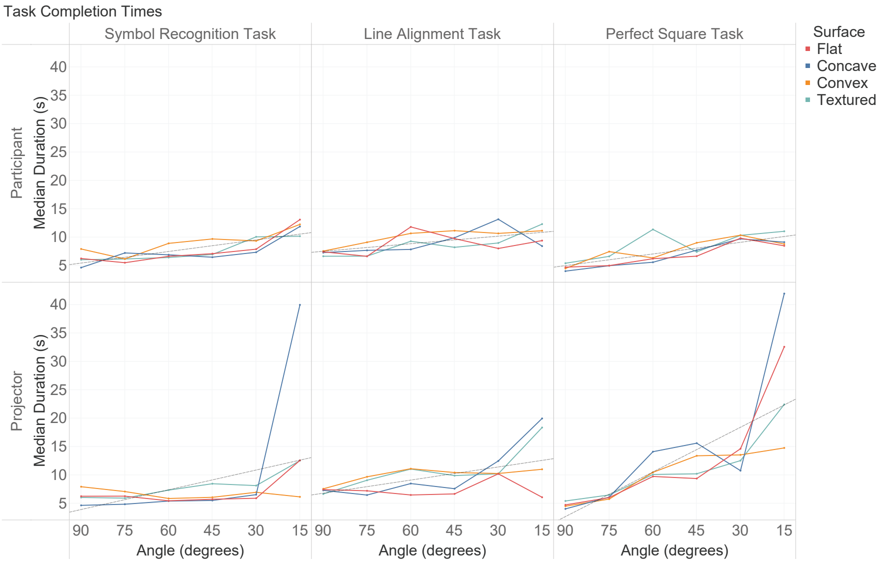


Figure 4.6: Completion Times with lines representing median completion times

4.5.2 *Accuracy*

The accuracy of each of the tasks was calculated differently. The accuracy of the symbol recognition task served as more of a test to ensure that participants were completing the task but the accuracy of the other tasks offers insights into participant understanding of the content at various angles.

SYMBOL RECOGNITION TASK The accuracy of the symbol recognition task was measured as whether or not the participant selected the correct option out of four symbols. The accuracy was 100% across all conditions. This is likely due to the simplicity of the task and how the correct answer was easily verified by looking at the stimulus more closely.

LINE ALIGNMENT TASK The accuracy of the line alignment task is the distance between the ideal placement of the line and the location that the participant chose. In the trials where the participant was placed at an oblique angle but not the projector, the participants were able to give very accurate answers across surfaces and initial viewing angles. However, on trials where the projector was placed at an oblique angle, participants gave increasingly inaccurate answers as the angle became closer. This may be a result of foreshortening of the image at acute angles where a small distance to the left or right from the participant's perspective corresponds to a significant distance along the projection surface.

PERFECT SQUARE TASK The accuracy of the perfect square task was calculated using the distance between the participant and the ocular point of the stimulus. The distance and variance of the answers were both higher as

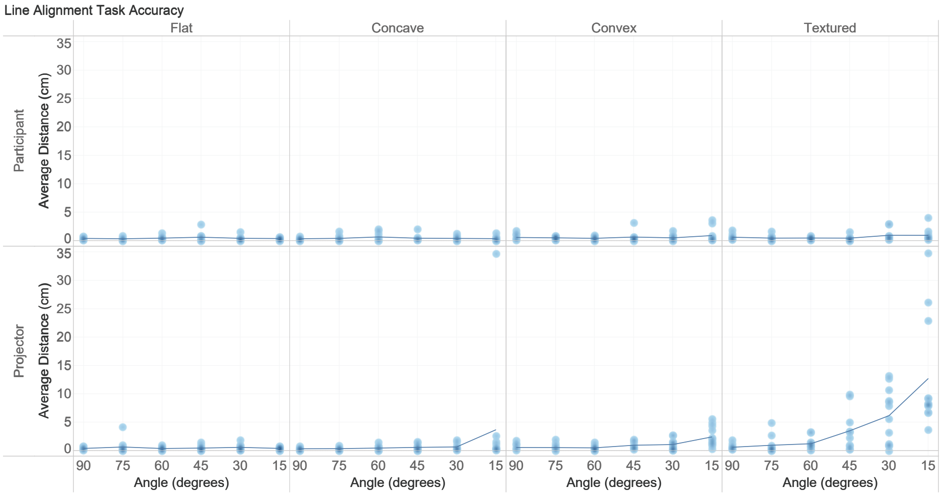


Figure 4.7: Line alignment task accuracy across continuous surfaces. Lines represent the mean distances

the angle of projection became smaller, but this effect was not observed in the trials where the participant was placed at an oblique angle to start. This may be explained by the fact that participants are used to seeing perspective distortions on flat walls when they are at oblique angles to an image and can use the wall itself as guidance to the correct viewing location.

4.5.3 *Preference Scores*

We collected NASA-TLX survey data using a 21-point scale. The results are summarized in Figure 4.9. Scores were generally similar across surface types with the exception of the mental demand on the Line Alignment task where concave and convex surfaces seemed to have much lower mental demand than the other surfaces. The perfect square task was generally more frustrating, required more effort and resulted in lower perceived success than the other tasks, which aligns with our observations in task completion times and qualitative feedback from participants.

4.5.4 *Qualitative Feedback*

Participant comments suggested the symbol recognition task was relatively easy. For example, P1 said "I thought the shape recognition task was pretty easy. I didn't find much challenging about it." and both P2 and P8 called it "pretty straightforward."

Many participants struggled with the line alignment task on the textured wall because the texture made it more difficult for them to locate the correct position for the bottom line. P7 expressed how the geometry of the textured

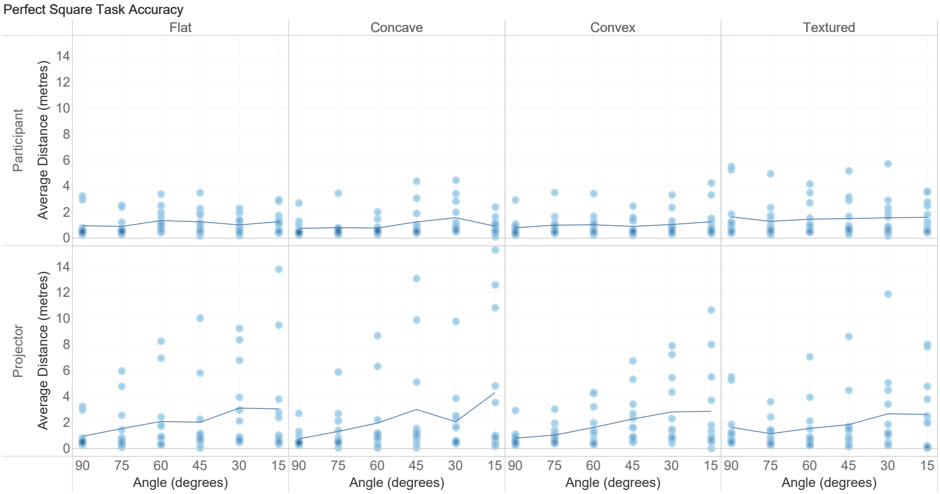


Figure 4.8: Perfect square task accuracy across continuous surfaces. Lines represent mean distances

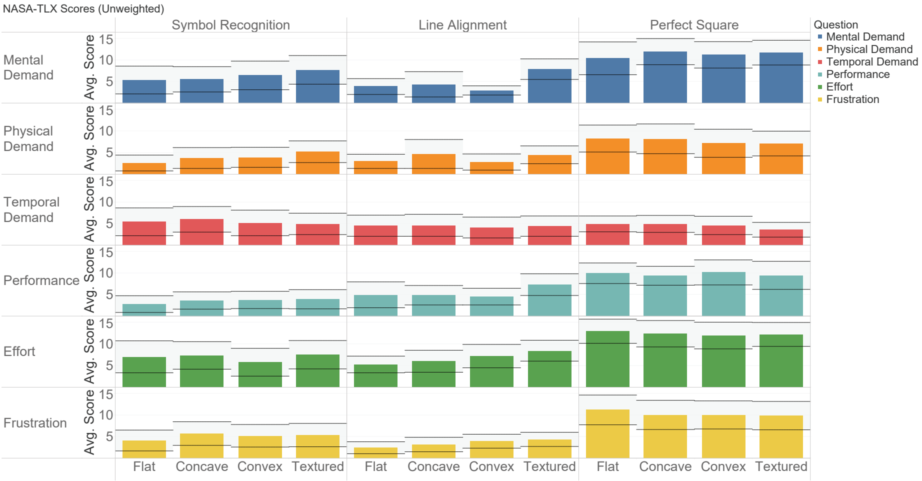


Figure 4.9: NASA-TLX scores (unweighted) across tasks

wall distorted the edges of the lines which made alignment difficult: "When the shapes were tilted or spread on a bumpy surface it was difficult to align them because their edges were no longer straight.". These comments were supported by participant performance in the logged data.

The perfect square task was the most challenging of all the tasks as participants had less certainty about whether or not they had the correct answer. P4 elaborated on how the lack of detail made it difficult to identify the location of the perfect square when they said 'Perfect square seemed really challenging in the most basic conditions: on a flat or curved wall, it was hard to identify whether the square was actually perfect or not since my brain would approximate what it was supposed to be.". They further elaborated on how texture actually provided clues that they used to identify the correct viewing location when they said “I could more easily identify the squares with the textured wall because I can easily see when a line is straight on the bulbs”.

5

EXPERIMENT 2: DISCONTINUOUS STIMULI

This chapter will focus on the effects of viewing angle and projection surface on user understanding of discontinuous stimuli. We define discontinuous stimuli as projections where the image has discontinuities at generic viewpoints. The conditions in this study represent areas A, F, G, and H on Figure 3.2.

5.1 SETUP

The setup, design, and procedure for this experiment were almost identical to those of the continuous experiment from chapter 4. The only change was in the surfaces presented to the participants in each condition.

5.1.1 *Participants*

We recruited 17 participants with binocular vision and use of both hands to participate in our study. However, data collected from P8, P10, and P13 were removed due to incomplete trials. We present the data from the 14 remaining participants (10 male, 4 female; 6 18–24 years old, 8 25–34 years old). All had binocular vision and use of both hands to participate in our study. Participants were recruited using online advertisements and word-of-mouth, and received $15 for successful completion of the one-hour study. Corrective eyewear was allowed in the study and did not impact the experience of the participants.

5.2 CONDITIONS

The tasks in this experiment were identical to those of the continuous experiment, but the surfaces were updated to a series that introduce image discontinuities at generic viewpoints.

5.2.1 *Surfaces*

We repeated the tasks in section 4.2.1 over each of the four surface conditions: Flat Wall, Lightly Textured Wall, Highly Textured Wall and Occlusion Wall. Our intention was to choose surfaces that would create discontinuities in the projected image to varying degrees.

FLAT WALL The Flat Wall (Figure 5.1a) serves as a control condition. The wall has a slight concrete texture but the geometry is flat. Content projected on this surface will be continuous regardless of angle and this corresponds to area A in Figure 3.2.

LIGHTLY TEXTURED WALL The Lightly Textured Wall (Figure 5.1b) has a pattern like a brick wall that creates small discontinuities in the image when the projector is at an oblique angle. At generic viewpoints, this corresponds to area E in Figure 3.2.

HIGHLY TEXTURED WALL The Highly Textured Wall (Figure 5.1c) has several protruding surfaces that cause occlusions and shadows at generic viewpoints. Because of the possibility for occlusion at some angles, this roughly corresponds to area F in Figure 3.2.

OCCLUSION WALL The Occlusion Wall (Figure 5.1d) consists of three vertical panels that protrude from the background wall at varying distances. If the projector is at an oblique angle to the Occlusion wall, the projection may appear behind one of the panels, occluding the view entirely for viewers at generic angles. An observer would need to move to see the stimulus, which corresponds to area G in Figure 3.2.

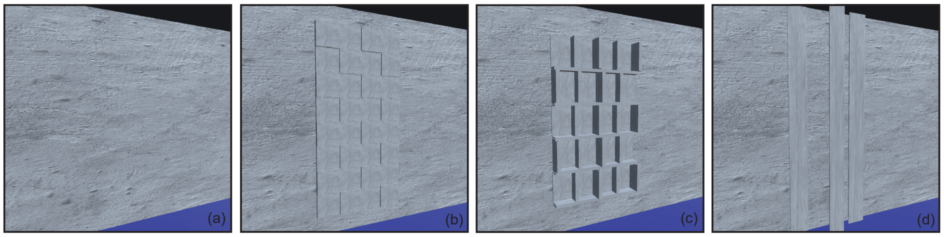


Figure 5.1: Surfaces: (a) Flat (b) Lightly Textured (c) Heavily Textured Wall (d) Occlusion Wall

5.3 RESULTS

5.3.1 *Task Completion Time*

Task completion times increased as the angle became more oblique whether the projector or the participant was placed at an oblique angle. However, the trials where the projector was placed at an oblique angle showed more variance and higher overall completion times than the trials where the participants were placed at an angle. This trend was most pronounced in the perfect square task where there is a significant increase in task completion time when the projector is placed at a 15° angle to the stimulus plane.

5.3.2 *Accuracy*

The measurements for accuracy were calculated in the same way as in chapter 4 for each of the tasks.

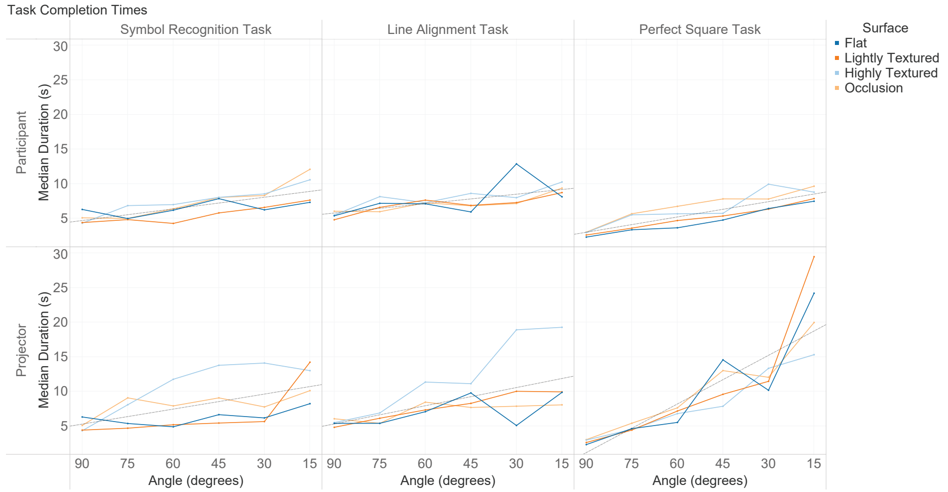


Figure 5.2: Completion times across discontinuous surfaces. Lines represent median completion times

5.3.2.1 *Symbol Recognition Task*

Participants answered all of the symbol recognition questions with 100% accuracy. This is the same result that was observed in the continuous experiment.

5.3.2.2 *Line Alignment Task*

The participants were generally more accurate in their answers in the discontinuous case (Figure 5.3) than the participants in the line alignment task on continuous surfaces (Figure 4.7). This may have been because the discontinuous surfaces offer more clues about depth and distance than completely continuous surfaces. The one exception is the highly textured wall where there is an increase in task inaccuracy as the placement of the projector became more oblique. A possible explanation is that the highly textured wall created many discontinuities on different depth planes at generic viewpoints. Without moving towards the ocular point, it was difficult to accurately judge where the lines were aligned.

5.3.2.3 *Perfect Square Task*

The magnitude and variance of the responses (Figure 5.4) were both higher as the angle of the projected stimulus decreased, but this effect was less pronounced in the trials where the participant was moved. There was no observed spike in inaccuracy at any of the angles which suggests that discontinuous surfaces were better than continuous surfaces at providing perspective clues consistently across viewing angles.

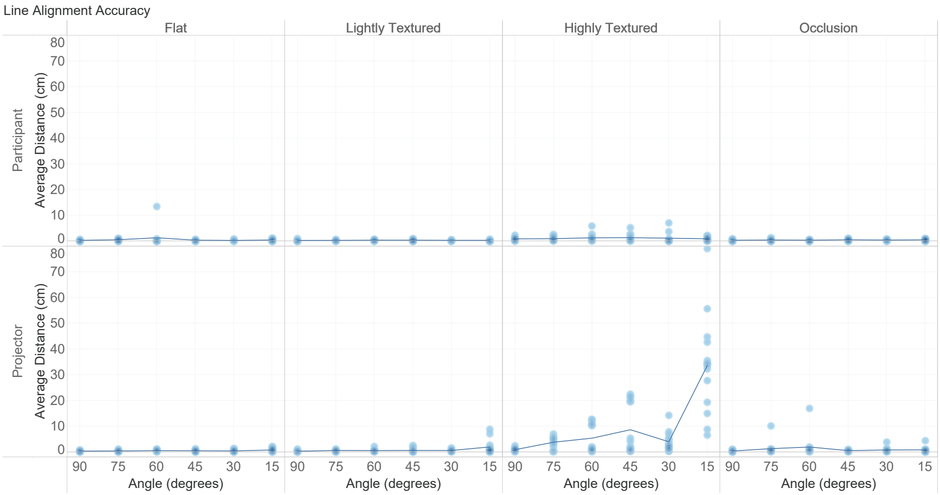


Figure 5.3: Line Alignment Task Accuracy. Lines represent the mean distances

5.3.3 *Preference Scores*

We collected NASA-TLX survey data using a 21-point scale. The results are summarized in Figure 5.5. Scores were generally similar across surface types with no discernible trends, which is surprising because many participants expressed frustration with the Perfect Square Task in the short answer responses.

5.3.4 *Qualitative Feedback*

As in the continuous experiment, many participants struggled with the Perfect Square task. Several participants also mentioned that they struggled with the highly textured wall, but did not elaborate on why it was challenging.

P15 offered insights into their strategies for finding the ocular point. They said "I mainly noticed the shape of the distorted figures to determine which direction to move in — for shapes that were stretched out and larger on one lateral side, I moved in the opposite direction for alignment, and in case of unaligned top/bottom boundaries, moving back and forth usually helped."

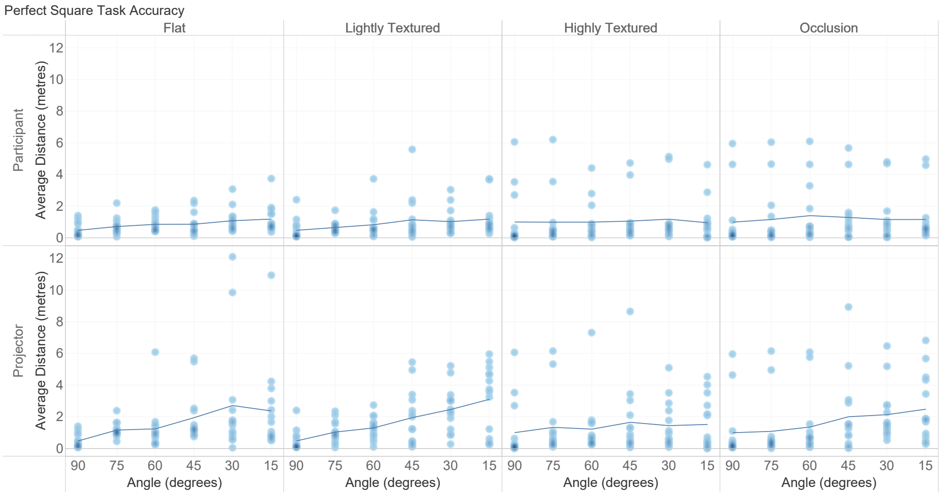


Figure 5.4: Perfect square task accuracy across discontinuous surfaces. Lines represent mean distances

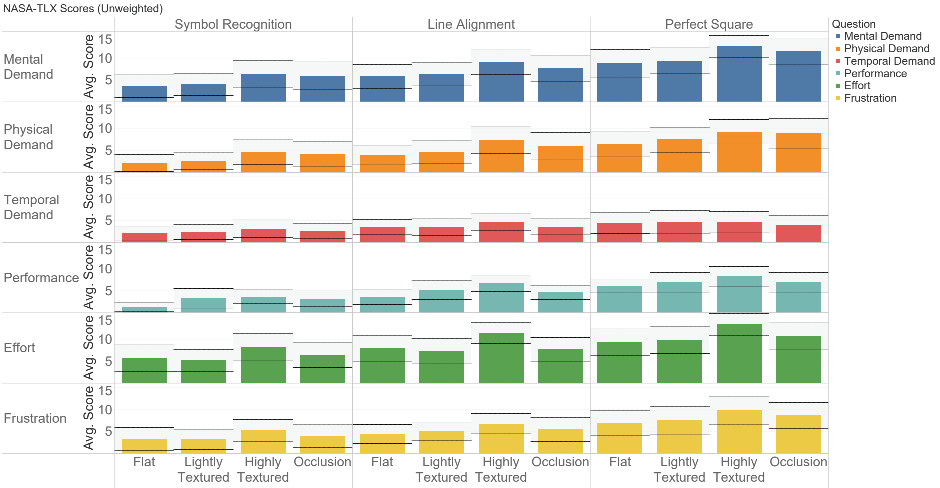


Figure 5.5: NASA-TLX Scores (unweighted) for Discontinuous Surfaces

6

DISCUSSION

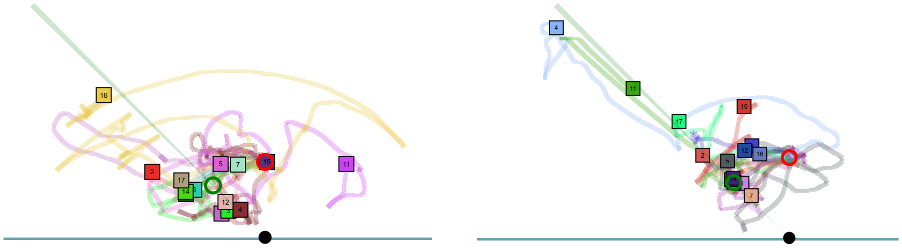
We explored how projection surfaces and viewing angles affect how well a viewer is able to understand anamorphic content. In this discussion, we elaborate on possible explanations for some of the observed behaviours and propose areas for further exploration.

6.1 MOTION PATHS

In addition to data on the completion times and performance of each of the participants, we also collected data on the location and rotation of the participant every half-second. The motion paths revealed interesting patterns across surfaces, tasks, and angles. These provide addition insights which help explain our quantitative observations.

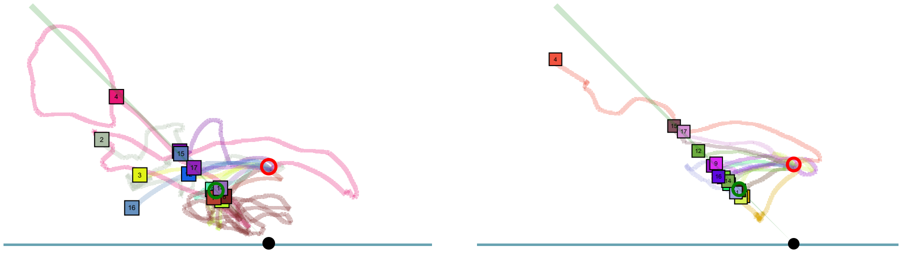
MOTION DIFFERENCES ACROSS SURFACE TYPES Across the discontinuous surfaces that we explored, more complex geometry on the surfaces seemed to give the participants more perspective cues that they could use to guide them to the correct viewing location (Figure 6.1). The flat wall condition had the least complex geometry, which resulted in a wider distribution of chosen locations in the final position of the trials. In contrast, almost all of the location choices on the highly textured wall lay on the ray coming from the centre of the stimulus to the ocular point, which tells us that the participants were able to find the correct viewing angle. The motion paths also cover less of the available space, which suggests that participants were guided by the perspective cues and more confident in their answers than in the other surface conditions. This behaviour was observed over many other angle combinations, which suggests that more discontinuities at generic viewpoints actually help observers in locating the ocular point.

MOTION DIFFERENCES BETWEEN PROJECTOR CONFIGURATIONS The angular distance between the ocular point and the observer is the same between configurations with the same angle. However, changing the configuration leads to drastically different movement patterns in participants. In Figure 6.2, it is clear that the trial where the projector is at an oblique angle creates much more variance for the final viewing angle than the trial where the participant is placed at an oblique angle relative to the projector. When participants were placed at an oblique angle to a projection, they were all able to identify the correct viewing angle and did not explore the rest of the space as much as they did in the other case. This suggests that placing the projector at an angle encourages more exploration but creates a less predictable movement pattern for the designer.



Flat Wall

Occlusion Wall



Lightly Textured Wall

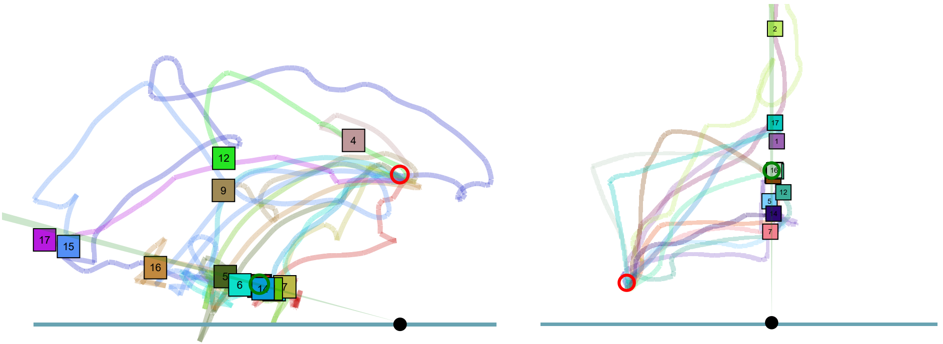
Highly Textured Wall

Figure 6.1: Motion Paths Across Surfaces in the perfect square task with the projector placed at 45°. The red circle is the starting point and the green circle is the ocular point. The black circle is the centre of the stimulus and the squares are the endpoints labelled with the participant number.

MOTION DIFFERENCES ACROSS TASKS Each of the tasks in the experiments were designed to encourage different levels of movement. The symbol recognition task represents suggested movement, the line alignment task represents recommended movement, and the perfect square task represents mandatory movement (Figure 3.2). These differences in the need for movement are reflected in the movement patterns observed (Figure 6.3). Some participants preferred to move closer to the ocular point in the symbol recognition task and more participants moved during the line alignment task. All participants moved closer to the ocular point in the perfect square task, but this was part of the instructions for the task. These observations suggest that symbol recognition tasks have higher tolerances for perspective distortions than tasks where relative placement of objects is important.

6.2 INTERACTION BETWEEN ANGLE AND DISTANCE

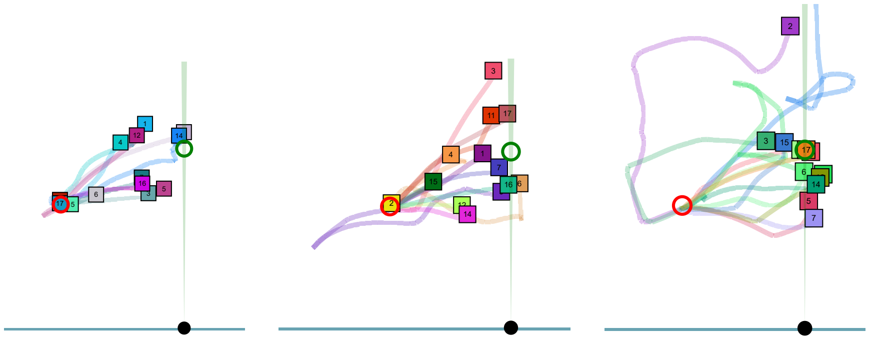
In our experiments, we focused on varying the angle of the participant or the projection. However, the distance to the stimulus is another factor that could affect an observer's experience. We chose a distance of 3m in all trials for consistency. Participants were able to identify the correct viewing angle, but there was considerable variance in the distance from the stimulus where they stopped. For example, in Figure 6.2, the participants in the trial where they were placed at an oblique angle to start were able to find the correct



Projector at 15 degrees

Participant at 15 degrees

Figure 6.2: Motion Paths where the projector is at an oblique angle vs where the participant is at an oblique angle. The red circle is the starting point and the green circle is the ocular point. The black circle is the centre of the stimulus and the squares are the endpoints labelled with the participant number.



Symbol Recognition Task

Line Alignment Task

Perfect Square Task

Figure 6.3: Motion Paths Across Tasks: The red circle is the starting point and the green circle is the ocular point. The black circle is the centre of the stimulus and the squares are the endpoints labelled with the participant number.

viewing angle, but there were big differences in how far they stood from the surface at that angle. For example, consider the location of P2 in the trial where the participant is placed at 15° to the image plane (Figure 6.2). Most of the other participants were clustered around the ocular point, but P2 was at the same angle and much farther away from the wall. Future work could explore techniques for reducing ambiguity in the ideal viewing distance.

6.3 RECOMMENDATIONS FOR DESIGNING ANAMORPHIC INTERACTION CUES

We distill the observations from our experiments into the following design recommendations for anamorphic interaction cues:

MOTIVATE MOVEMENT USING PERSPECTIVE CLUES To encourage movement on a specific path, project content onto surfaces with complex geometry that has varying distances from the ocular point. However, try to reduce perspective distortions to the image by angling the virtual projector approximately orthogonal to the projection surface. This provides clues to the observer about how to change their position to be closer to the ocular point without skewing the source image too much. As seen in Figure 6.2, this prompts a more predictable path to the desired viewing angle than angling the projector at an oblique angle for the observers to find.

ENCOURAGE EXPLORATION THROUGH AMBIGUITY In contrast with the previous recommendation, a designer can encourage exploration of the space by creating anamorphic interaction cues that are more ambiguous. Projection surfaces with fewer discontinuities or projections from oblique angles both create ambiguity in the image at generic viewpoints which prompts observers to explore the space further to find the ocular point. As seen in Figure 6.1, surfaces with less geometric complexity tend to encourage meandering paths to the ocular point when participants explore the space. Figure 6.2 shows how oblique projection angles can induce enough visual ambiguity that viewers move in different directions to gather more information on the scene before moving to the ocular point. P15 is an example of a participant who moved away from the direction of the ocular point and explored the space before finding the correct angle.

CUSTOMIZE FOR CONTENT The content presented affects how much participants are willing to move to see it. For example, content with very recognizable symbols or faces has higher tolerance for perspective distortion and may not lead to observer movement [11]. In these cases, it might be necessary to project onto surfaces with more complex geometry to obscure the content from more angles, such as on the textured wall in Figure 4.5d. This also applies to different task types. For example, Figure 6.3 shows how the same projector configuration and projection surface can encourage different movement patterns depending on the task type. Participants submitted their answers without moving as much in the symbol recognition task as they did in the line alignment task, which is interesting because neither task required the participants to move. The perfect square task required movement from the participant, which is why all of them moved closer to the ocular point.

OBFUSCATE THROUGH OCCLUSION OR OBLIQUENESS Designers can limit the visibility of certain interaction cues by intentionally occluding the content using geometry. A cue can be fully occluded behind geometry from a certain angle such as by projecting on the other side of the convex wall in Figure 4.5c or partially occluded as in on the highly textured wall in Figure 5.1c. Extreme projection angles can also be used to obfuscate information. If an image is projected from very close to the projection surface, the image can be so distorted that it is unrecognizable from other viewing angles.

7

PROTOTYPING SAR EXPERIENCES USING VR

VR offers a solution to quickly prototype spatial setups and preview them in an immersive fashion. However, there may be differences in how viewers interact with immersive experiences in VR versus how they interact with the environment in the physical world. Prototyping SAR experiences can often be cumbersome and require adjustment of cameras, sensors, and projectors. This creates barriers to rapid prototyping and experimentation. Mäkelä et al. [27] identified differences in attributes such as user performance and display efficiency when prototyping large display research in VR. We are interested in exploring how this effect extends to SAR environments evaluated using VR prototypes.

In this chapter, we describe how an experiment could be designed and administered to identify performance differences on perspective-finding tasks between SAR and VR. Due to technical and logistical issues, we were not able to run the experiment, but we believe our description here could help others to conduct such an experiment in the future.

7.1 APPARATUS

This experiment is designed to compare performance in VR and SAR through the same experimental tasks using different technologies. The SAR and VR conditions of this study take place in the same room, with a world-aligned 3D scan of the room replacing the view in the VR version.

SAR APPARATUS Our SAR setup consists of four Christie projectors with 4k resolution in a room with approximately 3.5m × 2.5m of space to walk. The participant carries a wireless keyboard to enter their responses to the tasks (Figure 7.1a).

To track the location of the participant's head, we use a baseball cap with reflective Vicon trackers attached to the brim and sample their location every half of a second (Figure 7.2a).

The surfaces were displayed on a 185cm × 60cm whiteboard. The surfaces were constructed from foam core and fastened to the whiteboard with clamps (Figure 7.2b,c,d). Between SURFACE conditions, the experimenter replaces the surface with the new surface board corresponding to the condition.

VR APPARATUS The experiment is designed to run on a standalone Quest Pro HMD in the same room as the SAR condition. A 3D scan is used to create a simulation of the room in a VR scene (Figure 7.1b). The orientation of the virtual space is aligned with the physical room. Participants are able to move through the space only by physically walking and carry a keyboard for controls, just like in the SAR setup . Their location is logged every half second.

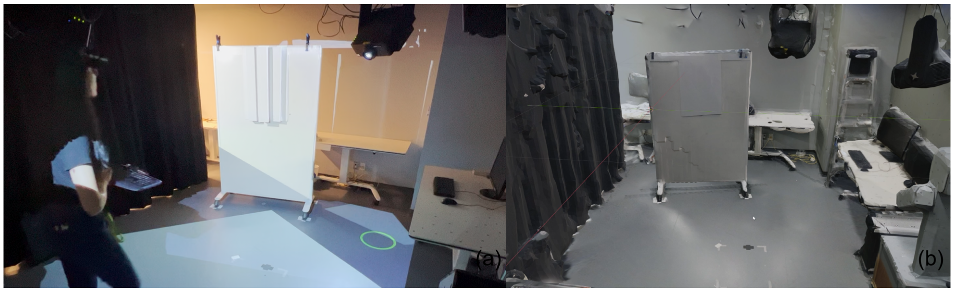


Figure 7.1: (a) The SAR environment with a green circle indicating the trial start location (b) The 3D scan of the same environment for the VR version of the trial

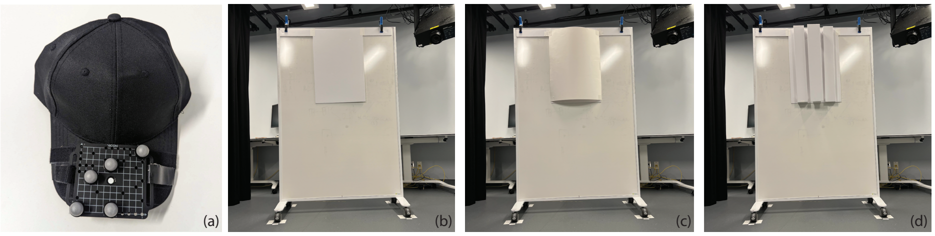


Figure 7.2: SAR condition setup: (a) The Vicon tracker hat for detecting the participant's head location and rotation. (b) Example of the flat wall condition (c) Example of a continuous surface (convex wall) (d) Example of discontinuous surface (occlusion wall)

7.2 TASKS

This experimental design only includes the perfect square task from chapters 4 and 5. The task is adapted to be the same across SAR and VR by making the participant hit a key on the keyboard when they wish to confirm their answer, and return to a neutral stating position prior to walking to the designated starting position for each task.

7.2.1 *SAR Surfaces*

The surfaces in this experiment mirror the convex wall of the continuous experiment and occlusion wall of the discontinuous experiment. Figure 7.2b shows the flat wall, Figure 7.2c shows the continuous wall, and Figure 7.2d shows the discontinuous wall.

7.2.2 *VR Surfaces*

The VR versions of all the walls were created using 3D scans of the physical artifacts from the SAR condition and post-processed to clean up irregularities in the scanned mesh.

7.3 PROCEDURE

SAR The experimenter begins by explaining the task to the participant and helping them adjust the Vicon tracker hat. After the experimenter switches the foam board to the correct surface for the condition, the participant runs through a calibration step. Next, participants began completing tasks in the SAR environment. Participants can take a break after each surface condition while the experimenter is changing the foam core surface. After the SAR tasks are completed, the participants fill out a post-study survey on the computer which has questions about the challenges that they faced in each of the SURFACE and TASK pairings, along with a NASA-TLX survey [16].

VR The experimenter begins by explaining the task to the participant and introducing them to the various controls on the Quest 2 device. Next, participants begin completing tasks in the VR environment. Participants are given the chance to take a break after each surface condition. After the VR tasks are completed, the participants are asked to fill out a post-study survey on the computer which has questions about the challenges that they faced in each of the SURFACE and TASK pairings, along with a NASA-TLX survey.

7.4 DESIGN

This experiment has a within-subjects design with three primary independent variables: TECHNOLOGY with two levels (VR and SAR); Projection SURFACE with 3 levels (FLAT, CONTINUOUS, DISCONTINUOUS; and ANGLE with 6 levels (15°, 30°, 45°, 60°, 75°, and 90°). Each of the ANGLE trials is repeated with 2 CONFIGURATION options that describe whether the participant or the projector was placed at an oblique angle while the other remained at 90° to the image plane (PROJECTOR and PARTICIPANT). The ANGLE repetition with 90° is only performed once because the CONFIGURATION is the same whether the participant or projector is at 90°.

The order of TECHNOLOGY is balanced between participants to ensure an even split. The order for each TASK and the ANGLE/CONFIGURATION trials is randomized and the ordering for SURFACE is counterbalanced using a Latin Square.

The primary measures computed from logs are *Accuracy* and *Completion Time*. The task is the perfect square task from chapters 4 and 5.

In summary: (2 TECHNOLOGIES × 3 SURFACES × 1 TASK × 11 ANGLES/CONFIGURATIONS) = 66 data points per participant.

7.5 DISCUSSION

Due to technical issues with the SAR setup, we were unable to run this experiment. However, we outline the analysis that could be done on data from the experiment.

TASK COMPLETION TIMES Task completion times are comparable across the VR and SAR conditions because the locomotion method, scale, and input methods are consistent across the conditions. The analysis can follow the techniques seen in chapters 4 and 5.

ACCURACY The accuracy of each task can be evaluated using the same methods outlined in chapters 4 and 5.

MOTION PATH DIFFERENCES Although the area available to the participants for movement is smaller in this experimental setup than in chapters 4 and 5, the path that each participant takes to reach the ocular point can still be analyzed for motion path shape and areas where they paused. This information could be visualized to show motion data from a bird's eye view, similar to to visualizations in chapter 6.

8

FUTURE WORK

Anamorphic interaction cues offer a way to encourage viewers to explore a space while interacting with projected content. While this work explored perspective distortions across various viewing angles and surfaces, many avenues for exploration remain in perceptual studies and interaction design.

ANAMORPHIC INTERACTION CUES IN THE WILD Display blindness is an effect where a user intentionally or unconsciously ignores a display because they do not expect there to be any interesting content on it [30]. With anamorphic interaction cues, a user would not only be less likely to ignore the cue, but would actively make an effort to reach a location where they can see and interact with it. Future work could explore whether observers interact with anamorphic interaction cues in more realistic settings that mimic a full museum exhibit as opposed to a controlled experiment with one stimulus at a time.

DYNAMIC OCULAR POINT MANIPULATION We explored how static anamorphic interaction cues can be used to encourage movement in an observer, but this could be extended to setups where the observer location is tracked throughout the experience. Dynamically changing the optical point based on the movement of the user could be used to simulate a 3D object using a 2D projection, similar to the techniques used in CAVE systems and view-dependent rendering. It could also be used to place anamorphic interaction cues at oblique angles relative to the user regardless of where they are in the space to guide them in different directions.

INTERACTION We did not explore pointing-based interactions with anamorphic interfaces, but future work could incorporate perspective-dependent pointing tasks such as using Perspective Cursor [23] to interact with SAR interfaces. The current experimental protocol calls for the use of a keyboard as input, but freehand gestures could also be used to make the experience resemble a real-world SAR experience more closely.

GROUP MOVEMENT We examined how people move in isolation, but future work could also explore how group movement could unlock new interaction opportunities. For example, a designer could choose to track where all of the viewers in an experience are standing and unlock different interactions when a certain group size has been reached at a location.

PERCEPTUAL LIMITATIONS Future work could explore how other factors affect perception of anamorphic interfaces. For example, researchers could vary the starting distance of the participant and the projector to explore how the distance between the surface and the stimulus affects perception. Another unexplored area is projection onto 3D objects. With a SAR system, a designer could project content from 360° on an object in the scene as opposed to the 180° that was explored in this work. With a system that projects all around an object, a participant could walk all around an object to find a good viewing angle.

9

CONCLUSION

We presented a design space for anamorphic interaction cues and the results from user studies investigating the effect of viewing angle and projection surface on user movement and understanding. We also discussed plans for an experiment comparing the performance of perspective-finding tasks in VR in comparison with SAR and discuss its implications for prototyping SAR experiences. We found that increased complexity and occlusions in projection surfaces actually aid viewers in finding the correct viewing angle, as long as some of the content is still visible from the user's initial viewing angle. These results are distilled into recommendations for designers of anamorphic SAR experiences so that they can create experiences that inspire curiosity and exploration across a variety of projection surfaces.

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