Reading on 3D Surfaces in Virtual Environments

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Figure 1: We investigated text renderings on different 3D shapes, including convex (sphere, cylinder), plane and concave surfaces, and measured their effect on reading performance and experience.

Abstract

While text tends to lead a rather static life on paper and screens, virtual reality (VR) allows readers to interact with it in novel ways: the reading surface is no longer confined to a 2D plane. We conducted two user studies, in which we assessed text rendered on different surface shapes in VR and their effects on legibility and the reading experience. Comparing differently curved surfaces, these studies disclose the impact of warp angles and view box widths on reading comfort, speed, and distraction. Our results suggest that text should be warped around the horizontal rather than the vertical axis, and we provide recommendations for the extent of warp and view box width. In a proof-of-concept application, we used everyday 3D objects as text canvases and studied them through an information-seeking task. The studies' implications inform VR interfaces and, more generally, the rendering of text on 3D objects.

Index Terms: Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Interaction design—Interaction design process and methods—User interface design;

1 Introduction

Although the popularity of new kinds of media is increasing, most information remains to be consumed via reading. At the same time, reading is also a traditional way of interacting with people's information in daily life, but with the advent of new technologies, reading patterns are constantly changing. People can access information faster, from anywhere, at any time, using mobile devices rather than solely paper. Whether on paper or digital devices, while the form of reading changes [6], text display has largely remained two-dimensional. As virtual reality (VR) systems enter the consumer market a broad range of games, applications and experiences have been created. Mostly through trial-and-error, User Interface (UI) design patterns in VR have emerged [1, 20]. While VR provides an immersive experience through 3D multimedia, text remains an important modality to convey information [16]. Guidelines exist for text layout, legibility, font and other text parameters for most display and device types [3, 28]. Text display in VR, however, has so far only been sparsely researched. While companies, such as *Oculus* and Google informally released their best practices around text presentation, a comprehensive analysis of displaying text in VR is still an active area of research.

Researchers have been actively investigating the display of text in 3D and mixed reality environments in recent years with an emphasis on plane surfaces: Rzayev *et al.* [26] conducted reading tasks on Augmented Reality (AR) displays to define effective text positioning strategies. Dingler *et al.* [7] investigated parameters for displaying text in VR, for which they assessed the display distance, angular height and text font. While Grout *et al.* [13] conducted a study about displaying desktop interfaces in 3D virtual space to analyze the performance of reading tasks on plane and concave surfaces, work by Lu *et al.* [17] indicated that curved screens could enlarge the view angle and potentially facilitate text display in the periphery to increase immersion.

On the other hand, a lot of text in our surroundings is found rendered on objects, such as signage, appliances, or consumer goods, whose surfaces are often non-planar. In VR, such objects are often covered by textures instead, whereas they could potentially provide textual information as they do in the real world. Current VR systems struggle, however, to provide the fine-grained resolution necessary to display small and effective textual content. In our work, we focus on curved text displays in VR and explore the factors that affect the reading experience, including comfort and effectiveness. Our contribution is as follows:

- We present findings from a user study with 16 participants comparing the reading experience on concave, convex, and plane surfaces in VR.
- Based on our findings, we subsequently focused on different warp angles and view box widths and conducted a second study with 18 participants to compare and elicit factors that influence legibility and reading comfort.
- Finally, we created an exploratory VR application which demonstrates how text renderings can be applied to commonly found, warped 3D objects.

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2 BACKGROUND

Our work is based on readability studies and text rendering in virtual environments, both of which we will briefly discuss in the following.

2.1 Screen Reading

Different factors affect screen reading performance and readers' subjective impressions. Mills and Weldon [19] investigated text reading on computer screens identifying parameters, such as character formatting and screen characteristics affecting readability. As for the characters, they mentioned that people read faster when characters were smaller, while for a single character, the legibility of larger characters is higher than of smaller ones. They also indicated that reading lightly coloured characters on dark backgrounds is preferable to when the refresh rate is low (50-60cps). In addition, once the line width of the text is different, the feeling of easy reading is different, and even when the length of each line is kept the same, as long as the number of words per line is different, users can quickly feel the difference.

Mayr *et al.* [18] focused on the relationship between pixel density and reading experience. While no quantitative findings regarding reading comprehension and speed could be found, the subjective reading experience seems to be positively affected on screens with higher pixel densities. Jankowski *et al.* [15] looked at integrating text with video and 3D graphics. Evaluating different font rendering styles and colours, they showed that rendered on a semi-transparent panel with a dark background improves the reading experience.

2.2 Text Rendering in Virtual Environments

With the proliferation of VR and AR devices, few studies focused on reading activities in virtual environments. Chen *et al.* [4] investigated how to display and access information in VR effectively concluding with a text layout taxonomy, which considered text quantity, visual attributes (e.g., font size, type, colour), and location. Evaluating a 'within-the-world' (object-space) *vs.* a 'heads-up display' (viewport-space) rendering, they found that heads-up displays benefit from text projected onto faces of objects in a 3D scene as they undergo pitch, yaw, and roll transformations. Polys *et al.* [22] produced similar findings showing that viewport interfaces outperform object space layouts in terms of accuracy, time, task difficulty, and subjective ratings. Dittrich *et al.* [10] focused on 2D and stereo projections finding that larger font sizes are required in environments with low angular resolution (6-13 arc minutes/pixel) compared to similar 2D display conditions.

Gabbard *et al.* [12] examined the influences of text drawing styles, background textures, and lighting on text legibility in outdoor AR. Sousa *et al.* [30] investigated ambient lighting conditions for when radiologists analyze and interpret images. Using VR headsets, they found performance-decreasing effects of unsuitable ambient conditions.

Rzayev *et al.* [26] compared different locations for rendering text on a heads-up display fixed in relation to the user concluding that what *Google Glass* proposed, *i.e.,* displaying text in the top-right periphery, tends to increase workload and reduce comprehension. Renderings in the centre or bottom (while walking) were found to be more effective text positions. Other investigations also explored the placement of text on plane surfaces within head-mounted displays [21] and developed techniques to enhance the text (subtitle) viewing experience [29].

Fewer studies investigated the presentation of text on surfaces other than planes. Grout *et al.* [13] explored text renderings on concave surfaces in the periphery as flat panels seemed to be more affected by distortions impairing reading performance. Moreover, Roh [25] mentioned that there are multiple benefits of using curved displays. For instance, the use of curved displays increases the immersive experience compared to flat displays as it provides a larger field of view. Meanwhile, curved displays could help users to scan and get more information at once compared with flat ones. Fafard *et al.* [11] presented a fish-tank VR display which created an immersive 3D experience.

More recently, Dingler *et al.* [7] investigated text parameters for reading in VR looking at text size, convergence, view box dimensions and text positioning to explore their impact on reading comfort levels. They listed the participants' preferences of the parameters, including text font and background, view box parameters as well as angular height. In their experiment, the view box dimensions also affect users' reading comfort level.

The above-mentioned studies informed a lot of the design considerations that went into our investigation. To allow designers of virtual environments to be more flexible when it comes to text renderings, we set out to explore the effects of different 3D surfaces on the reading experience. Since everyday objects can be warped in both concave and convex ways, our work is the first step towards investigating the effects of replacing simple object textures with textual information on reading performance and user experience.

3 3D READING SURFACES

While the main purpose of Grout *et al.* [13] exploring concave interfaces was to exploit the use of 3D space, we focused on the rendering of text on 3D objects as they may appear in different shapes (spheres, cones, cubes, etc.) in VR environments. Therefore, we started an investigation into plane, concave, and convex surfaces. In the following, we present the rationales behind each of our designs.

- **Plane**: Plane surfaces are the most common form of reading interfaces both in the physical and digital world. We use them, therefore, as a baseline condition in our investigation. A sample plane reading surface is presented in Figure 1, second from the right.

- **Concave**: Concave interfaces have been studied by Grout *et al.* [13], who found that reading performance improved on larger panels when rendered on concave displays comparing to a flat surface. The concave warp (Figure 1, rightmost) effectively enlarges the text in the periphery of the users' view and, therefore, can be easier to read.

- **Convex**: Fafard *et al.* [11] presented a physical mixed reality reading display—so-called fish-tank—for multiple users to interact with. They warp its contents around two axes: vertical and horizontal, resulting in a spherical display. There are other forms of convex interfaces: by unpacking the effect of text warped around a single axis, it results in two types of cylinders: vertical and horizontal.

Sphere: Sphere (Figure 1, leftmost) is a combination of equal warp around both the vertical and horizontal axes. Radius and font size define the warp degree. Spheres are essential building blocks for many 3D virtual environments containing balls and planets, for example. Spherical warp also occurs with a magnifying glass where the centre is warped stronger than the periphery.

Vertical Cylinder: A vertical cylinder (Figure 1, middle) is curved along the vertical axis with a flexible height. It appears in VR as renderings of poles, posts, or columns. Other objects, such as bottles or glasses, are warped around the vertical axis, which can contain text content, such as ingredient descriptions. The degree of the warp is determined by the cylinder's radius.

Horizontal Cylinder: Horizontal cylinder (Figure 1, the second from the left) results from a rotation of the vertical cylinder. Its height (referred to as width in the following) depicts the horizontal plane, and its radius determines the degree of warp. Horizontally warped objects can be found in the form of scrolls or rolls.

4 STUDY 1 – SURFACE STUDY

To assess the effects of these shapes on reading performance and experience, we conducted a pilot study comparing text renderings on these basic shapes: plane, concave, and convex.

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4.1 Study Design

We employed a within-subject design to assess the influence of four surface conditions on the reading experience, namely: 1) plane, 2) concave, 3) sphere, and 4) horizontal cylinder. To make the curved surface comparable, we set the same degree of warp for each surface (90°). The details for measuring the warp of the surfaces are described in the next section. For assessing the reading experiences, we measured:

- Objective: reading speed (based on the self-paced button press to indicate the completion of text reading) and comprehension (number of questions answered correctly in a total of ten post-reading questions).
- Subjective: comfort level, ease of reading, perceived reading speed, understanding, distraction, and immersion.

4.2 Study Apparatus

We built a VR environment using Unity3D, in which we could import text and adjust shape design parameters, such as distance, view box, warp angles, heights and widths. We used the Oculus Rift CV1 system, which came with a head-mounted display (HMD), a pair of controllers, and two infrared sensors which can track the position of headset and controllers. The screen resolution of the HMD is 1080×1200, while the field of view(FoV) is 110 degrees diagonal. An Alienware Aurora R7 with an Intel Core i7-8700K CPU@3.70GHz and NVIDIA GeForce GTX 1080 ran the virtual environment for the user study.

We set the following UI parameters based on the recommendation by Dingler *et al.* [7]:

- View box: The view box displays a total of 9 lines, which was kept consistent across all conditions. Each line comprised around 40 characters.

- Text font: Sans-serif Arial text with light colour was used, based on Dingler *et al.'s* [7] recommendation.

- Background: To minimize the distractions from the surrounding environment we used a dark starry sky and a dark blue color (*#13171A*) as a background of the view box [19].

- Font angular size: We chose angular sizes within the recommended range of common LogMAR scale sizes [24] which also fell into the range suggested by Dingler *et al.* [7], namely 1.4°.

- Curved text: We used *CurvedUI* in Unity's asset store to warp the text. A flat plane would have a warp angle of 0°, whereas a warp angle of 180° would turn the plane into a sphere or cylinder. We modified the angle to 90° for the concave display and to -90° for the convex displays. The sphere interface adjusted both vertical and horizontal angle of the canvas while the concave and convex displays tweaked the horizontal arc of the canvas.

- Content position & field of view of the view box: Curved text implies that different text parts are displayed at slightly different distances. For example, the text on the sphere is curved inward, downward, left and right, thus the position of each line is not at the exact same location. As a result, we indicate its position by its centre, i.e., 3 meters from the camera. Since in VR, angular representation is more reliable than other parameters to measure the range of distance, we measure the width of view box by FoV. Specifically, we decided the horizontal FoV by considering the angular height of the font and the number of characters preferred by users [7]. The vertical FoV of the view box was determined by the angular height of the font and the number of lines preferred by participants [7]. As such, the horizontal FoV of the view box was set to 24.9°, while the vertical FoV to 17.4°.

Besides each study condition, we also included a guide page for participants to familiarize themselves with the controls to minimize novelty effects. For each condition, the text was presented at the centre. The text could be scrolled up and down via the controllers.

We ensured the texts had similar difficulties by selecting them from a corpus of standardized reading assessment for English as a second language [23]. Each text contained 550 words and came with ten comprehension questions which allowed us to calculate the objective comprehension scores. To avoid ordering effects the sequence of the surfaces was counterbalanced through a Latin Square design and the texts were randomly allocated to each condition.

4.3 Participants

We recruited 16 participants (8 women, 8 men) with an average age of $M = 25$ ($SD = 3.5$) years from our university's network with backgrounds in finance, accounting, information system, IT, business IT, psychology and math. Three of them were native speaker while the others' native tongue included Mandarin, Indonesian, Farsi, Cantonese, Hindi / Urdu, and Malay. All of our participants were proficient in English, however, and used English as their primary language. Eight wore glasses during the test, one wore contact lenses, while the rest did not need vision correction. Most of our participants had used VR applications once or twice before, and two owned Google VR glasses. One participant had never used VR before. In terms of frequently-used devices for reading, participants indicated phone and PC. Twelve said that they read daily on their phones, and five were daily users of printed media, such as books.

4.4 Procedure

We first welcomed participants into the lab, introduced them the goal of the study, and explained each step of the experiment in detail. We handed them a plain language statement and asked them to read and sign a consent form. We then applied a short demographic survey, which included questions on the existence of any potential eye-sight issues, prior experience with VR systems, and general reading habits. Before starting the experiment, participants were asked to adjust the headset and familiarise themselves with the environment and controls using a guide page displayed in VR. We then administered an initial assessment on motion sickness [14], including checking for symptoms of eye strain, fatigue, and general comfort.

For each condition, participants were guided through the UI and asked to read a text that was randomly allocated to that condition. The time for each reading session was automatically recorded, and after the end of the text was reached, a short comprehension test, which included ten questions, was administered outside the VR.

After each condition, participants completed a survey assessing immersion and subjective reading experience on Likert-style rating scales (with 1='Strongly Disagree' and 7='Strongly Agree'). Questions were taken from a short version of the Presence Questionnaire as suggested by Schwind *et al.* [27]. Subjective assessments included the perceived reading speed, comfort level, ease of reading, perceived comprehension, and distraction. This procedure was repeated for each of the four conditions.

After the completion of all reading tasks, we conducted a semi-structured interview to ask about general preferences and comments about the reading experience, which we audio-recorded. The entire study session lasted less than an hour for each participant, which we compensated with a $10 voucher.

4.5 Results

We applied full-factorial ANOVAs to our parametric measures of reading speed and comprehension and Friedman tests for non-parametric scores, such as self-ratings.

4.5.1 Objective Measures

With regard to **reading speed**, the ANOVA did not yield a statistically significant difference between the surface conditions ($F(3,60) = 0.072, p = 0.975$). Similarly, we did not find a statistically significant difference in **comprehension** as assessed through the comprehension tests ($F(3,60) = 0.815, p = 0.491$).

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4.5.2 Subjective Measures

Regarding **reading comfort**, a Friedman test showed a statistically significant difference in comfort level ($\chi^2(3) = 12.74, p = 0.005$). Pairwise comparisons yielded a statistically significant difference between reading on a cylinder and reading on a sphere ($Z = -2.664, p = 0.008$) with the cylinder being rated $Mdn = 5(SD = 1.26)$ and the sphere $Mdn = 2.5(SD = 1.42)$. There was no statistically significant difference between the remaining conditions.

A Friedman test on **ease of reading** yielded a statistically significant difference, $\chi^2(3) = 11.928, p = 0.008$. Pairwise comparisons resulted in a statistically significant difference between reading on a sphere and reading on a plane ($Z = -2.847, p = 0.004$) with the sphere being rated $Mdn = 3(SD = 1.82)$ as opposed to the plane $Mdn = 5(SD = 1.16)$.

With regard to **perceived reading speed**, we did not find a significant difference between different display surfaces ($\chi^2(3) = 4.329, p = 0.228$). Similarly, **understanding** did not yield a significant difference between condition ($\chi^2(3) = 3.735, p = 0.292$).

In terms of **distraction**, however, there was a statistically significant difference ($\chi^2(3) = 9.965, p = 0.019$) with a significant difference between reading on a sphere and reading on a plane ($Z = -2.722, p = 0.006$). The sphere was rated $Mdn = 4(SD = 1.79)$ as opposed to the baseline $Mdn = 1(SD = 1.57)$.

The tests did not show any difference between conditions for **immersion** ($\chi^2(3) = 1.304, p = 0.728$).

4.6 Discussion

The results of the pilot study showed mostly subjective differences with regard to reading comfort, ease of reading, and distraction. While the baseline of a plane surface was preferred in terms of ease of reading and providing less distraction, the comparison of two convex interfaces yielded that the horizontal cylinder was more comfortable to read on than the sphere.

The participants who disliked reading commented that "*reading on the sphere is very disturbing, the focus was too stretched in the middle due to its shape. I felt like my eyes had to make an effort to move from left to right, top to bottom, and it was hard to concentrate.*". Another participant mentioned "*It made my eyes feel a bit unfocused because the shape of the text at the edge is smaller than in the middle (like a fish-eye shape). It hindered me from reading at normal speed. I had to lower my reading speed.*" Although the cylinder was also warped, the feedback of the participants was different from the sphere. They felt reading on the cylinder made them feel easier to concentrate "*I can easily concentrate on the middle and read the text line by line*" and "*It seems to highlight the sentence I am reading right now, which made me feel I read very quickly.*"

While we could not confirm that warping text around objects increased the immersion when compared to 2D reading interfaces in VR, it may be inevitable at times to render text across 3D objects rather than plastering the environment with 2D labels. The main take-away from this study, therefore, indicates that if the text is warped around 3D objects, it is more comfortable for the reader to do so over a single (cylinder) rather than two (sphere) axes.

To investigate such one-dimensional warp in more depth, we conducted a second user study focusing on cylinders in both horizontal and vertical orientation as well as the degree of warp and how different warps may affect the user experience.

5 Study 2 – Warp Study

Based on the insights from the surface study, we set out to explore in more detail the differences of different convexly curved displays in VR, namely cylinders and spheres with various warp degrees and view boxes. Concave surfaces can be effective when the view box size surrounds the user in VR [13]. However, we found fewer cases of text presentation on a concavely shaped object in natural VR environments. Therefore, we removed this condition from the subsequent study. Similarly, we focused on convex interfaces rather than text on a plane as we were interested in text renderings across 3D warped objects in particular and the difference therein.

Therefore, we conducted this second lab experiment focusing on convex shapes, including spheres, vertical cylinders, and horizontal cylinders. Also, we aimed at putting warped reading interfaces into a real reading environment in VR to gather user feedback. Hence, this study consists of two parts with the first part assessing the effect of shape and warp degree and the second part exploring an example application of a reading environment in VR.

5.1 Study Design

We employed a within-subject design with multiple independent variables, namely 1) three shapes (sphere, vertical cylinder, and horizontal cylinder) 2) three warp angles (50°, 70°, and 90°) and 3) two different view box widths (FoV: 22.6° and 33.6°), resulting in a $3 \times 3 \times 2$ experimental design.

The sequence of the text content was randomly allocated to the reading surfaces while the reading sequence of the surface was counterbalanced using a Latin-square design. We used articles from Wikipedia about major cities in the world. The length of each article was about 150-170 words with a Flesch–Kincaid reading score of 60 to 65 to ensure similar text difficulties. In this study, we measured:

- *Objective* reading speed, reading accuracy, self-corrections, and comprehension.
- *Subjective* comfort level, ease of reading, perceived reading speed, understanding, and concentration.

All of these questions were presented using Likert-style scales from 1 to 7 (with 1='Strongly Disagree' and 7='Strongly Agree'), while legibility was measured by running a Running Record task [5], i.e., having participants read out loud the text in front of them and recording the errors committed. Before switching to the second part of the study where participants explored an example reading application, we also invited participants to customize each shape's setting by adjusting the preferred warp angle as well as the FoV for each surface. This procedure has been successfully used by Dingler *et al.* [7] to elicit text parameters, but data on FoV and warp degree were so far missing.

5.2 Settings

We used the same setup as described in the previous study. In addition to the different surfaces, we also used three different warp angles (50°, 70° and 90°),i.e., the vertical angle of the canvas for sphere and the horizontal arc of the canvas for cylinders. Further, we experimented with two widths for the view box (FoV: 22.6° and 33.6°). Therefore, 50° was the flattest and 90° the most curved setting. For convex surfaces, the distance between the centre point and the user was kept constant, while the surfaces' edges are progressively bent away from the viewer. In our experiment, we set a fixed distance from the centre point of the surface to the users' position as 3 meters.

The dimension of the view box was also shown to affect the reading performance by Dingler *et al.* [7] and Mills and Weldon [19], who indicated that the line width affected ease of reading. To explore which length would improve the reading performance in our experiment, two view box widths were selected while the height was kept constant. These two different widths were set as 22.6° and 33.6° while the vertical FoV of the view box was 26.3°.

5.3 Participants

We recruited 18 participants (9 women, 9 men) with an average age of $M = 23$ ($SD = 4.6$) years from our university's network, none of which had participated in the previous study. Seven participants reported to have corrected vision, eight were native speakers while

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the native tongues of the remaining included Hindi, French, Persian, Tamil, Urdu and Cantonese. However, all participants were proficient in English. Ten participants had used VR equipment once or twice before, while six had no prior VR experience and two used it frequently. Nine participants indicated to read at least half an hour on a daily basis, and the most popular reading device was reported to be mobile phones and PCs, as well as printed media. The whole study took around one hour, for which we compensated participants with a $10 gift voucher.

5.4 Procedure

We welcomed participants to our lab and—after having explained the purpose of the study and let them sign a consent form and a plain language statement—we administered a short demographic survey, which included questions on eyesight, reading habits, as well as prior experience with VR.

After putting on and adjusting the headset, participants were guided through a similar tutorial as in the first study, which introduced them to the different controls. Throughout the experiment, participants were offered to take a rest at any time, in case they experienced signs of discomfort or motion sickness. The first part of the experiment comprised $3 \times 3 \times 2 = 18$ conditions and ended with three customizable displays. For each condition, we asked participants to read out loud the text, which we recorded for later analysis.

After each text, we administered a survey to assess the reading experience in terms of subjective measures like perceived readability, reading comfort, and perceived comprehension. To minimize disruptions, we administered these surveys as forms in the VR. Comprehension questions were delivered and recorded verbally by the experimenter.

After the completion of the 18 reading conditions, we presented participants with each of the three reading surfaces and provided controls for them to customize the FoV as well as the degree of warp to their most comfortable level. Participants were then asked to read aloud the text being displayed with their custom settings.

After having completed the reading and surface customization, we invited participants to enter the second part of the study, which comprised an example environment filled with reading interfaces to be explored (see Figure 2). We instructed participants to find certain information on three different object types, namely 1) on an advertising pillar, 2) a paper scroll, and 3) different bottles. This part was used for collecting qualitative data on these reading experiences. The following questions set the tasks:

- Where will the Metallica concert take place?
- Which is the main ingredient in Heinz Ketchup?
- Which Egyptian God teared out the eye of Horus?

The questions were designed not with the intention of assessing comprehension, but rather to guide participants through the experiment and find relevant information.

To answer these questions, participants had to navigate through the environment and interact with its objects by picking up bottles, scrolls (horizontal cylinder), and locating the respective advertising pillar (vertical cylinder). The objects' text was printed in different warp angles, including some of the same warp angles as in the previous study. Moreover, we implemented a feature where participants could morph the warped surfaces to a flat surface by pressing the button on the controller. The goal was to provide a direct comparison between reading on a warped surface to a plane. Text could then be scrolled up and down on all objects and surfaces, which provided more detailed information despite spatial constraints. Participants were free to explore the environment for as long as they wished after having answered all three task questions. Upon completion, we conducted a semi-structured interview, in which we collected qualitative feedback on 3D reading surfaces and their applications.

Figure 2: Screenshots of objects in the example application with rendered text onto warped 3D objects, including a scrollable advertisement column (left), a bottle with ingredients (up right), and an unfolded warped surface (bottom right).

5.5 Data treatment

To evaluate legibility of text rendered on the different surface conditions, we applied another Running Record task [2], which requires participants to read out loud. Legibility is subsequently analyzed by taking into account reading speed and accuracy. In the following, we describe how we processed this data and calculated the metrics:

• ***Reading Speed (RS)***: The time was calculated after removing filler words, such as "*emmm, uhhh*" or unrelated opening statements made by participants. The number of words read are referred to as *WA*. The reading time (RT) is used for calculating the reading speed (RS) for each text display, which resulted in the following equation:

$$RS = \frac{WA}{RT} \tag{1}$$

• ***Self-correction***: For the transcripts, according to the procedure of the Running Record [2], each time a word is added, deleted or read the wrong way, an ***Error*** is counted. Words that are mispronounced do not count as an error. If participants self-correct a word or sentence by re-reading, it is not recorded as error but considered a self-correction.

• ***Accuracy of reading (AR) & Accurate Words per Minute (AWPM)***: similar to Grout *et al.* [13] the accuracy of reading is based on the errors and the number of words in a paragraph and calculated as follows:

$$AR = 100 - \frac{Errors}{WA} \times 100 \tag{2}$$

$$AWPM = \frac{WA - Errors}{TR} \times 60 \tag{3}$$

where the Error term in the equation represents the number of errors the participant committed.

5.6 Results

Based on the data we collected, we applied factorial ANOVAs to the objective measures such as reading speed as well as subjective measures like comfort level. Additionally, we calculated Pearson correlations for testing the relationships between different measurements. The audio records were transcribed and analyzed following the Running Record method. Finally, we analyzed participants' preferences of warp angles and view box widths for each shape in the customization phase.

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5.6.1 Objective Measures

No statistically significant difference was found among all objective measures in terms of the three factors (shapes, warp angles, and view box widths) and their interactions.

With regard to **reading speed**, the ANOVA did not detect statistically significant difference in terms of shapes ($F(2,306) = 0.428, p = 0.652$), warp angles ($F(2,306) = 0.016, p = 0.984$) and view box widths ($F(1,306) = 0.001, p = 0.972$). There was also no interaction effect (all $p > 0.05$).

In terms of **AWPM**, the tests did not yield a statistically significant difference for shapes ($F(2,306) = 0.009, p = 0.991$), warp angles ($F(2,306) = 0.012, p = 0.988$), and view box widths ($F(1,306) = 0.002, p = 0.963$) either.

As for **self-corrections**, there was also no statistically significant difference between shapes ($F(2,306) = 2.128, p = 0.121$), warp angles ($F(2,306) = 0.158, p = 0.854$), and view box widths ($F(1,306) = 1.318, p = 0.252$). No interaction effect could be detected (all $p > 0.100$).

Similarly, we did not find significant differences in **comprehension** which was assessed through the comprehension tests regarding shapes ($F(2,306) = 0.427, p = 0.653$), warp angles ($F(2,306) = 1.862, p = 0.157$), and view box widths ($F(1,306) = 3.844, p = 0.051$). No interaction effect was observed (all $p > 0.100$).

5.6.2 Subjective Measures

To summarize, we found no statistical significant difference in ease of reading, perceived reading speed, understanding, concentration, but only comfort level. Regarding **comfort level**, there was statistically significant differences between the view box widths ($F(1,306) = 4.021, p = 0.046$) and warp angles ($F(2,306) = 6.490, p = 0.002$), but not between shapes ($F(2,306) = 2.879, p = 0.058$). Reading on the short view box ($FoV = 22.6°, Mean = 5.81, SD = 1.13$) seemed to be better than reading on the long view box ($FoV = 33.6°, Mean = 5.56, SD = 1.23$). Post-hoc Tukey showed that reading comfort level on the most distorted surface ($90°, Mean = 5.36, SD = 1.32$) was statistically significantly lower compared to reading on a less curved ($70°, Mean = 5.90, SD = 1.04, p = .002$) surface and the flattest surface ($50°, Mean = 5.80, SD = 1.13, p = .017$), while there was no difference between 50° and 70°. The post-hoc analysis also indicated that reading on the horizontal cylinder ($Mean = 5.88, SD = 1.10$) was more comfortable than on the sphere ($Mean = 5.50, SD = 1.24, p = 0.045$). No interaction effect was found (all $p > .050$).

As for **ease of reading**, there was no statistically significant difference found for shapes ($F(2,306) = 1.320, p = 0.269$), warp angles ($F(2,306) = 1.644, p = 0.195$), and view box widths ($F(1,306) = 0.959, p = 0.328$). No interaction was found (all $p > 0.100$).

With regard to **perceived reading speed**, no significant difference was found for shapes ($F(2,306) = 1.747, p = 0.176$), warp angles ($F(2,306) = 0.504, p = 0.604$), and view box widths ($F(1,306) = 1.059, p = 0.304$). No interaction effect was found (all $p > 0.500$).

Regarding **understanding**, no significant difference was found for shapes ($F(2,306) = 0.235, p = 0.791$), warp angles ($F(2,306) = 0.289, p = 0.749$), and view box widths ($F(1,306) = 0.126, p = 0.722$). Moreover, no interaction effect was found (all $p > 0.500$).

In terms of **concentration**, we did not find a significant difference for shapes ($F(2,306) = 0.413, p = 0.662$), warp angles ($F(2,306) = 0.457, p = 0.634$), and view box widths ($F(1,306) = 1.349, p = 0.246$). No interaction was found either (all $p > 0.100$).

5.6.3 Correlation

Pearson correlations were performed to determine the relationship between objective and subjective measures. Overall, our results indicate that there are positive correlations among subject measures including comfort level, ease of reading, perceived reading speed, understanding, and concentration. However, the results also suggested that the subjective measures generally do not correlate well with the objective measures (except some small, positive correlations regarding reading speed).

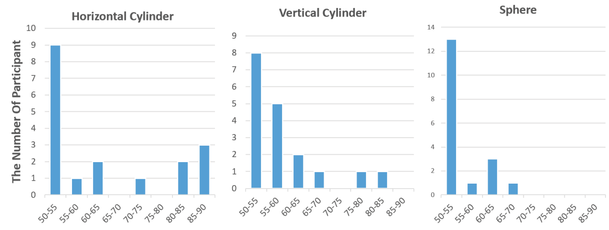

Figure 3: Participant preferences for warp angles.

The statistics showed that there are large, positive correlations between **comfort level** and and other measures including perceived reading speed ($r = 0.662, n = 324, p < 0.001$), understanding ($r = 0.509, n = 324, p =< 0.001$), and concentration($r = 0.663, n = 324, p < 0.001$). It also showed a medium, positive correlation with ease of reading ($r = 0.456, n = 324, p < 0.001$).

In addition, **ease of reading** also had a medium, positive correlations with variables, including perceived reading speed ($r = 0.384, n = 324, p < 0.001$), understanding ($r = 0.297, n = 324, p < 0.001$), and concentration ($r = 0.483, n = 324, p < 0.001$).

Moreover, **perceived reading speed** had large, positive correlations with understanding ($r = 0.617, n = 324, p < 0.001$) and concentration ($r = 0.570, n = 324, p < 0.001$), as well as a small, positive correlation with reading speed ($r = 0.277, n = 324, p < 0.001$).

Furthermore, **understanding** had a large, positive correlation with concentration ($r = 0.511, n = 324, p < 0.001$) and a small, positive correlation with reading speed ($r = 0.240, n = 324, p < 0.001$).

Finally, **concentration** had a small, positive correlation with reading speed ($r = 0.149, n = 324, p = 0.007$).

5.6.4 Preference

In the elicitation phase where we allowed participants to customize their reading surfaces, a set of preferred parameters about warp angles and view box widths were collected.

• ***Warp Angles***: The participants' preference for the warp angles of the display is shown in Figure 3. Participants preferred the warp angle between 50° to 55° (less curved) for all of the shapes. For sphere surfaces, nearly 3/4 of the participants chose the warp angle between 50° to 55°. No participants preferred more than 70° for sphere surfaces. For horizontal cylinder surfaces, half of the users selected the warp angle 50° to 55°, while the choices of others sparsely distributed between 55° to 90°. For vertical cylinder surfaces, most of them picked the warp angle between 50° to 60°.

• ***View Box Widths***: Figure 4 shows the preference results of the participants regarding view box widths in all shapes, and it can be seen that the width was centralized around 270 to 300 units regard of all shapes. As the scale of view box is 0.005 while the distance from the participant to the centre of the view box is 3 meters, we could calculate the horizontal FoV from the equation shows as follows:

$$FoV = arctan(\frac{width \times scale}{2 \times distance}) \times 2; \quad (4)$$

where width in the equation indicates the width of the view box. The results showed that participants preferred 25.4° to 28.1° as horizontal FoV of the view box.

5.6.5 Interview Results from Application Study

• ***Curved Version vs. Flat Version***: From the interview feedback gathered from the second part of the study (application scenario), 12

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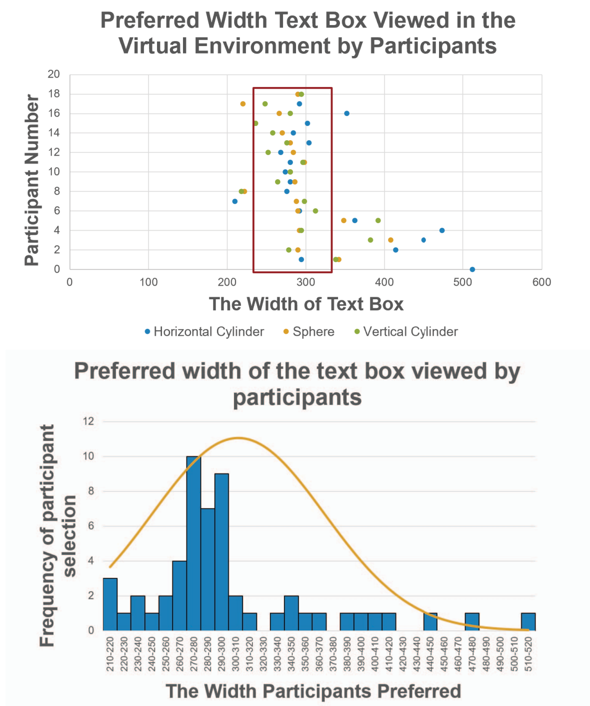

Figure 4: Participants preferences for view box widths.

participants (66%) reported the curved display was more immersive (in terms of showing text on objects like bottles) while the unfolded flat version was easier to read when comparing the curved version with the flat version. One participant commented, "*The curved display like normal in the real world, but the flat one is pretty easy to read, I like both of them.*"

• ***Factors affecting the reading experience***: During the interview, 10 participants (56%) mentioned that warp angles highly affected their reading experience in VR. The flat version seemed easiest to get information from, but for the slightly curved displays, most participants preferred reading on the convex display. Most participants found that since the HMD was connected by a wire, it was difficult to move which meant that when they were looking for information on the advertisement pillar, it was difficult to go the exact and comfortable reading position. In such cases, they preferred to read the flat version instead of the curved one.

5.7 Discussion

The results of our warp study indicate that comfort levels are affected by warp angle and view box width. High extent of warp (in our case was 90°) resulted in a lower level of comfort. The general reading comfort level was positively correlated to the perceived reading speed, understanding concentration, and ease of reading. In other words, a surface with a higher level of reading comfort encourages readers to think that their reading quality has improved.

However, the actual reading speed and accuracy of the comprehension test did not correlate well with the subjective results. We identified two possible reasons for this: First, our comprehension tests might not be able to tell the subtle difference with participants' subjective feelings. That is, the individual reading experience was not reflected by the set of questions we chose for comprehension tests. Second, since it is hard to measure if participants actually finished reading in VR, we applied the read-out-loud protocol [2] for objective reading speed measures, which might not represent the "real" reading speed of participants.

We further give recommendation for the widths of the view box and the warp angles based on the preference of participants. Considering their preferences, the horizontal FoV of view box should range from 25.4° to 28.1° when the vertical FoV is 26.3°, and the warp angle should be around 50° to 60° for all the three convex shapes, especially sphere and vertical cylinder. Our results also confirmed that in terms of comfort level, reading text rendered on a cylinder is better than reading on a sphere in VR. Moreover, the trade-offs between immersive reading and ease-of-reading in VR should be considered. According to participants' comments in our application study, warping generally seems to impact the perceived ease of reading negatively, but it can enhance the sense of immersion provided by VR in reading on objects, such as bottles.

6 Key Insights and Implications

In the following, we summarize our key findings as a guideline for future designs of text rendered on 3D surfaces in VR:

- Text renderings warped around a single axis (cylinder) are more comfortable to read than those warped around two axes (sphere).
- Two-axes warp (sphere) seems to distract from the text compared with a plane interface and, therefore, provides less ease of reading.
- Reading on less curved display (50° to 70° of warp) is considered more comfortable.
- Reading comfort, ease of reading, perceived reading speed, understanding, and concentration are positively correlated with subjective reading impressions. However, they do not necessarily correlate well with users' actual reading performance.
- Participants generally prefer the warp angle of curved displays to be between 50° to 60°.
- When reading text on curved surfaces in VR, the FoV of the view box is recommended to be between 25.4° to 28.1°, according to participants' preference.
- There is a trade-off between the ease of reading and an immersive reading experience when rendering text on curved objects like bottles. While the warp generally seems to negatively impact the perceived effectiveness of reading, there is an element of immersion to the usage of 3D objects as text canvases.

7 Limitation and Future Work

We identified some limitations of the current research and potential directions for future work. First, we only varied the horizontal width of the view box with a fixed vertical FoV, while in real use cases, vertical FoV can also be adjustable. However, as the vertical FoV of the HMD was limited, we decided to vary the horizontal FoV only. Second, instead of using a wireless HMD, we implemented our study with Oculus Rift CV1, which restricted the movement of the users in exploring the VR environment for the second application study. Nevertheless, participants were able to use teleportation and virtual walking techniques to traverse through the virtual environment. Third, we were using self-paced control and read-out-loud protocol to determine the text reading speed. More advanced technologies, such as eye-tracking, can be used in the future to determine the reading speed more accurately. Furthermore, although our results showed that there was a trade-off between ease of reading and sense of immersion in VR reading, we have not analyzed how we should balance those trade-offs, leaving space for future investigations. In our application scenario we focused on simple scrolling as a way to navigate text on 3D surfaces leaving room for explorations into alternative ways to control the reading flow through, for example, explicit gestures [9] or more implicit ways of interactions, including eye tracking [8]. Finally, the UI parameters (such as font, text size,

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and view box) of a reading interface can be subject to interaction effects on reading performance and experience, which should be considered.

8 Conclusion

Text in VR is predominantly rendered in a 2D fashion. In this work, we explored the effect of rendering text on 3D surfaces with different warp directions and degrees. In two user studies, we investigated how plane, concave, and convex surfaces would affect users' reading experience. Our results show that if text is warped around objects in a 3D environment, it should be done using a single axis. Further, the horizontal FoV of the view box and warp degree should remain within the range of 25.3° to 28.1° and 50° to 70° respectively in order to remain comfortable and provide a smooth reading experience. The insights from our studies allow designers of virtual environments to be more flexible but conscious when it comes to text renderings. Since common 3D objects are often warped in either a concave or convex direction, our work is the first step towards replacing simple object textures with textual information.

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