

User Preference for SharpView-Enhanced Virtual Text during Non-Fixated Viewing

Trey Cook*

Green Mountain Technology

Nate Phillips†

Mississippi State University

Kristen Massey‡

Mississippi State University

Alexander Plopski§

Nara Institute of Science and Technology

Christian Sandor¶

Nara Institute of Science and Technology

J. Edward Swan II||

Mississippi State University

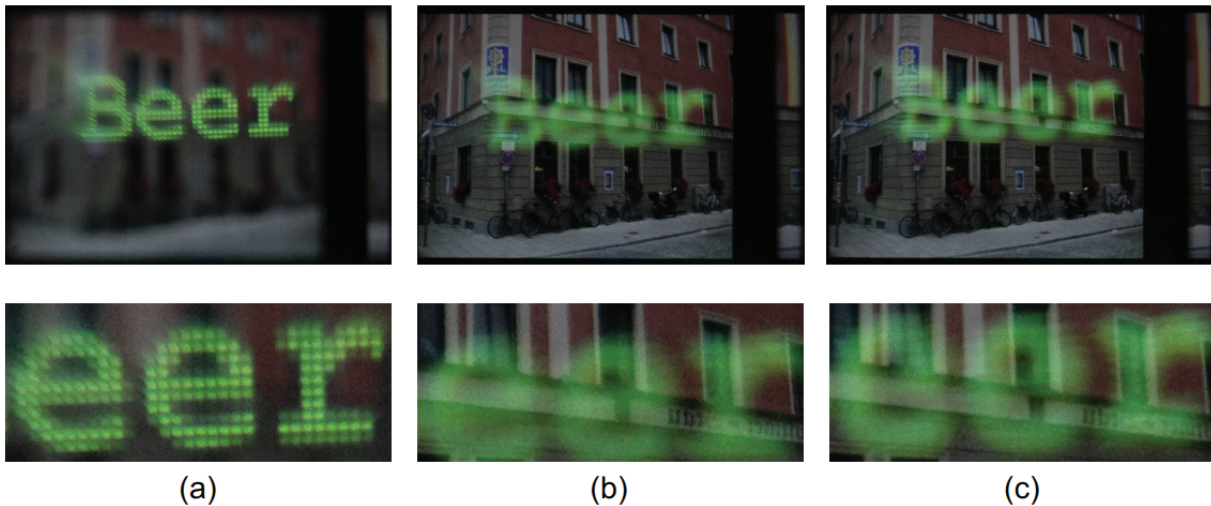


Figure 1: With fixed-focal length augmented reality (AR) displays, there is often a significant focal difference between the AR content and the real world content. The SharpView method [17] sharpens out-of-focus AR content, to improve its appearance. The purpose of the work in this paper is to measure whether SharpView improves the legibility of out-of-focus text labels. This figure shows an AR label at a near focal distance, 1.25 diopters (D) = 0.8 meters, seen in front of an image of a building at 0.12 D = 8.1 meters. In (a), the camera is focused on the AR text; note that the building is out of focus. In (b), the camera is focused on the building; the text is now out of focus. In (c), SharpView is applied to the text; the edges of the letters have increased contrast. Note that a camera cannot completely capture how this scene appears to a human eye.

ABSTRACT

For optical see-through head-mounted displays, the mismatch between a display’s focal length and the real world scene inadvertently prevents users from simultaneously focusing on the presented virtual content and the scene. It has been shown that it is possible to ameliorate the out-of-focus blur for images with a known focus distance, by applying an algorithm called SharpView. However, it remains unclear if SharpView also improves the readability and clarity of text rendered on the display. In this study, we investigate whether users reported increased text clarity when SharpView was applied to a text label, and how the focal demand of the display, the focal distance to real world content, and gaze condition affect the result. Our results indicate that, in non-fixated viewing, there is a significant user preference for SharpView-enhanced text strings.

*e-mail: hfcook3@gmail.com

†e-mail: Nathaniel.C.Phillips@ieee.org

‡e-mail: km1035@msstate.edu

§email: plopski@is.naist.jp

¶email: chris.sandor@gmail.com

||email: swan@acm.org

©2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

This is an author version preprint. The final version is available as: Trey Cook, Nate Phillips, Kristen Massey, Alexander Plopski, Christian Sandor, J. Edward Swan II, “User Preference for SharpView-Enhanced Virtual Text During Non-Fixated Viewing”, Proceedings of IEEE Virtual Reality (IEEE VR 2018), Reutlingen, Germany, March 18–22, 2018, pages 394–400, DOI: 10.1109/VR.2018.8446058.

Index Terms: augmented reality — context switching — sharpening — accommodation

1 INTRODUCTION

In the last few years, interest in commercial Augmented Reality (AR) development and applications has risen dramatically, as seen by the recent proliferation of commercial Optical See-Through Head-Mounted Displays (OST-HMDs) systems such as the Microsoft HoloLens, the Google Glass, and the Meta 2, among others. This technology underlies a rapidly growing field, with the potential to shape human experience in novel and unforeseen ways [2, 19, 24]. However, unfortunately, the application of OST-HMDs in this field is held back by a number of unresolved problems, such as the relationship between the typically fixed focal distance of virtual text in AR displays and the varied focal distances of fixation points in the real world.

In many modern AR head-mounted displays, there is a single specific viewing distance for AR content. This is helpful for device manufacturers because implementing a multi-focal AR display system would be both expensive and a significant engineering challenge. However, this approach does cause some potential problems for AR applications. These include the vergence angle and accommodative effort mismatch problem, which has been studied at some length [23].

Fixed AR viewing distances also have another important down-

side. When users wear an OST-HMD they are also, by extension, interacting with the real world. Since the real world does not exist at a single focal distance, switching rapidly between fixation on a real object to fixation on a fixed virtual plane takes some significant effort and has been shown to produce exhaustion, lead to eyestrain, and hinder the effectiveness of some AR applications [7].

To overcome or alleviate the negative symptoms of the switching problem in AR, without resorting to an expensive hardware solution, a particular form of virtual image manipulation, the SharpView algorithm [17], was considered. This algorithm essentially attempts to reverse the natural process by which our eyes bring distant objects into focus. In this process, a user fixates, or accommodates to, a distant object, by adjusting the lens shape and pupil size to reduce the visual blur surrounding that object. The SharpView algorithm predicts the degree of blurring that naturally occurs as users fixate on other focal planes and then attempts to reverse it, bringing the non-fixated virtual plane into clearer focus. This, in turn, may reduce eye fatigue and mental effort, as a user’s eyes no longer have to repeatedly swap between focal distances.

In using this algorithm, Oshima et al. [17] discovered that it could be applied successfully to virtual images, potentially allowing them to be incorporated into AR applications more effectively. This is an important result, lending credence to the idea that blur manipulation could be used to control, modify, or dampen a user’s accommodative reflex. However, certain questions still remain. The SharpView algorithm was tested with a fairly narrow range of images, none of which contained any textual information. Since textual information is likely to be important to many future context-switching applications, it is important to test SharpView specifically on text. Further, there are good reasons to believe that SharpView will not be as effective at enhancing text-based images. Letters, of course, are sometimes differentiated by relatively minute differences, while many letters’ straight lines represent something of a weakness for the SharpView algorithm.

Therefore, this work attempts to determine whether experimental observers would express a preference for SharpView-enhanced AR text when gazing at real world objects (Figure 1). Such a result would indicate that SharpView is potentially applicable for and useful in text-based applications, such as you might expect to see for a virtual tour guide program, a map heads-up display, or even some sort of social media feed. If true, blur control could potentially be used to reduce the need for context switching in text-based AR applications, provide a more comfortable end user experience, and increase the usefulness and effectiveness of AR experiences. Our results indicate that users indeed preferred seeing text that has been enhanced with SharpView when gazing at real objects not on the virtual fixation plane. Overall, the main contribution of our paper is a psychophysical experiment to investigate whether applying SharpView to AR text presents an enhanced user experience and increases the usability of AR.

2 RELATED WORK

This work was motivated primarily by the biophysical and visual effects of focal depth mismatch, context switching, and accommodation/vergence mismatch. Both of these characteristics can result in notable visual discomfort and fatigue and can even affect depth perception [13, 23]. Further, it has been shown that accommodation/vergence mismatch can notably impact task performance, reaction to stereoscopic changes, and visual acuity [8].

Context switching, defined as “the switching in visual and cognitive attention between real-world and virtual information” has been shown to cause task performance deterioration at six meters and significant amounts of visual fatigue at all tested distances [6, 7]. However, focal distance switching, defined as “the change in accommodation as a user’s focus switches between one distance and another,” has been shown to cause a deterioration in task perfor-

mance and accuracy, in all tested cases [6, 7].

This is, perhaps, not surprising, in that our eyes accommodate through a muscular reaction to perceived blur; accommodative effort then, in turn, drives our vergence angle response [23]. Rapidly switching between differing focal distances can thus be expected to cause exhaustion or frustration over a significant length of time, especially in older subjects whose ability to rapidly and easily accommodate has diminished [5, 16].

Of course, our research does not represent the only effort to counteract these effects. Some researchers, for example, have constructed adjustable AR displays, using liquid-crystal lens with modifiable focal power [3, 11]. Other researchers have created displays with discrete multi-focal fixation planes [9, 14]. These AR displays could potentially be used to prevent or at least ameliorate the negative effects stemming from fixed-focal length displays. However, in practice, these solutions may not be optimal; they involve expensive or complicated designs that might be too costly or engineering-intensive for large-scale production.

This brings us to less expensive or more versatile solutions to the fixed-focal length display problem. Most of these solutions are implemented on the software level, making them cheaper and less effort-intensive than hardware-based solutions. Some holographic projection designs, for example, may be able to provide accurate focal control, along with wide fields of view, high resolutions, and aberration correction [15]. Accommodation-invariant displays are also a reasonable, and highly economical, adaptation to the fixed-focal length problem. These display designs attempt to entirely remove the accommodative cue, by ensuring a constant blur gradient, and drive depth perception primarily by vergence angle [12]. Another blur manipulation strategy, the SharpView algorithm, represents a different approach to fixed-focal length displays; instead of creating a constant blur gradient, the SharpView algorithm creates a focus-specific modification of the rendered CG. Given the image I that the system would like the user to see and the estimated point spread function of the eye p , SharpView computes a sharpened image S that should be displayed on the OST-HMD, so that

$$I = S * p. \quad (1)$$

Here, the symbol $*$ represents a convolution operation. In other words, SharpView predicts the amount of sharpening that should be applied to the image, so that when the sharpened image S is displayed on the OST-HMD, the user perceives it to be the intended image I . SharpView approximates the user’s PSF with a Gaussian function

$$P(x,y) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2+y^2}{2\sigma^2}\right), \quad (2)$$

where σ models the distribution of the light from any pixel (x,y) on the display of the HMD onto the retina. If the pupil size, the user’s focus distance, and the focal length of the HMD are known, the size of σ on the HMD screen can be recovered. This allows p to be computed, and, thus, S can be estimated. For details, please refer to [17].

Although SharpView presents a simple way to enhance a presented scene, it has been thus far only verified on images. As discussed previously, it would be interesting to determine the feasibility of using blur manipulation to reduce the negative effects of fixed-focal length devices for text-based images in AR. This would expand on previous efforts involving SharpView. Unlike standard images, text-based graphics represent a unique use case for SharpView. In textual images, fine details are often quite important (for example, ‘c’ vs. ‘o’ or ‘l’ vs. ‘1’), and many of these fine details can be distorted during the application of SharpView. Further, textual images represent an important use case for augmented reality. Displaying text, without associated context-switching or focal distance-switching problems, would grant AR applications a broad range of potential use cases and affordances.

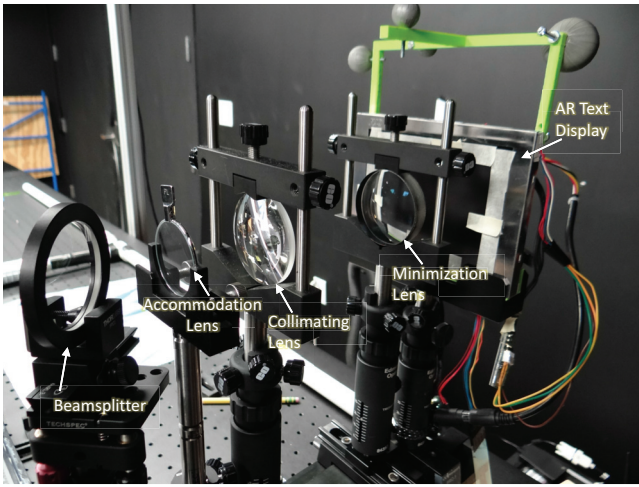


Figure 2: The haploscope, originally developed by Singh et al. [21]. For this experiment, the haploscope was used to render the AR text label at different focal distances. Placing different powered lenses in the accommodation lens holder changed the AR text distance.

3 EXPERIMENT

The experimental goal was to determine if observers prefer AR text content to be sharpened, and, if so, to further determine what factors affected the degree of desired sharpening. SharpView enhancement is intended to make fuzzy, out-of-focus AR text more legible and clear. If the sharpening works as intended, observers could potentially read short, AR text labels without completely focusing on them. If this outcome is achievable, then applying the SharpView method to AR text labels could have various benefits, including decreased eyestrain and increased user performance.

Therefore, the purpose of this experiment was to measure the amount of preferred sharpening applied to a short AR text label. Observers were required to select between two AR text strings with varying amounts of applied sharpening. Based on a series of such choices, observers' preferred degree of sharpening was determined. Two *gaze* conditions were examined: (1) when the observer was gazing directly at the AR text label, and (2) when the observer was gazing at real world content, and seeing the AR text label in the near periphery. Both conditions were measured at different levels of focal distance. The hypothesis was that in the first condition, when observers were gazing directly at the AR text label, and therefore were likely focused on it, they would not prefer any added sharpening. However, in the second condition, when observers were focused at a different distance than the AR text label, they would prefer some degree of added sharpening.

3.1 Method

3.1.1 Apparatus and Setup

To appropriately control accommodative demand, a *haploscope* was used (Figure 2). The *haploscope* is an optical see-through AR display, which is mounted on an optical workbench. It is comprised of four main parts: an LCD screen on which AR text content can be generated; a series of optical elements that collimate and minify the image displayed on the LCD screen; an accommodative lens that focuses the collimated virtual image to a specific focal distance; and, finally, a beamsplitter, which allows observers to see the real environment, while also reflecting AR content to the observer's eye [10, 18, 20–22]. For this study, observers used the device monocularly with their right eye. This experiment also used a standalone monitor, positioned at one of three distances, to act as a real focal target (shown in Fig. 3), and a keyboard for observer input.

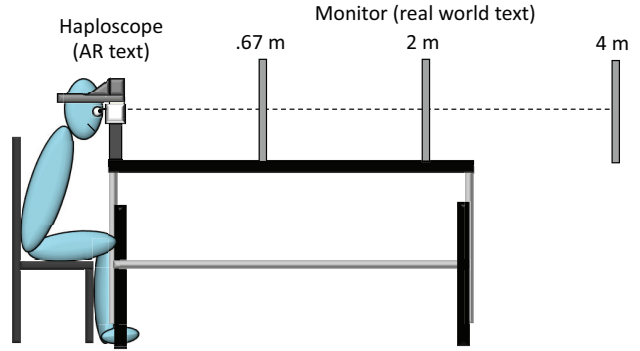


Figure 3: The experimental configuration. Observers viewed AR text labels through the haploscope, and viewed real text on the monitor. Changing the monitor's position changed the real text distance.

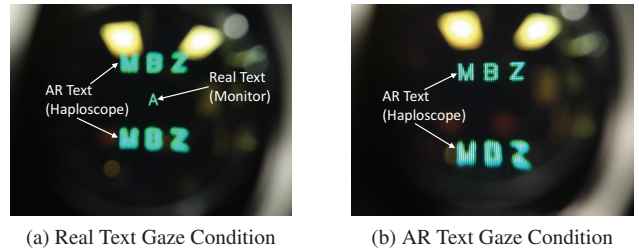


Figure 4: (a) Real text gaze condition; observers were instructed to gaze exclusively at the letter 'A', displayed on the monitor. (b) AR text gaze condition; the real text did not appear, and observers were instructed to gaze exclusively at the AR text.

It may be of further interest to briefly discuss the optical setup to this apparatus in more detail [21]. The image produced by the screen was positioned such that it was at the focal length of the 10 diopter (D) minimization lens, creating a virtual image behind itself. The 10 D collimating lens was then positioned such that it was focused on the virtual image produced by the minimization lens, collimating that minified image. When this collimated image entered the accommodative lens, it became focused at $1/p$ meters, where p was the power of the lens in diopters. The beamsplitter, then, reflected this image into the observer's right eye, while still allowing them to see the real world normally [10, 18, 20, 22].

Since we were trying to simulate what would happen if a user was looking at the real world while simultaneously attempting to parse text presented through an AR system, it was important to set up experimental conditions that replicated this scenario. To do this, we had a device that could display AR images at a variety of focal distances and a standalone monitor that stood in the center of an observer's field of view. In the real gaze condition, observers were asked to gaze exclusively at the image on the standalone monitor and, while doing so, to select the "most legible" of the two displayed text strings (shown in Fig. 4a). It is worth noting that there could be some concerns as to whether all observers were able to perform this task without unintentionally looking directly at the AR text strings.

As shown in Figure 4, the two text strings were presented equidistant from a user's center of focus, and from the image of the letter displayed on the real monitor. For each trial, the upper or lower position of each text string was randomized. After each observer selection, the screen was blanked for 3 seconds. These methods addressed observer bias that could occur because of the vertical placement of the text strings.

3.1.2 Experimental Design

Observers: For this experiment, there were 10 observers total, but one observer did not finish the last monitor condition, and the other observer vocalized his or her inability to focus on the AR text. Therefore, only 8 observers were used in the analysis. Of these 8 observers, 5 were male and 3 were female. The observers varied in age, with the majority 18 to 25 and two above 50. Because accommodative ability decreases with age [5, 16], older observers were sought. In addition, there was a range of other vision deficiencies within the observers; 4 of the 8 observers used corrective eyewear. Three of the experimental observers repeated the experiment 3 times, which is accounted for in the analysis.

Independent Variables: Observers saw 2 different *gaze* conditions: real text, and AR text. In the *real text* gaze condition (Figure 4a), observers viewed the real text on the monitor (Figure 3), and saw the AR text in the haploscope. Observers were instructed to keep their gaze on the real text, even though they made a judgment about the legibility of the AR text. In the *AR text* gaze condition (Figure 4b), the monitor was not present, and observers saw the AR text in the haploscope. Observers were instructed to look directly at the AR text as they made their legibility judgment.

The AR text was presented at 5 different *AR text distances*: 0, 0.25, 0.5, 1.5, or 3 D (optical infinity, 4, 2, 0.67, or 0.33 meters). These distances were realized by placing a lens of the correct optical power in the accommodation lens holder (Figure 2). The monitor was placed at 3 different *real text distances*: 0.25, 0.5, or 1.5 D (4, 2, or 0.67 meters).

From an observer’s point of view, changing either the AR text distance or the real text distance changed the angular size of the letters. Therefore, in either case, the rendered size of the letters was adjusted, so that the observer always viewed text of a constant angular size.

Dependent Variable: As discussed in Equation 2, sigma σ indicates the degree of sharpening. For each trial, this sigma value was the measured dependent variable. As seen in Figure 5, observers used a *downward staircase* procedure to indicate a sigma value. This is a common testing method from the field of psychophysics [1, 4]. In a downward staircase, the quantity being investigated starts off at two extremes. When an observer makes a selection that indicates a preference for a lower sigma value, the high value drops; when an observer makes the opposite choice, the high value rises (Figure 5). The amount of change in the high value was static ($\Delta = 0.4$) initially, but changed to ($\Delta = 0.2$) once observers switched direction for the first time. These values were selected because a .2 change in sigma was determined to be the smallest observable change. These points represented the threshold effect; we might not expect subjects to exhibit strong preferences for minor changes in sharpening, but as the difference between the displayed text strings grows, we expect the displayed phenomenon to cross the user’s awareness/preference threshold.

For each trial, the measured sigma was either the average of 6 reversal points, or, if six reversals were not found within 21 trials, the average of all the reversal points.

Design: For each experiment, the observer experienced one trial for every unique combination of independent variables, resulting in 2 (gaze) \times 5 (AR text distance) \times 3 (real text distance) = 30 data points. Trials were presented in random order.

3.2 Procedure

In this experiment, observers were given a set of trials, one for each combination of the independent variables. Each trial was composed of a sequence of choices between two AR text images displayed on the haploscope, each with a different sigma value (the

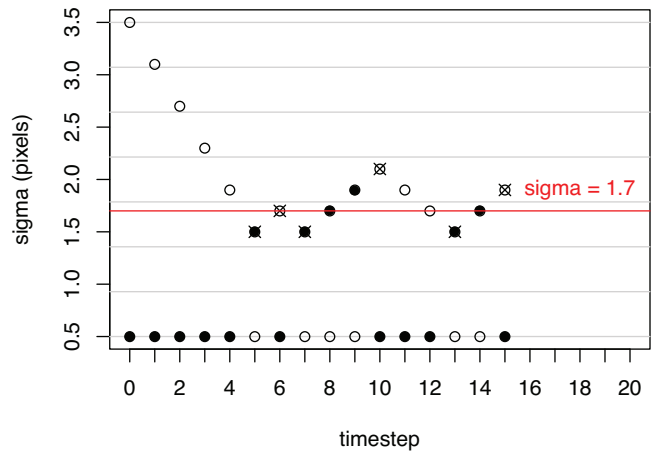


Figure 5: Downward staircase results for a single trial. At the beginning of the trial (timestep = 0), observers saw two extreme sigma values, sigma = 0 and sigma = 3.5. At each timestep, observers made a choice, represented by a dark circle, which determined the sigma value for the next timestep. An “X” indicates a reversal point, when users. For each trial, the recorded sigma value was the average of the first 6 reversals, or the average of all the reversals completed within 21 timesteps.

amount of applied sharpening). The downward staircase method determined the sequence of choices in each trial. The *static text string* stayed locked at sigma = 0.5, which produced no sharpening, while the sigma value of the *dynamic text string* changed based on the staircase (Figure 5). Each time the dynamic text string, with the higher sigma value, was selected, its sigma value increased, making the SharpView enhancement ever more pronounced. However, when the static text string, with sigma = 0.5, was selected, the sigma value of the dynamic text was lowered, reducing the amount of SharpView enhancement.

Adjustment of the AR text was an important calibration step in the experiment. Since observers have unique facial features, the centering of the standalone monitor letter in the field of view (Figure 4a) differed between observers; therefore, before performing the experiment, each observer first performed a calibration task. This task, which the observer practiced in the training run, required the observer to simply align a capital letter ‘O’ with a crosshair target. The crosshair was displayed by the haploscope AR system, and the ‘O’ was displayed on the standalone monitor, in such a position that the AR text was appropriately centered in a user’s view when the ‘O’ was aligned to the crosshair. The observer was asked to do this calibration step between each real/AR distance change, and was not allowed to proceed with the experiment until they confirmed that the system was calibrated to the best of their ability.

Once an observer was instructed to begin the trial, that observer was instructed to indicate whether the upper or lower text string was more legible (Figure 4) within three seconds. This time limit was selected through pilot experimentation, balancing the need to prevent observers from over-thinking, while also hopefully avoiding instances where observers did not have time to consider the differences between the presented images.

4 EXPECTED RESULTS

Our primary hypothesis, as displayed in Figure 6, was that users, when they are looking at a real object not on the virtual fixation plane, prefer SharpView-enhanced text displays to regular text displays. If this hypothesis is true, we would expect to find support for it in the data that we gathered from observers. Specifically, we would expect

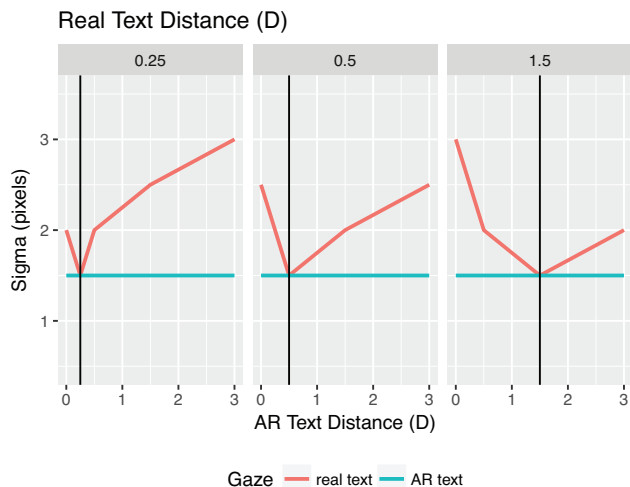


Figure 6: The expected results; the data shown in blue and orange is schematic.

users to prefer a higher sigma value when they are looking at a plane other than the virtual image plane.

However, in the AR gaze condition, which acts as a control for this experiment, we expected observers to prefer a much lower sigma. When an observer gazes at the virtual focus plane, they are, of course, focused on the AR text. Thus, it stands to reason that subjects would prefer very little sharpening to be applied to the text, leading to a low sigma value. This value is expected to range somewhere between a sigma of .5 (where no sharpening occurs at all) and a sigma of 1.5 (where changes to the text begin to be readily discernible). The blue line at sigma = 1.5 in Figure 6 reflects this prediction.

In the real gaze condition, the real text distance sometimes coincided with the AR text distance. As such, since the real text and the AR text are being displayed on the same focal plane, indicated by the vertical black line in Figure 6, we would expect users to prefer low sigma values as in the AR text gaze condition. Finally, as the distance between the virtual and real fixation planes increases, we would expect to see users begin to prefer more sharpening, as the difference in focal demand between the two planes increases.

5 RESULTS

Figure 7 shows the results. The data displays considerable variation in sigma. Nevertheless, several of the predicted patterns from Figure 6 can be seen. In each monitor distance panel, observer preferred sigma is lower for the AR gaze condition than for the real text gaze condition. In addition, the preferred sigma increases more quickly with respect to monitor distance in the real text condition than in the AR condition. Both of these findings indicate that, as the virtual and real fixation planes diverge, observers begin to prefer more sharpening.

A repeated-measures factorial ANOVA was then conducted, which examined the effects of lens power (5 levels), monitor distance (3 levels), and gaze condition (2 levels); observer (8 levels) was the random independent variable. The ANOVA model properly captured the fact that 3 observers contributed 3 repetitions of the experiment, while the remaining 5 observers contributed a single repetition.

There was a main effect of lens power (focal demand) on sigma ($F_{(4,28)} = 3.3, p = 0.024$). Observers chose different sigma values for different lens powers; they chose the highest for 0 D (sigma = 2.1 pixels) and 3 D (sigma = 2.0 pixels), and the lowest for 1.5 D (sigma = 1.9 pixels). This was expected, because the focal

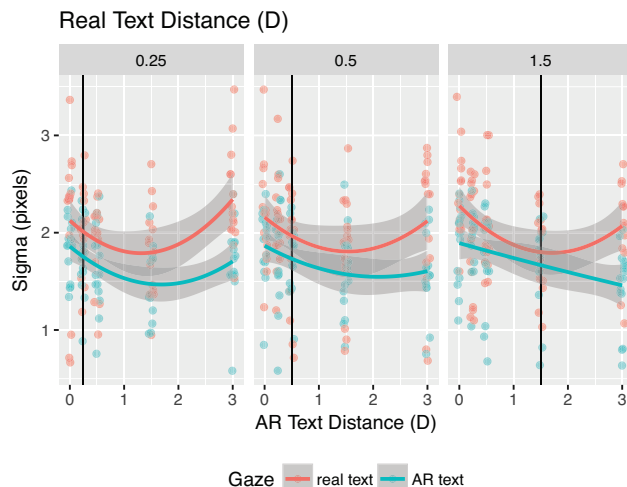


Figure 7: The results, shown in the form of Figure 6. The collected data is shown as points, color-coded according to gaze condition, and for clarity slightly jittered according to lens power. The point clouds are also fitted with parabolic regressions ($y = b_0 + b_1x + b_2x^2$). The dark gray shading represents ± 1 standard error about each regression.

difference between the real world and AR text was the greatest at the most extreme focal distances. There was also a main effect of gaze condition on sigma ($F_{(1,7)} = 20.2, p = 0.003$), where observers chose sigma = 2.1 pixels for the AR text when looking at the real text, as opposed to sigma = 1.8 pixels when looking directly at the AR text, for a difference of 0.3 pixels. There was no effect of monitor distance on sigma ($F < 1$), and there were no significant interactions.

Based on these results, Figure 8 gives the results according to the two significant effects of gaze condition and lens power. Here the parabolic regressions give the best prediction of expected sigma values y according to lens power x ; For the real text, $y = 2.2 - 0.51x + 0.17x^2$, and for the AR text, $y = 1.9 - 0.31x + 0.071x^2$. Together, these models explain $R^2 = 16.8\%$ of the variation in Figure 8.

6 ANALYSIS AND DISCUSSION

Before an in-depth examination of the experimental results is commenced, it is important to note a few things. First, because this data is based on threshold-testing methodology, observers might have not necessarily selected the same option every time when presented with a given choice. It was even possible for observers to encounter a particular choice and not be able to distinguish a difference between the two presented text strings. In that case, they would have had to select their choice randomly.

Because of this, and the more subjective nature of threshold testing, finding the underlying trends behind our data is a difficult task. Further increasing this difficulty is the limited number of experimental trials that were run.

However, these findings do contain some results that stand out rather strongly. As seen above, observers, on average, significantly preferred a higher sigma/sharpening value in the real condition than they did in the AR condition. This fits our hypothesis that users will prefer sharpened images in cases where they are not looking directly at the image. As expected, in the AR case, users preferred low or no sharpening values, on average.

We also see that observers, on average, preferred the highest degree of sharpening at the lowest lens power, in both gaze conditions. This effect could be related to a couple of separate issues. The first

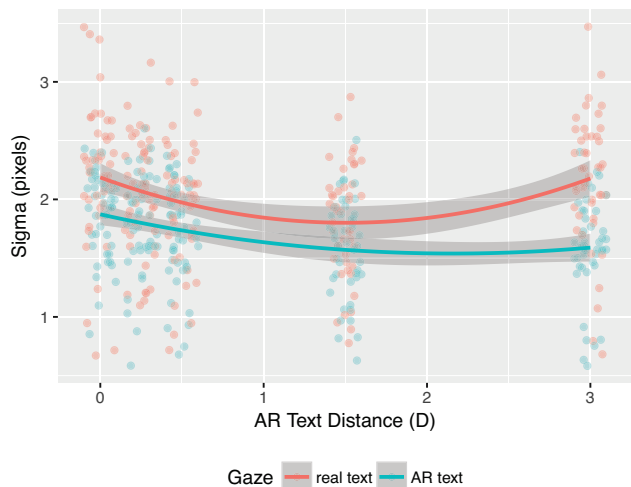


Figure 8: The results, in the form of Figure 7, but collapsed over monitor distance. This figure shows the significant effects of gaze condition and lens power.

is that, since the focus was farther away, some users may have had more difficulty accommodating to that distance or accommodating quickly. This could potentially cause either an increased desire for sharpening, to bring the image into clearer focus, or decreased image legibility, reducing observer accuracy. The second possible cause of this issue is that, as a result of the focal distance, the object appears very blurry at more normal fixation points; it is possible that this additional blurring makes SharpView enhancement less visible or less useful, or simply adds additional randomness to user selection.

In contrast, the cumulative results presented in Figure 6 seem much more open to interpretation. It does seem clear that the real gaze condition, in most cases, is notably more variable than the AR gaze condition, but, beyond that, it is difficult to observe meaningful trends. With more data, it might be possible to better understand the relationship between the AR text distance, the real text distance, individual physiological differences, and users' preferred sigma, but, with this current effort, we can not conclusively draw any further conclusions.

We do believe, however, that this experiment, and Figures 6 and 7, show a definite user preference for some degree of sharpening when focusing on a real-world object and trying to parse AR text. This finding validates the research so far and implies that further research into sharpening technology and its effects could be useful for future AR context-switching applications and methodologies. Armed with an effective sharpening algorithm, eye tracking equipment, and a durability and flexibility that most AR devices don't currently have, it is quite possible that AR could come to occupy a whole new paradigm of large-scale personal information deployment in novel areas: urban environments, navigation platforms, and other environments with significant visualizable or textual information surrounding a three-dimensional construct.

7 CONCLUSIONS

Mastering adaptive blur could lead to a more streamlined, intuitive augmented reality experience with the end goal of allowing users to understand and process virtual information seamlessly in their interactions with the real environment. Thanks to the typical design modalities of AR displays, this issue of a fixed virtual depth vs. a varying real-world depth is likely to continue to be an important design issue for AR research and applications. The finding that users looking at real-world objects do prefer a degree of sharpening for

AR text opens up many potential improvements to existing design approaches in AR, and, further, suggests that additional research in this area could be highly beneficial.

8 FUTURE WORK

This work advances the scientific community's understanding of text-based blur algorithms by showing that AR users prefer a blurring effect on AR text when gazing at real targets. In conjunction with Gabbard et al.'s research [6], this could then lead to a further investigation of blurring effects, with the potential for development of exciting new methods to alleviate eye fatigue, improve textual clarity, and enhance usability for augmented reality applications.

Such future work could also overcome some of the limitations of this current research effort-providing larger sample sizes, and, thus, greater statistical significance; examining new sharpening and blur manipulation algorithms; examining the relationships between sigma and other, previously unconsidered, independent variables; and conducting a series of context switching studies specifically related to eye fatigue and other physiological phenomenon.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation, under awards IIS-1018413 and IIS-1320909, to J. E. Swan II, the Japan Society for the Promotion of Science under awards Grant-in-Aid for Scientific Research (B) #15H02737 and Grant-in-Aid for Young Scientists (B) #17K12726, and the NAIST Global Collaborative Program 2017.

REFERENCES

- [1] K. E. Adolph. Psychophysical Assessment of Toddler's Ability to Cope with Slopes. *Journal of Experimental Psychology. Human Perception & Performance*, 21(4):734, 1995.
- [2] R. T. Azuma. A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments*, 6, 1997.
- [3] H.-S. Chen, Y.-J. Wang, P.-J. Chen, and Y.-H. Lin. Electrically Adjustable Location of a Projected Image in Augmented Reality via a Liquid-Crystal Lens. *Optics Express*, 23(22):28154–28162, 2015.
- [4] T. N. Cornsweet. The Staircase-Method in Psychophysics. *The American Journal of Psychology*, 75(3):485, 1962.
- [5] T. Fukuda, K. Kanada, and S. Saito. An Ergonomic Evaluation of Lens Accommodation Related to Visual Circumstances. *Ergonomics*, 33(6):811–831, 1990.
- [6] J. L. Gabbard, D. G. Mehra, and J. E. Swan. Effects of AR Display Context Switching and Focal Distance Switching on Human Performance. *IEEE Transactions on Visualization and Computer Graphics*, in press, 2017.
- [7] D. Gupta. An Empirical Study of the Effects of Context-Switch, Object Distance, and Focus Depth on Human Performance in Augmented Reality. Master's thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA, 2004.
- [8] D. M. Hoffman, A. R. Girshick, K. Akeley, and M. S. Banks. Vergence–Accommodation Conflicts Hinder Visual Performance and Cause Visual Fatigue. *Journal of Vision*, 8(3):33–33, 2008.
- [9] X. Hu, X. Hu, and H. Hua. Design and Tolerance of a Free-Form optical System for an Optical See-Through Multi-Focal-Plane Display. *APPLIED OPTICS*, 54(33):9990 – 9999, 2015.
- [10] C. Hua. The Effect of an Occluder on the Accuracy of Depth Perception in Optical See-Through Augmented Reality. Master's thesis, Mississippi State University, Starkville, Mississippi, USA, 2014.
- [11] R. Konrad, N. Padmanaban, E. Cooper, and G. Wetzstein. Computational Focus-Tunable Near-Eye Displays. In *ACM SIGGRAPH 2016 Emerging Technologies*, p. 3. ACM, 2016.
- [12] R. Konrad, N. Padmanaban, K. Molner, E. A. Cooper, and G. Wetzstein. Accommodation-Invariant Computational Near-Eye Displays. *ACM Transactions on Graphics (TOG)*, 36(4):88:1–88:12, 2017.
- [13] M. Lambooj, M. Fortuin, I. Heynderickx, and W. IJsselstein. Visual Discomfort and Visual Fatigue of Stereoscopic Displays: A Review.

Journal of Imaging Science and Technology, 53(3):30201–1–30201–14, 2009.

- [14] S. Liu, Y. Li, P. Zhou, X. Li, N. Rong, S. Huang, W. Lu, and Y. Su. A Multi-Plane Optical See-Through Head Mounted Display Design for Augmented Reality Applications. *Journal of the Society for Information Display*, 24(4):246 – 251, 2016.
- [15] A. Maimone, A. Georgiou, and J. S. Kollin. Holographic Near-Eye Displays for Virtual and Augmented Reality. *ACM Transactions on Graphics (TOG)*, 36(4):85, 2017.
- [16] C. Neveu, T. Blackmon, and L. Stark. Evaluation of the Effects of a Head-Mounted Display on Ocular Accommodation. *Presence: Teleoperators and Virtual Environments*, 7(3), 2006.
- [17] K. Oshima, K. R. Moser, D. C. Rompapas, J. E. Swan, S. Ikeda, G. Yamamoto, T. Taketomi, C. Sandor, H. Kato, et al. SharpView: Improved Clarity of Defocused Content on Optical See-Through Head-Mounted Displays. In *Proceedings of the IEEE Symposium on 3D User Interfaces*, pp. 173–181. IEEE, 2016.
- [18] N. Phillips and J. E. Swan. A Procedure for Accurate Calibration of a Tabletop Haploscope AR Environment. In *Proceedings of the IEEE Virtual Reality*, pp. 259–260, 2015.
- [19] H. Regenbrecht, G. Baratoff, and W. Wilke. Augmented Reality Projects in the Automotive and Aerospace Industries. *IEEE Computer Graphics and Applications*, 25(6):48–56, 2005.
- [20] G. Singh. *Near-Field Depth Perception in Optical See-Through Augmented Reality*. PhD thesis, Mississippi State University, Starkville, Mississippi, USA, 2013.
- [21] G. Singh, S. R. Ellis, and J. E. Swan II. The effect of focal distance, age, and brightness on near-field augmented reality depth matching. *arXiv Preprint*, arXiv:1712.00088, Nov 2017.
- [22] J. E. Swan, G. Singh, and S. R. Ellis. Matching and Reaching Depth Judgments with Real and Augmented Reality Targets. *IEEE Transactions on Visualization and Computer Graphics*, 21(11):1289–1298, 2015.
- [23] F. M. Toates. Accommodation and Convergence in the Human Eye: A Control Analysis. *Measurement and Control*, 2(3):T29–T33, 1969.
- [24] D. Van Krevelen and R. Poelman. A Survey of Augmented Reality Technologies, Applications and Limitations. *International Journal of Virtual Reality*, 9(2):1–20, 2010.