Intuitive User Interfaces for Real-Time Magnification in Augmented Reality

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ABSTRACT

Various reasons exist why humans desire to magnify portions of our visually perceived surroundings, e.g., because they are too far away or too small to see with the naked eye. Different technologies are used to facilitate magnification, from telescopes to microscopes using monocular or binocular designs. In particular, modern digital cameras capable of optical and/or digital zoom are very flexible as their high-resolution imagery can be presented to users in real-time with displays and interfaces allowing control over the magnification. In this paper, we present a novel design space of intuitive augmented reality (AR) magnifications where an AR head-mounted display is used for the presentation of real-time magnified camera imagery. We present a user study evaluating and comparing different visual presentation methods and AR interaction techniques. Our results show different advantages for unimanual, bimanual, and situated AR magnification window interfaces, near versus far vergence distances for the image presentation, and five different user interfaces for specifying the scaling factor of the imagery.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**;
• **Computing methodologies → Computer graphics**.

KEYWORDS

Augmented Reality, Magnification, 3D User Interfaces

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1 INTRODUCTION

Human vision allows us to perceive our surroundings via light in the visible spectrum, e.g., emitted by or reflected off materials in the environment. However, our visual acuity is naturally limited by the density of rods and cones on the retina. If the size of a physical object's projection on the retina falls below a perception threshold, we are unable to perceive it or its details visually. For instance, a vehicle moving away from us causes its retinal size to shrink, which means it is gradually perceived with fewer and fewer details until it becomes indistinguishable from the background.

Magnification is the process of increasing the angle that an object in our visual field subtends at the eye, e.g., through the use of a magnification lens. While analog binoculars and monocular telescopes have been used to magnify visuals for a long time, two digital technologies have much promise for human-computer interaction in this field. First, *digital cameras* are now capable of reaching a superior resolution than the human eye. Second, *augmented reality* (AR) see-through head-mounted displays (HMDs) enable us to seamlessly blend imagery with our view of the real world. By integrating a camera and an AR display, we can register and overlay a captured image in real time over the same portion of a user's visual field—and we can magnify it.

In this paper, we explore the design space of real-time AR based magnification. We present intuitive user interface approaches that are based on an AR magnification testbed in which a high-resolution digital camera captures the visuals and an AR HMD selectively magnifies the imagery within the bounds of the user's left and/or right hand or a situated window, while maintaining a natural (unmodified) view in the remainder of the user's visual field.

The main contributions of this work are as follows:

(1) We present and discuss a design space for intuitive AR magnifications, leveraging an AR HMD, high-resolution camera, and different user interfaces (UIs).
(2) We describe a functional prototype implementation using commercial-off-the-shelf (COTS) devices and explore alternative user interfaces and visual parameters in the design space with a human-subject experiment (N=20).
(3) We discuss our results with respect to challenges and benefits related to the different aspects of AR magnifications we explored.

In the remainder of this paper, we first discuss related work in Section 2. We then describe a design space for AR magnifications and the experiment we performed to explore it in Section 3. The results are presented and discussed in Section 4. A general discussion is provided in Section 5. We conclude the paper in Section 6.

2 RELATED WORK

Magnification devices have long been used to provide enhanced visual acuity across many sizes and distances, e.g., microscopes, magnifying glasses, monoculars, binoculars, and telescopes. These devices are employed for a wide range of application fields such as physical or biological research, medical applications such as surgery and dentistry, defense, astronomy, and accessibility for people with low vision [24], to name a few. With the advent of AR

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technology [20, 38], a variety of AR-enabled vision enhancement prototypes and techniques emerged, including some related to the system and interaction methods discussed in this paper.

In related work, optical zoom lenses have been integrated into or attached to AR displays to optically magnify the view of the real world users are seeing. A prime example are "AR loupes" for use in microsurgical procedures, including neurosurgery and dentistry, and other medical applications [30, 34]. Such AR loupes combine the advantages of microsurgical loupes with optical see-through AR HMDs to gain the ability to overlay AR information in a surgeon's visual field, e.g., to improve their situational awareness or provide navigation guidance [25]. Others implemented similar functionality with video see-through AR displays. For instance, Oskiper et al. [29] used a binoculars-like video see-through device called "augmented reality binoculars" that integrates a wide field of view camera along with a narrow field of view camera to provide either an unmagnified or zoomed-in AR view of a real scene. Hoang and Thomas [19] proposed an "augmented viewport" consisting of zoom lens cameras to provide AR users with magnified imagery of a real space or objects at a distance to allow for more accurate interaction with the remote objects. Further, Orlosky et al. [28] used a head-mounted camera pair to which they attached telescopic lenses for see-through magnification, exploring different interface mechanisms for controlling the magnification state. Orlosky et al. [27] further discussed the calibration and visual integration of head-mounted cameras with AR displays. Conversely, Fan et al. [13] integrated an AR HMD with a head-mounted camera using a wide-angle lens to not magnify the user's view but rather *compress* a larger visual field from outside the user's natural field of view into the user's view to enhance awareness of otherwise unseen objects around the user.

Other researchers investigated interfaces that involved magnifying certain objects within an AR HMD user's visual field but leaving the remainder of the visual field unchanged. For instance, Narumi et al. [26] developed a system that can detect and segment food, in their case cookies, within a video see-through AR HMD's camera feed to scale it up in real time, thus giving the illusion of eating larger/more food than one really consumes. Work by Choudhary et al. [5, 11] used a head-mounted camera and machine learning to detect and segment the heads of people in order to magnify them in a user's visual field, allowing the user to identify people around them even if these people are far away from the user [7–10].

Related work further made use of hand-held AR displays for the purpose of magnification. A prime example is work by Rekimoto [31], who proposed a hand-held palmtop-sized video see-through approach, which he termed the "magnifying glass," based on which he designed an AR system called "NaviCam," which inspired a large body of research on similar interfaces. For instance, more recent work by Čopič Pucihar and Coulton [12] performs digital magnification via hand-held AR and pre-captured high resolution imagery of real content.

A large body of related work stems from the field of accessibility, where researchers' goal is to use AR technology to improve the visual acuity of individuals with low vision. For instance, Stearns et al. [35] proposed an AR display of live imagery from a finger-worn camera for real-time magnification for users with low vision, e.g., for reading. Gopalakrishnan et al. [15] looked at various visual enhancement techniques and applications for people with low vision, including magnification among other enhancements (e.g., outlines, inverting colors, etc.). Ueda et al. [37] proposed "IlluminatedZoom," using periodically zooming eyeglasses and a high-speed projector in an optical see-through system to provide dynamic, synchronized lighting to accentuate and enhance a particular region or object at a given magnification.

Further work related to AR magnification includes Avery et al. [1], who explored the use of externally captured imagery of an environment to allow an AR user to see what is behind physical objects. While not focused on live imagery, it does include a mode allowing the user to digitally zoom in on the augmented imagery of an occluded real scene. Toet [36] does not use traditional AR, but instead developed a mode with gaze tracking for real-time control of a pan-tilt camera with a telephoto lens to provide an inset close-up image overlay on top of, for instance, security camera footage being viewed on a screen.

However, while the aforementioned related work looked extensively at different use cases and technologies to integrate magnification into AR systems, we are not aware of previous work looking at 3D UIs to intuitively control the imagery that is overlaid over one's visual field. We address this gap in this paper, i.e., we investigate different interaction techniques and visual presentation methods.

3 EXPERIMENT

Our study evaluated three AR magnification UI aspects based on intuitive *hand interaction* interfaces: (a) the control and persistence of the AR *window* displaying the magnified imagery, (b) the stereoscopic depth or *vergence distance* at which the AR imagery is presented, and (c) interaction techniques for varying the *scale* of the magnification. The experiment protocol was approved by the institutional review board of our university.

3.1 Participants

After initial pilot tests, we estimated the effect size of the expected strong effects, and based on a power analysis with G*Power 3 [14], we made the decision to recruit 20 participants. 13 male and 7 female (ages 18–40, mean 25) participants took part in the experiment. Participants were recruited from the local university community. All participants had normal or corrected to normal vision; 7 wore glasses and 2 wore contact lenses.

3.2 Material

Our participants wore a Microsoft HoloLens 2 optical see-through AR HMD with a $1{,}440 \times 936$ resolution per eye, 52 degrees diagonal with 43 degrees vertical and 29 degrees horizontal field of view [1], about 20 pixels per degree of resolution [2], and 60 Hz update rate for the AR stimulus presentation. Participants were instructed to perform the HoloLens' eye calibration procedure, which matches the rendering parameters to their interpupillary distance and eye location. On top of the HMD, collimated at a vertical offset of 9 cm, an SVPRO ELP 4K digital camera was mounted with a Sony IMX317 sensor for low-light environments, $3{,}840 \times 2{,}160$ camera resolution, 2.8–12 mm varifocal lens providing a variable field of view between 50 degrees and 125 degrees (in our experiment calibrated to 70 degrees to provide full overlap with the HoloLens' display field of

[1] https://uploadvr.com/hololens-2-field-of-view/
[2] https://kguttag.com/2020/07/08/hololens-2-display-evaluation-part-2-comparison-to-hololens-1/

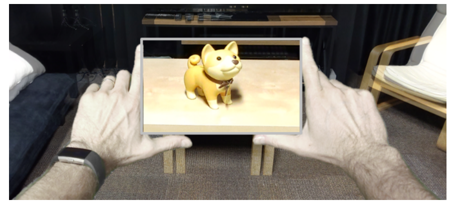
(a) Real view

(b) Unimanual

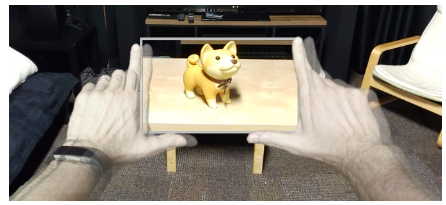
(c) Bimanual

(d) Situated

Figure 1: Illustration of three manual user interfaces to specify a magnification window: (b) *unimanual*, where only the fingertips (index finger and thumb) of one hand (left or right) are used to form a window, (c) *bimanual*, where a window is formed between the bounds of the fingertips of both hands, and (d) *situated*, where a window remains persistent within the user's head-referenced view but the bounds of the window can be adjusted using pinch-and-drag gestures at the lower left and upper right corner if desired.



(a) Near Vergence ("In Hands")



(b) Far Vergence ("Through Hands")

Figure 2: Illustration of two depths (vergence distances) at which the magnified imagery may appear in AR: (a) at near vergence (background appears with double vision) as if looking at the imagery held in one's hands, or (b) at far vergence (foreground appears with double vision) as if looking at the distant imagery through one's hands.

view), and a 30 Hz frame rate. For rendering, system control, and logging we used an Alienware laptop with an Intel Core i7-7820HK CPU at 2.9 GHz, 16 GB of RAM, Nvidia GeForce GTX 1070 graphics card, which was running Windows 10 Pro. The AR visual stimulus consisted of virtual imagery generated by the Unity engine (version 2020.3.13f1) using Microsoft's Mixed Reality Toolkit (MRTK). For the physical input device condition described below, we used a Griffin PowerMate rotating multimedia controller (see Figure 3d).

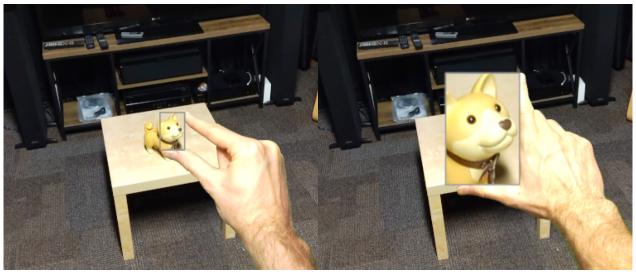
We performed the study in a 15 m × 15 m wide laboratory space. Participants could freely move within a 2 m × 2 m area of the laboratory, with a 360-degree field of regard, and various objects placed in the space around them. The layout of the immediate surroundings of the participants during the experiment is shown in Figure 1. View distances varied between objects placed on a table immediately in front of the participants when they started the experiment to objects placed at the largest distance of about 10 meters from this point when looking down the length of the laboratory.

3.3 Methods

For this study, we used a within-subjects design. As factors, we tested three relevant AR magnification aspects.

- **Magnification Window UI** (see Figure 1):
  - Unimanual: *A rectangular AR window is formed between the fingertips (index finger and thumb) of one hand (left or right). This window is* perishable, *only visible while the user's hand is held up.*
  - Bimanual: *In this case, the AR window is formed between the bounds of the fingertips of both hands. This window is* perishable, *only visible while the user's hands are held up.*
  - Situated: *A rectangular AR window remains persistent within the user's view but the bounds of the window can be adjusted using pinch-and-drag gestures at the lower-left and upper-right corner.*
- **Magnification Vergence Distance** (see Figure 2):
  - Near Vergence ("In Hands"): *Magnified AR imagery is stereoscopically presented within the bounds of the magnification window within arm's reach; similar to looking at an image held in one's hands (i.e., background appears with double vision).*
  - Far Vergence ("Through Hands"): *Magnified AR imagery is stereoscopically presented as seen through the bounds of the magnification window at optical infinity; similar to looking at a distant image through one's hands (i.e., foreground appears with double vision).*
- **Magnification Scale Factor UI** (see Figure 3):
  - Scale-by-Size: *Users increase the size of the AR window to increase the magnification factor.*
  - Scale-by-Distance: *Users bring the AR window with their hand(s) closer to their head to increase the magnification factor.*
  - Scale-by-Voice: *Users indicate the magnification factor verbally by using the keyword "Mag" (short for magnification) followed by the factor, e.g., "Mag Ten" for ten-times magnification or "Mag One" for a one-to-one mapping.*
  - Scale-by-Device: *Users increase or decrease the magnification factor by turning the rotating knob of a hand-held Griffin PowerMate device (can be held and turned in one or two hands).*
  - Scale-by-Slider: *Users indicate the magnification factor by dragging the lever of an AR slider presented in mid-air in front of them at the lower portion of their view (head-referenced to allow users to manipulate it at any head orientation).*

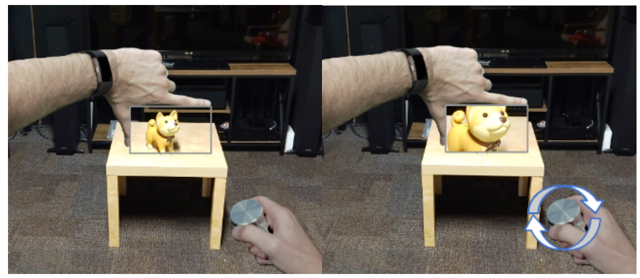
Each participant experienced all conditions. Participants first experienced the three magnification window UIs, followed by the two vergence distances, and last but not least the five UIs to change the magnification scale factor, all in randomized order.



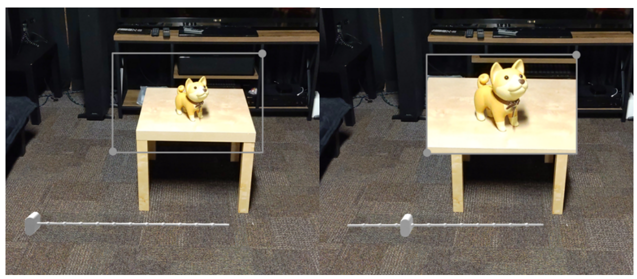
(a) Scale-by-Size

(b) Scale-by-Distance

(c) Scale-by-Voice



(d) Scale-by-Device



(e) Scale-by-Slider

Figure 3: Illustration of five techniques to change the scale factor of the magnified AR imagery: (a) *Scale-by-Size*, where users increase the window size to increase the magnification factor, (b) *Scale-by-Distance*, where users bring their hand closer to their head to increase the magnification, (c) *Scale-by-Voice*, where users verbally indicate the magnification factor (here with the keyword "Mag" followed by the factor), (d) *Scale-by-Device*, where users use a rotation knob to adjust the magnification factor, (e) *Scale-by-Slider*, where users drag the lever of an AR slider presented in mid-air in front of them to change the magnification.

3.3.1 Task and Procedure. After giving their informed consent, participants received an introduction to oculars, magnification, and AR HMDs. Participants then donned the HoloLens 2 and completed its eye calibration procedure, after which they experienced the conditions in the order specified in Section 3.3.

In line with a semi-controlled experimental design methodology [21], participants were assigned their tasks, but they were given more freedom when it comes to when, where, and how to perform the tasks. Hence, for each version of the three AR magnification aspects, participants were instructed to magnify (a) an object that is far away, (b) an object that is small and close by, (c) distant text, and (d) take a picture of a magnified object (using the HoloLens' "Take Picture" verbal command).

After completing these tasks, participants were asked to take off the HoloLens 2 and to answer the questionnaires described in Section 3.3.2 as well as a demographics questionnaire. The AR part and the questionnaires each took about 30 minutes.

3.3.2 Feedback Measures. We collected both subjective estimates and qualitative feedback from the participants. During an informal pilot testing event of a prototypical implementation with five local experts in the field of AR or visual perception, we discussed the AR magnification aspects and appropriate means to evaluate them, followed up with a literature search on relevant questionnaires, and designed the following measures based on our findings.

For our *subjective measures*, we used the following standardized questionnaire and designed our own itemized rating and ranking scales (inspired by the Simple Usability Scale [3], AttrakDiff [18], User Experience Questionnaire [32, 33]):

(1) **Intuitiveness Ratings** (1=very low, ..., 7=very high):
- *Three magnification window UIs: "How easy was it to learn/understand the techniques?"*
- *Two magnification vergence distances: "Does the imagery appear intuitively at the depth you would have expected?"*
- *Five magnification scale factor UIs: "How easy was it to learn/understand the techniques?"*

(2) **Preferences Rankings**: "Rank ... regarding overall preference."

- *Three magnification window UIs (1st choice to 3rd choice).*
- *Two magnification vergence distances (1st choice to 2nd choice).*
- *Five magnification scale factor UIs (1st choice to 5th choice).*

(3) **Perceived Task Load**: We used the raw version of the standardized NASA Task-Load-Index (TLX) questionnaire developed by Hart et al. [17] to assess the load perceived by participants with each AR magnification UI. It consists of six sub-scales: mental demand, physical demand, temporal demand, effort, frustration, and overall performance. Answers were given on a 1-to-7 scale, where 1 is very low and 7 is very high. The only exception is the overall preference sub-scale, where 1 is failure and 7 is perfect.

(4) **Usability Criteria—AR Window UIs**: "Please give us your subjective ratings of each of the three magnification window UIs with respect to these usability criteria (1=very low, ..., 7=very high)."

- *Hedonic Qualities: How pleasurable and appealing is it?*
- *Pragmatic Qualities: How practically useful is it (utility/usability)?*
- *Attractiveness: Overall impression of the technique; do users like it?*
- *Perspicuity: Is it easy to get familiar with the technique?*
- *Efficiency: Can users solve their tasks without unnecessary effort?*
- *Dependability: Does the user feel in control of the interaction? Is it secure and predictable?*
- *Stimulation: Is it exciting and motivating to use the technique?*
- *Novelty: Is the design of the technique creative? Does it catch the interest of users?*
- *Fatiguing: How fatiguing is it to use the technique?*

(5) **Usability Criteria—AR Vergence Distances**: "Please give us your subjective ratings of each of the two magnification focus distances with respect to these criteria (1=very low, ..., 7=very high)."

- *Visual Disruption/Interference: When looking at the magnified imagery overlaid over your view of the real world, how much does it disrupt your view of the real world?*
- *Visual Fatigue: How fatiguing/straining is it to look at this imagery?*
- *Difficulty Focusing: How difficult is it to focus the eyes on the imagery?*
- *Effort Switching Depths: When looking at a real-world target at a long distance and then looking at the magnified visuals, how much visual effort does this switch take?*
- *Hand-Eye-Coordination Effort: How much hand-eye-coordination effort does it take to align the target with the magnified visuals with one's hand(s)?*

Additionally, to better understand participants' perceptions and preferences in relation to the different AR magnification aspects, we collected *qualitative feedback*, which mainly consisted of asking them "why?" after they responded to the subjective scales. Further, we asked them to respond to the following open-ended questions with respect to each version of the three AR magnification aspects:

- *"In which circumstances do you see the ... being useful?"*
- *"Do you have any further comments on the general technique ...?"*
- *"Do you have any further comments on the specific implementation of ... or the display/tracking hardware that was used?"*
- *"Do you have any comments on why the AR magnification is already (or could in the future become) better/worse than traditional binoculars/monoculars?"*

4 RESULTS AND DISCUSSION

Overall, from our qualitative feedback we learned that all of our participants indicated that AR magnification has a lot of potential, in particular once the AR form factor and technologies mature. As one participant put it: *"there is no reason not to have it"* and *"it is compelling value-added for AR displays"* with respect to magnification as a default application on AR HMDs in the future. Effectively, in order to enable this functionality, all a commercial AR display needs is a good camera and reasonable tracking.

Preference Rankings. The preference rankings of the AR magnification UI aspects are shown in Figure 4. For the three *magnification window UIs*, half of the participants preferred the situated UI as their first choice, and half of them preferred either the bimanual or unimanual UI. Both the situated and bimanual UIs show overall high preferences. For the two *vergence distances*, preferences are split, with half of the participants preferring the near vergence (in hand) and half the far vergence (through hand). For the five *scale factor UIs*, the preferences clearly indicate that participants did not like the scale-by-slider UI. Overall high preferences can be seen for the scale-by-size, scale-by-voice, and scale-by-device UIs, with slightly less preference for scale-by-distance.

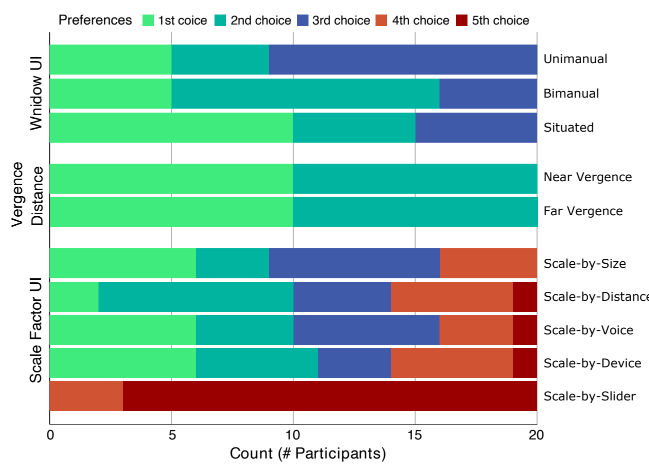
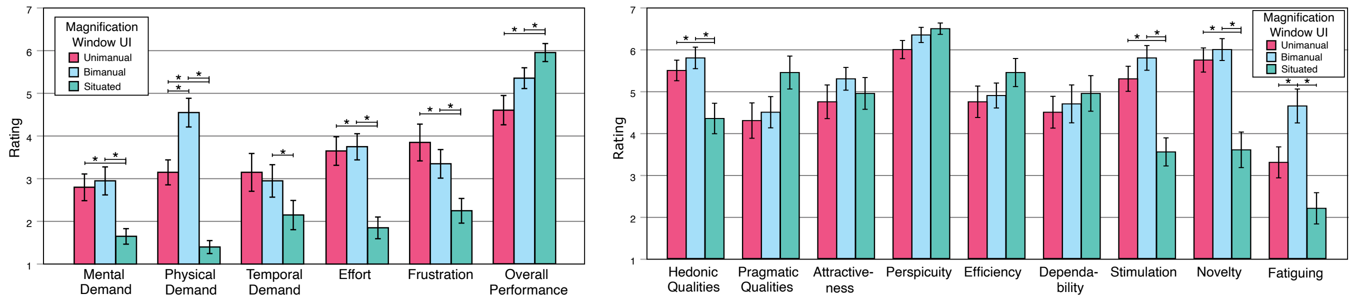


Figure 4: Preference rankings. The x-axis indicates the number of participants who rated the aspects in first to last place.

Analysis. We analyzed both the subjective estimates and qualitative data we collected to understand the AR magnification aspects. For the *subjective data*, we analyzed the responses with repeated-measures ANOVAs and Tukey multiple comparisons with Bonferroni correction at the 5% significance level. We are aware that the use of parametric tests for Likert-scale ordinal data is an ongoing debate in this field—we side with the arguments for the use of parametric tests [22, 23]. The other assumptions of the parametric statistical tests were confirmed or corrected for, e.g., using Shapiro-Wilk tests and Q-Q plots for normality testing and Greenhouse-Geisser corrections in case Mauchly's test indicated non-sphericity. We further analyzed the *qualitative data* based on Braun and Clarke's thematic analysis approach [2], which consisted of multiple rounds of reading the responses to get familiar with the data, followed by iterative coding through multiple revisions grouped into themes. We describe our subjective responses and discuss them with the help of our qualitative feedback in the following sections.



(a) Perceived Task Load

(b) Usability Criteria

Figure 5: Results for the three magnification window UIs: (a) perceived task load (lower is better, except for *overall performance*) and (b) usability criteria (higher is better, except for *fatiguing*). The whiskers indicate statistical significance. The error bars show the standard error.

4.1 Magnification Window UIs

We analyzed the differences between the three magnification window UIs in terms of perceived task load, usability criteria, and qualitative responses as described in Section 3.3.2.

4.1.1 Results. Figure 5 shows the subjective responses for the three magnification window UIs.

We found a significant main effect for all sub-scales of the NASA TLX questionnaire. Specifically, for *mental demand*, $F(2, 38) = 10.18$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.35$, for *physical demand*, $F(2, 38) = 53.03$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.74$, for *temporal demand*, $F(1.49, 28.29) = 5.58$, $\mathbf{p = 0.015}$, $\eta_p^2 = 0.23$, for *effort*, $F(2, 38) = 24.88$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.57$, for *frustration*, $F(2, 38) = 9.82$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.34$, and for *overall performance*, $F(1.51, 28.64) = 9.39$, $\mathbf{p = 0.002}$, $\eta_p^2 = 0.33$. Pairwise comparisons showed that the situated window was rated significantly better than the two other UIs (except for temporal demand, where the difference to the unimanual UI was not significant). We also found that the bimanual UI was rated to cause significantly higher physical demand than the unimanual UI.

We further found a significant main effect for four of the usability criteria. Specifically, for *hedonic qualities*, $F(2, 38) = 9.70$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.34$, for *stimulation*, $F(2, 38) = 17.83$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.48$, for *novelty*, $F(2, 38) = 19.17$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.50$, and for *fatiguing*, $F(2, 38) = 20.28$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.52$. We found no significant effect (maybe a trend) for *pragmatic qualities*, $F(2, 38) = 2.92$, $p = 0.066$, $\eta_p^2 = 0.13$ and *perspicuity*, $F(2, 38) = 2.50$, $p = 0.096$, $\eta_p^2 = 0.12$. We found no significant effect for *attractiveness*, $F(2, 38) = 0.64$, $p = 0.53$, $\eta_p^2 = 0.03$. We looked at all pairwise comparisons for the significant usability criteria and found that the situated window was rated significantly worse than the two other UIs (except for fatiguing, where the difference to the unimanual UI was not significant). We further found that the bimanual UI was rated as significantly more fatiguing than the unimanual UI.

4.1.2 Discussion. Looking back at Figure 4, we see that the participants' *preferences* were split between the situated UI on the one hand and either of the two unimanual/bimanual UIs on the other hand. In the following, we take a more holistic look at the subjective estimates and qualitative responses and condense them into themes and potential explanations for their preferences.

Fatigue. The most often mentioned comment participants made for the difference between the interfaces was *"fatigue."* In Figure 5(a), we see that *effort* was lower for the situated UI than for the unimanual/bimanual UIs. Moreover, *physical demand* was highest for the bimanual UI, followed by the unimanual UI, and lowest for the situated UI. A similar result is shown in Figure 5(b) for usability ratings of *fatiguing*. However, qualitative responses were largely split into two groups in terms of their interpretation of this point. The first group (half of the participants) explained their preference of the more hands-free situated UI with the point that both the unimanual and bimanual UIs require users to hold up their hands in mid air in front of their head. The more experienced participants linked this challenge to the well-discussed *"Gorilla Arm Syndrome"*, referencing the *Minority Report* interface, which used similar hand gestures (though for a different purpose) [6, 16]. Conversely, the opposing group acknowledged that fatigue is an issue but pointed out that—compared to the use of real binoculars—having to hold up one's hands without the extra weight of a physical ocular device or camera makes this in comparison a much less fatiguing interface with a lot of promise for everyday use.

Duration. The second most often made comment by the participants was regarding the intended duration of use. Again, we observed two groups advocating for different uses of the interfaces. The first group used terms like *"continuous," "over time,"* or *"long duration"* to describe the benefits of the situated UI. One participant stated the intended use of the situated UI as: *"Any situation when you don't want to turn the view on/off and just leave it on; where zoom is desired for a long duration, like at a theater or sports event."* They described the continuous magnified view with words like *"convenient"* and *"comfortable."* However, the second group pointed out that the situated UI provides *"insufficient control"* over the window, *"gets in the way"* when looking around, and making it appear and disappear causes *"overhead"* and *"visual distraction."* The most often used term by this group was *"quick"* when describing the benefits of the unimanual or bimanual UIs, with some describing them as *"just-in-time," "there when you need it,"* or *"on-demand."* All participants indicated that the unimanual/bimanual UIs are mainly useful in situations when a quick magnified view is intended, e.g., as one participant put it: *"when someone wants to gain quick visual awareness of something far away for a short time (identify/understand)."* An example mentioned by multiple participants was: *"taking quick* *snapshots (pictures/videos) of a part of my view."* However, the same participants acknowledged that the unimanual and bimanual UIs require more cognitive resources (see in particular *mental demand* in Figure 5a) and make it difficult to multitask as either one or both hands are occupied, indicating that they are mainly useful for tasks that require quick or full attention by the user.

Integration. While the aforementioned two participant groups were largely entrenched in their preferences, a few participants indicated that they would prefer to have all of them available as needed. One participant remarked: *"if you could combine them in one interface, the system would be awesome."* The general consensus seems to be that each window UI has its own uses and challenges, but none can take on all uses of the others, implying that an integration of the interfaces may be the optimal path forward. In fact, both unimanual and bimanual UIs can be integrated easily, delineated by how many hands/fingers are visible in the field of view, while a toggle/gesture can be used to switch to the situated UI.

4.2 Magnification Vergence Distance

We analyzed the differences between the two magnification vergence distances in terms of visual perception criteria and qualitative responses as described in Section 3.3.2.

4.2.1 Results. Figure 6 shows the subjective responses for the two magnification vergence distances.

We found that the near vergence produced a significantly higher *visual disruption/interference* than the far vergence, $F(1, 19) = 7.12$, $\mathbf{p = 0.015}$, $\eta_p^2 = 0.27$, caused significantly more *visual fatigue*, $F(1, 19) = 4.70$, $\mathbf{p = 0.043}$, $\eta_p^2 = 0.19$, and required significantly more *effort switching depths*, $F(1, 19) = 23.00$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.55$. We found no significant effect for *difficulty focusing*, $F(1, 19) = 0.05$, $p = 0.83$, $\eta_p^2 = 0.02$, nor for *hand-eye coordination effort*, $F(1, 19) = 1.73$, $p = 0.20$, $\eta_p^2 = 0.08$.

4.2.2 Discussion. As shown in Figure 4, participants' *preferences* for the two vergence distances were split in half with rather conflicting opinions. In the following paragraphs, we discuss the subjective estimates and qualitative feedback supporting these preferences.

Switching Vergence. The results shown in Figure 6 clearly show that participants rated the near vergence as worse than the far vergence. In particular, they rated the near vergence as significantly worse in terms of *effort switching depths*, *visual fatigue*, and *visual disruption*. Supported by our qualitative comments, all participants indicated that the near vergence caused them to have to adjust their eyes to verge on something up-close after first looking at something far away in the real world. In particular, repeated *far–near–far* vergence changes were rated as highly fatiguing. In contrast, maintaining a far vergence with the AR imagery avoided this issue. In that sense, participants agreed that the far vergence provided the better visual experience. A related point is that the HoloLens 2 has a focal distance of two meters[3], which means that neither the near nor far vergence distances exactly matched the focal distance of the display, leading to a vergence-accommodation conflict that may have additionally contributed to visual disruptions and fatigue.

[3]https://learn.microsoft.com/en-us/windows/mixed-reality/design/comfort

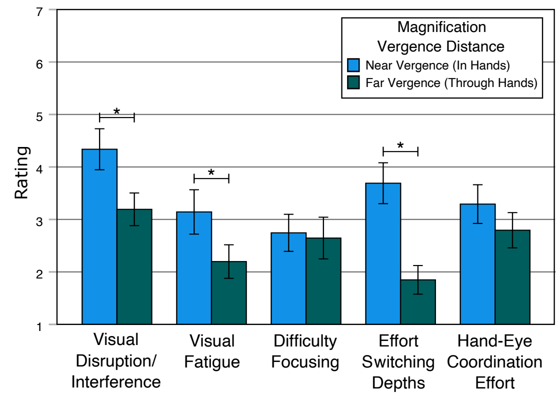


Figure 6: Results for the usability criteria for the two AR window vergence distances (see Sec. 3.3.2). The whiskers indicate statistical significance. The error bars show the standard error. Lower is better

Hand Integration. However, while the results in Figure 6 seem to paint a clear picture of the far vergence ("through hands") being better, only half of our participants preferred it overall (see Figure 4). The main comments we received from the other half were mainly related to the way the near vergence ("in hands") integrates with their hands when using the unimanual or bimanual UIs. One participant phrased the benefits of the near vergence magnification like this: *"Even if it is technically the same size, it gives me the illusion that I am holding it close to my face, like putting a paper closer to my face to see it better."* Another participant stated: *"It felt more natural for the image sitting in my hands to be at the same focus as my hands,"* and *"it makes the screen seem like a physical object, like holding a phone; very easy to understand immediately."* Another explanation for their preference of the near vergence we heard from multiple participants was that it integrates better in the context of having to interact with other close-up objects, such as other devices in one's hands.

Integration. As indicated above, while the more objective visual aspects seem to favor the far vergence, the aforementioned subjective factors are an important aspect to keep in mind when designing an interface for casual/power users. Only a few of our participants indicated that they *"liked them both"* whereas the large majority had a strong preference for one of them. While it seems difficult to integrate both vergence distances in one interface, e.g., adaptively changing the vergence distance, it seems more reasonable to allow users to choose their preferred vergence distance. As one participant said: *"I think both of them felt equally intuitive but in different ways. It would make sense if you could switch between the two for different tasks."*

4.3 Magnification Scale Factor UIs

We analyzed the differences between the five magnification scale factor UIs in terms of perceived task load and qualitative responses as described in Section 3.3.2.

4.3.1 Results. Figure 7 shows the subjective responses for the five magnification scale factor UIs.

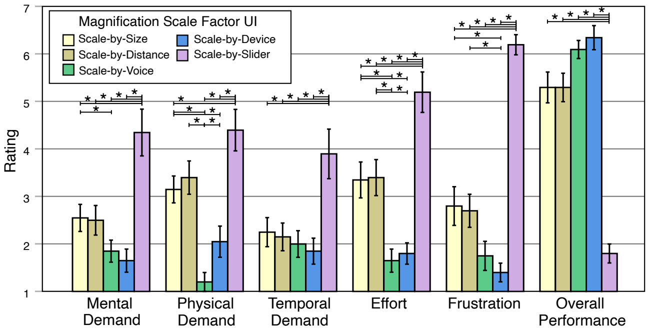


Figure 7: Results for perceived task load (NASA TLX) for the five magnification scale factor UIs (Sec. 3.3.2). The whiskers indicate statistical significance. The error bars show the standard error. Lower is better (except for *overall performance*).

We found a significant main effect for all sub-scales of the NASA TLX questionnaire. Specifically, for *mental demand*, $F(2.29, 43.48) = 13.73$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.42$, for *physical demand*, $F(2.90, 55.06) = 22.23$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.54$, for *temporal demand*, $F(2.01, 38.17) = 9.93$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.34$, for *effort*, $F(2.33, 44.19) = 26.25$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.58$, for *frustration*, $F(4, 76) = 61.56$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.76$, and for *overall performance*, $F(2.60, 48.72) = 55.64$, $\mathbf{p < 0.001}$, $\eta_p^2 = 0.75$. We looked at all pairwise comparisons and found that for all sub-scales, the scale-by-slider UI was significantly worse than all other UIs (except for physical demand, where the difference to scale-by-distance was not significant). We further found that scale-by-size caused higher mental demand than scale-by-voice, scale-by-size caused higher physical demand than scale-by-voice and scale-by-device, scale-by-distance caused higher physical demand than scale-by-voice, scale-by-device caused higher physical demand than scale-by-voice, scale-by-size required higher effort than scale-by-voice and scale-by-device, scale-by-distance caused required higher effort than scale-by-voice and scale-by-device, and scale-by-device caused lower frustration than scale-by-size and scale-by-distance.

4.3.2 Discussion. In the following paragraphs, we go through the five magnification scale factor UIs and discuss the subjective estimates and qualitative feedback (starting with the clearest cases).

Scale-by-Slider. Participants' preferences (see Figure 4) were very clear in that they did not like the scale-by-slider UI, which is also visible in the task load results in Figure 7. These results show a significantly lower overall performance, higher effort and physical demand for mid-air hand movements, and general frustration. In our qualitative feedback, we found concerns about the use of an additional AR mid-air interface, fatigue caused by such interfaces for tasks that require many changes in scale factors, and just having to look at the slider to be able to move it when one really wants to look at the magnified imagery. We did not hear a single positive comment about the AR slider interface.

Scale-by-Device. The scale-by-device UI was rated overall very high by our participants. The device resulted in ratings of low mental demand, low effort, and low frustration, but high overall performance (see Figure 7), matching our expectations of a well-polished and trusted device for input. Many of our participants commented that it is *"extremely easy to understand and make very precise adjustments"* and *"feels very comforting and precise."* However, at the same time we heard a lot of comments from our participants that it really only works with the unimanual and situated UIs as you need one hand on the device, or otherwise you have to iterate between the device and mid-air, which would greatly reduce the performance. One participant mentioned: *"An integrated knob on the headset would probably be ideal."*

Scale-by-Voice. The scale-by-voice UI resulted in the lowest overall physical demand among the scale factor UIs with a high overall performance and low task load (see Figure 7). Participants in particular praised it for being *"hands-free"* and *"comfortable."* Other participants remarked that they appreciated the *"specificity of calling out the magnification numbers"* using commands like "mag five" as it made it clearer to understand how much the imagery is currently magnified. However, others stated that while the voice commands were *"fun and immediately gratifying,"* they would not want to use them in loud, noisy, or social environments. As one participant put it: *"I don't think that I would actually want to use them with other people around; shouting out what you want isn't ideal in settings where you need to be quiet."*

Scale-by-Distance. The conceptual benefit of this technique is that no additional interface is needed but the scale factor is implicitly set by the position of the AR magnification window in front of a participant's head. Participants can change the magnification scale factor by moving the window with their hands farther away or closer to their head. While the scale-by-voice and scale-by-device UIs scored higher, our results generally convey a positive impression of this technique (see Figure 7). One participant mentioned: *"I personally just really enjoyed being able to magnify it by pulling the window closer to me; it felt like taking something far away in the distance, and bringing it closer."* Another participant stated: *"the window relative interfaces were just more enjoyable to use and you immediately understand what's happening without explanation."* However, we also received some criticism for the scale-by-distance technique, mostly related to the required precision of hand movements when trying to magnify a distant object. It was best put by one participant: *"I found it difficult to see the imagery, move my hands back/forth, and keep my hands in the right position, all at the same time."*

Scale-by-Size. The scale-by-size UI shared many of the usability aspects of the aforementioned scale-by-distance technique. While we found no significant differences between these two techniques in the subjective data (see Figure 7), we did identify a general theme in the qualitative data. Participants indicated that they preferred lateral hand movements as in the scale-by-size UI over forward/backward movements as in the scale-by-distance UI for controlling the magnification factor. One participant stated: *"Window-size relative makes the most sense intuitively whether that has to do with the zoom motions on phones or from watching them doing that in sci-fi movies. Something about that just feels like it is the right way. But both window techniques are efficient and easy to learn."*

Integration. Overall, our participants expressed generally positive comments for all UIs and highlighted different benefits and use cases (except for the scale-by-slider UI), suggesting that AR magnification systems may offer multiple UIs depending on users' preferences or integrate those that can be combined. As discussed above, both window-relative approaches (scale-by-distance and scale-by-size) are very easy for users to understand, but, given the choice between these two techniques, the scale-by-size UI seems preferable. If not using one of these UIs, it seems possible to combine the voice commands with the orthogonal modality of a knob mounted on the AR HMD to provide the added sensitivity over the magnification scale factor when needed.

5 GENERAL DISCUSSION

Overall, we received enthusiastic feedback from our participants for the different UIs for AR magnification, and most of them wondered why magnification is not by default integrated into AR HMDs. Multiple of our participants expressed in their qualitative feedback that intuitive magnifications like this add a lot of *"easy-to-understand functionality"* and *"value-added"* to any AR HMD system that can be grasped even by novice users. All participants pointed out in some form that the concept in general is very *"intuitive"* and *"compelling."* One participant stated: *"I'm looking at the next 'killer app' for AR HMDs."* In the following, we discuss some of the larger findings, challenges, limitations, and potential directions for future work.

User Interface Aspects. In our experiment, we looked at three essential aspects of AR magnification interfaces: the window UI, the vergence distance, and the scale factor UI. We compared three UIs to create and modify a window in real time in which (or through which) the magnified imagery is presented in AR. Our results show support both for unimanual/bimanual and situated interfaces, implying that each has benefits in different contexts, especially depending on the length of use and fatigue associated with their use. We further compared two vergence distances at which the magnified imagery is presented in AR. We found a lot of objective benefits for using a far vergence distance (i.e., seeing the AR imagery "through" one's hands at a far vergence distance) for one's visual perception and fatigue, but half of our participants still preferred a near vergence distance (i.e., seeing the AR imagery as if holding a picture "in" one's hands) due to the way the AR imagery integrates with one's hands similar to a smartphone or tablet. Last but not least, we compared five UIs to change the scale factor of the magnified imagery. Our results showed that participants generally liked two window-relative interfaces where either the size of the window or the distance of the window from one's head implicitly define the scale factor, and most participants rated and ranked the voice-based or device-based interfaces highly, though these are not considered useful in every context, while none of our participants liked interacting with a slider in mid-air.

Hardware Aspects. For this work, we implemented a hardware and software testbed and framework to explore different user interface aspects, relying entirely on available COTS devices. The used Microsoft HoloLens 2 AR HMD already provided a lot of useful functionality for the purpose of AR magnifications, while all of our participants agreed that some hardware aspects still have ways to go. The most common comments by our participants were that the *hand tracking* as provided by the HoloLens 2 is sub-par for some users' hands, depends on the region of where the hands are in one's visual field, and depends on the hand orientation, which needs to be improved in the future. A further suggestion by our participants was to use a *higher-resolution camera*, which is a reasonable fix in the future, e.g., using commercial cameras with higher resolution that fulfill the visual requirements, and could arguably be integrated into future sensor device platforms like the HoloLens. Other suggestions were targeted at the *display*, e.g., a larger vertical (downward) field of view would make hand interaction less fatiguing, and a higher display resolution would reduce the magnification factor that is needed to see details in the camera imagery in AR.

Limitations. First of all, we make no claims that these UIs or visualizations presented and tested here in this work are the only ones possible or that they are optimal. However, to the best of our knowledge, we are not aware of prior work looking at similar intuitive AR magnification UIs to which we could have compared our work. This work should be understood as a largely exploratory research to encourage future work in this direction. Second, we did our best to recruit a diverse participant sample from experts to novices, from young to old, but we acknowledge that more participants would give a better understanding of different aspects related to diversity, equity, inclusion, and accessibility. In particular, accessibility is a topic for future work, especially with respect to people with *low vision*, for whom even a moderate magnification may prove useful for everyday use, and people with *motor conditions*, for whom future work may look at more hands-free techniques.

6 CONCLUSION

In this paper, we presented a design space for intuitive real-time AR magnifications, involving an AR HMD, a high-resolution camera, and different 3D user interfaces. We evaluated three aspects of AR magnifications, looking at UIs for defining the AR window in one's visual field in which the magnified imagery should appear, the vergence distance at which this information should be presented, and UIs for defining the scale factor of the magnified imagery. Our results showed different interesting subjective estimates and qualitative effects, supporting future research and development in this direction. Future work may consolidate these findings with performance data, e.g., how efficient the techniques are for zooming in on objects and examining the magnified material. Future work should also focus on the discussed limitations of current display and sensor hardware and may include extensions such as potential stereo camera solutions for additional depth cues [4]. Higher-quality displays and sensors may lead to a wider adoption of AR magnification across a range of application fields. Future research could also expand the sample size and diversity, and explore hybrid methods that blend different techniques, considering that users' preferred methods may vary depending on the situation.

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