Magnification Lenses for Small-Scale Augmented Reality Instructions

Lucchas Ribeiro Skreinig*
Graz University of Technology

Denis Kalkofen
Graz University of Technology

David Ritter
Graz University of Technology

Peter Mohr
Graz University of Technology

Markus Tatzgern
Salzburg University of Applied Sciences

Dieter Schmalstieg
University of Stuttgart

Ana Stanescu†
Graz University of Technology

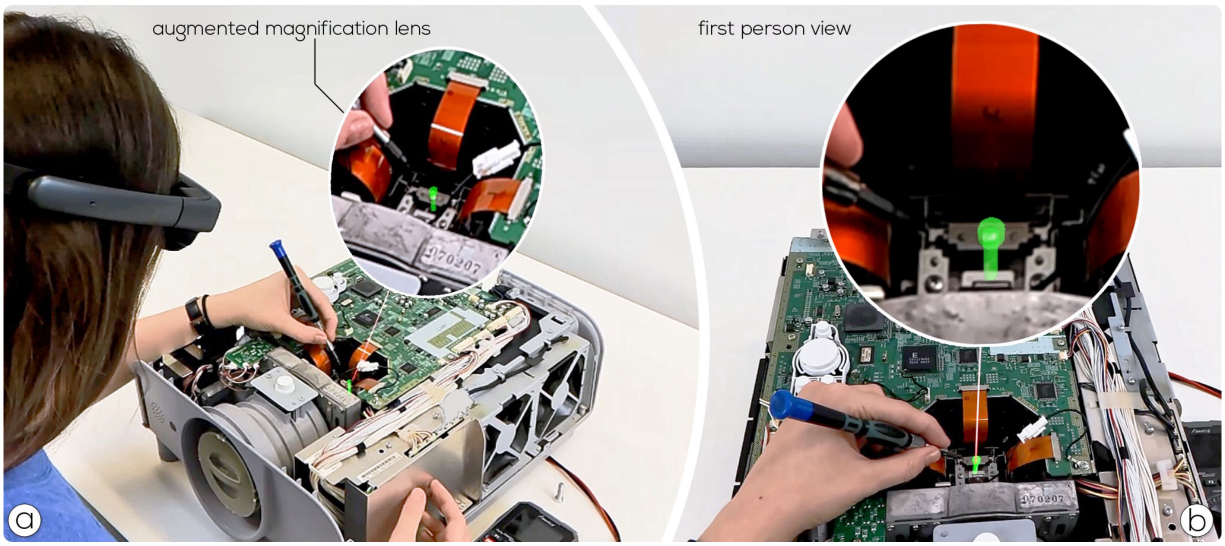


Figure 1: (a) Small parts are visualized in-situ for augmented reality instructions, supported by a magnification lens that shows an enlarged view of the environment and of the augmented instructions. (b) We magnify the user's real view and the associated virtual instructions to assist with the localization and visibility of small details.

Abstract

Small-scale objects that are difficult to see or distinguish from their surroundings are common in assembly and maintenance procedures. Augmented reality (AR) instructions involving such small parts may be difficult to perceive and lead to misinterpretations. This paper explores the use of AR magnification visualizations for small-scale instructions. Through an iterative design process and evaluation, we examine how magnified AR views impact user behavior, visual attention, and subjective perception in the context of AR instructions. Our findings demonstrate that live AR magnification assists task guidance, providing a strong foundation for future work on AR-assisted instruction and precision interaction design.

Index Terms: Augmented reality, visualization, instructions, magnification.

1 Introduction

Augmented reality (AR) guidance systems typically overlay digital information directly onto physical objects. Previous work has demonstrated clear advantages of registered AR visualizations over non-registered instructions [23]. However, research has focused mainly on medium to large objects, such as toy construction bricks [27, 6], vehicles and industrial objects [23, 30, 38], or household appliances [42]. The challenges of providing AR instructions on a *small scale*, when manipulation tasks involve physical components that typically require millimeter-scale precision, remain underexplored. We address this important research gap, as even minor inaccuracies in instruction details can lead to errors or ambiguities.

For example, screws or small electronic components are part of many assembly and maintenance procedures and are notoriously difficult to identify or place accurately. The challenges of working at small scales are further increased in narrow work areas, such as circuit boards, which are densely packed with visually similar components. Magnification offers a potential solution for working on a small scale. Previous work has explored digital magnification techniques that enlarge the real-world view using an AR head-mounted display (HMD), for instance, to improve vision for medical professionals during surgery [34, 24] or for people with visual impairments [43]. However, these techniques are designed to help with perception, and the experience of interacting with a live magnified view while also receiving guidance has not yet been considered.

In this paper, we describe an AR magnification lens that enhances the visibility of small physical objects and corresponding augmented instructions (see Figure 1). Spatial proximity between the magnified view and the real-world location facilitates mental linking of the zoomed-in view with the corresponding work area. Unlike pre-rendered magnified virtual views [12, 13], we use the AR headset's camera to provide a live view with continuously updated magnification from the user's perspective, integrating AR instructions with a zoomed-in view of the user's hands and tools.

*e-mail:lucchas.ribeiroskreinig@tugraz.at
†e-mail: ana.stanescu.xr@gmail.com

The design of our AR magnification lens is based on a series of formative studies and a user evaluation. The formative studies enabled us to fine-tune the lens visualization based on insights from users experiencing the combined magnification and instruction visualizations. We also distilled AR hardware requirements directly from user feedback and observations. The refined design was evaluated in a controlled user study (N=24) assessing both objective performance (task completion time, error rates, gaze behavior) and subjective measures (workload, usability, user preferences). Our experimental tasks are representative of real-world scenarios involving fine-grained repair procedures, thereby ensuring reasonable ecological validity of the collected insights.

In summary, our work makes the following contributions:

- We explore the design space (visualization style, display technology, overall user experience) of AR magnifications for instruction delivery while performing tasks at a small scale.
- We present insights from a series of formative user studies that lead to a novel live AR magnification lens design.
- We present the implementation of our lens design and its validation in a formal user study.
- Based on the results of the formal user study, we put forward design guidelines for integrating AR magnification lenses with AR instruction systems.

2 Related Work

Research on AR for instructional support has gained significant attention due to its potential to enhance user experience and efficiency in various tasks. AR instructions have been demonstrated to improve over video instructions [48] and common 2D instruction manuals [35] by reducing cognitive load [49], errors [45] and the time needed to localize parts [23]. However, as the effectiveness of visual instructions, magnified or not, commonly depends on the visualization used to communicate them, we first review visualization techniques for AR instructions before discussing related work on AR lenses and AR magnification.

2.1 Visualizations for AR instructions

AR instructions often include 3D-registered guidance cues to help users understand spatial relationships and task sequences [19]. Early work [15, 23] demonstrates how AR instructions can be integrated into the environment. Overlaying visualizations at the object location in a see-through display leads to faster localization and less head movement compared to a 2D screen. Other recent work [9] has examined AR as a support tool for assembly training, highlighting its benefits in industrial scenarios and demonstrating how spatially aligned instructions can support manual processes [10].

Subsequent research focuses on comparing visualization styles. Khuong et al. [27] compare wireframe overlays with side-by-side visualizations for assembly, reporting better performance for side-by-side views with solid rendering. This result is attributed in part to limitations in tracking accuracy, which affect the quality of the registration. Later studies revisit this question. The work by Blattgerste et al. [5] compares multiple visualizations for LEGO assembly instructions: 3D in-situ, 2D in-situ, 3D wireframes, and side-by-side. The findings indicate that in-situ views outperform side-by-side approaches, with static 3D in-situ overlays performing best. Jasche et al. [25] compare semi-transparent mesh overlays with simplified wireframes, with optional explanatory videos. Results show that semi-transparent meshes reduce error rates and that the videos improve usability, particularly for complex assembly steps. Similarly, LaViola et al. [30] compare in-situ AR, 3D side-by-side AR, and paper instructions in scenarios involving occluded objects. The findings show that AR visualizations outperform paper instructions and that in-situ visualizations outperform 3D side-by-side views in terms of completion time.

While these studies provide a foundation for AR-assisted assembly, there remain gaps in understanding the optimal types and combinations of visualizations for different types and sizes of objects. Our work builds on prior research, but focuses especially on object assembly tasks involving small parts and fine details. As our baseline visualization style, we adopt the commonly used overlays of semi-transparent meshes [25, 30].

2.2 Lenses and magnification in AR

The magic lens paradigm, introduced as a see-through 2D interface by Bier et al. [4], overlays a widget that reveals new information about objects, showing detail and context at the same time. Applied to AR and virtual reality (VR), Looser et al. [32] propose a hand-held lens for virtual content, revealing details or providing magnification. Later, they present a tangible device that acts as a magnification lens for selective viewing of augmented content [33]. Kalkofen et al. [26] introduce a magic lens for overlaying contextual details on real objects in a lens.

Most magnification approaches either digitally enlarge the video texture or optically enlarge the real world. Kiss et al. [28] visualize microscope images on AR displays and investigate their placement. To magnify the user's view, optical enlargement can use a physical magnifying lens mounted on a headset [37] or bring the camera closer to the object. For example, a finger-mounted camera can be used to enlarge text for accessibility purposes [43, 44]. An alternative for magnification is an approach which replaces the real-world view with realistically rendered virtual content inside the lens [12]. This approach can provide superior resolution and contrast, but are restricted to static views only, as moving physical objects or unknown scene elements are not visible in the magnification.

Live video magnification lenses have been proposed for medical applications, where head-worn surgical loupes are already commonplace. For example, five surgeons tried a video-based magnification lens placed between their view and the target area on a patient [34]. While dissatisfied with the video quality, participants expressed a positive response to the use of the lens. Ilo et al. [24] propose another magnification lens and evaluate it in a study with six surgeons. Their implementation magnifies the entire view of the video see-through (VST) headset. The prototype led to poor usability scores due to device limitations (bulky, low resolution, no stereo vision), but surgeons appreciated the gaze interaction for zooming.

Similar VR magnification lenses (or "loupes") have been used in the dental domain [13], where magnification has been shown to improve upper body posture [7, 2]. Dastan et al. [13] describe a lens-like VR widget for drill positioning that presents entirely virtual content within the magnified view. This approach requires precise tracking to register the virtual lens content with the real world, and also occludes the real world. Another application of AR magnification involves the human body [11], where body parts are segmented and magnified. This work focuses on the perceptual augmentation of a segmented scene element, whereas instructional magnification supports object perception within the workspace, with the user performing interactions within the magnified area.

Magnification of the user's view in an AR interface in a broader context was investigated by Schubert et al. [40], who considered three aspects: window UI, vergence distance, and scale factor UI. Their findings indicate that users prefer situated magnification windows over hand-controlled alternatives, as they require less effort. Furthermore, they found that repeatedly switching vergence between the real world and closer virtual content resulted in higher fatigue levels. In our work, we focus on spatially situated magnification in an instructional context for bi-manual object manipulation

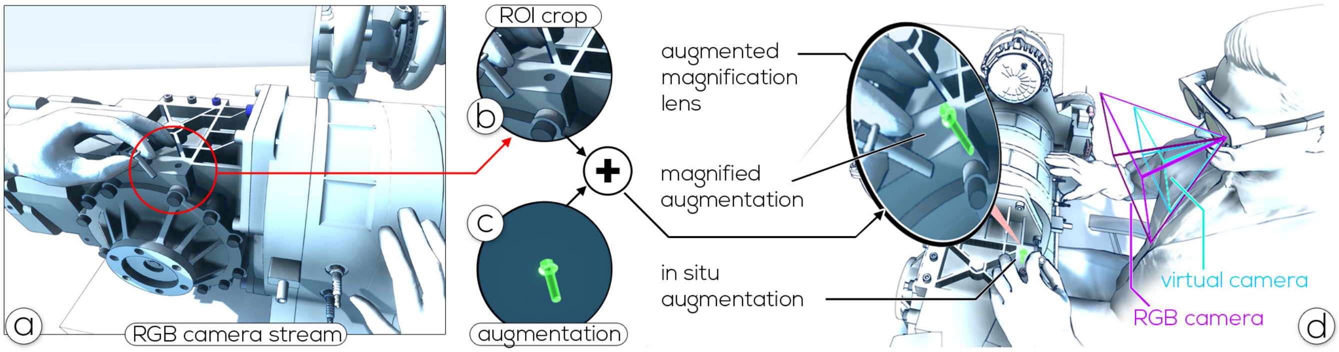


Figure 2: System overview: The in-situ instruction is displayed in the user's HMD. (a) In addition, an RGB stream from the HMD camera is captured. (b) The region of interest (ROI) is extracted at the projected location of the current instruction, (c) which is also rendered through a calibrated virtual camera. (d) Both images are combined and shown in the magnification lens.

tasks such as assembly or maintenance.

Magnification in VR has been used for precise target selection [50, 39]. These interaction techniques focus on purely virtual elements rather than understanding the real world in AR. Having control over the appearance of the VR world, the optimal interaction is very different from the AR scenarios on which we focus.

Our work moves beyond previous work by investigating magnification support for users manipulating real objects while considering small-scale AR instructions. We explore the presentation style of the instructional content and the overall design of the user experience. Guided by formative user studies, we iteratively refine and improve the design of the proposed AR lens visualization before validating it in a formal user study.

3 System Overview

Our system addresses the challenges of presenting AR instructions in small-scale scenarios. At the intended small scale, conventional visualizations fail to provide sufficient visual detail. To avoid this limitation, we designed an instructional system that combines spatially registered guidance with a digital magnification lens.

Therefore, from an initial analysis of the problem domain, we formulate several design goals. Since visual augmentations within AR magnification lenses have not been studied in related literature, we explore different visualization styles to gain insights about their usage in magnification lenses for small-scale AR instructions.

3.1 Design goals

Detail magnification AR instructions for small-part assemblies often lack sufficient visual detail to distinguish nearly identical parts or identify small features within larger components. To address these challenges, we introduce a magnified view of the real-world target area overlaid with registered instructions, as illustrated in Figure 2. The visualizations support users in localizing small components and understanding the associated instructions. We designed our system to enhance the clarity and visibility of visual information without cluttering the user's view.

Aligned perspectives Following best practices set forth by previous work [17], we align the magnified view with the user's view. We take into account that users continuously shift their gaze while working and stabilize the magnified viewpoint on the current area of interest, thereby avoiding interruptions to the workflow.

Spatial coupling We aim to seamlessly integrate instructions with real-world elements. All instruction steps are visualized as AR overlays registered on or near corresponding real-world objects, as we try to avoid frequent focus shifts between real and virtual content placed at different depths, following Schubert et al. [40]. Spatially coupling the magnification lens with the physical world items ensures that users can always access the detail view without shifting their attention too far from the task area, while keeping the virtual objects consistently visible.

3.2 Visualization styles

Semi-transparent mesh Similar to the in-situ visualization, augmentations in the magnification lens are displayed as 3D meshes. See Figure 3c for an example.

Outline rendering This style highlights augmentations by rendering the outline of the object. Outlines are less obstructive than meshes, ensuring visibility of the physical structures. See Figure 3d for an example.

Adaptive transparency Using the hand tracking features of the headset, this visualization dynamically reduces the opacity of augmentations shown in the lens, thereby reducing occlusion as the user's hands approach the target area. See Figure 3e for an example.

Animated mesh In this style, we render animated instructions that mimic object movement over time, thereby showing processes (e.g., object insertion) and geometric hints (e.g., mounting direction). See Figure 3f for an example.

3.3 Implementation

We chose an HMD as the target platform to enable bi-manual interactions, allowing users to perform assembly or maintenance tasks effectively. The magnification feature utilizes the HMD camera's outward-facing live video feed. Our magnification method first identifies the region of interest (ROI) in the video feed as texture coordinates based on the projected locations of the spatially registered augmented instruction in world space (Figure 2a). The video texture within the ROI is then scaled to 120% to magnify its view. To handle cases where the ROI moves out of bounds of the video texture, a clamp function is applied to prevent rendering artifacts. The result is a magnified portion of the real-world view (Figure 2b), which is centered on the area of interest as long as it is present in the camera view, even if the user is not looking directly at it.

We access the camera's intrinsic and extrinsic parameters, which describe the camera's optical characteristics and pose in space, from the headset API. A virtual camera is placed in the same position as the real-world camera to render the augmentations from the same perspective as the real-world elements (Figure 2c). The virtual camera renders the augmented instructions with a transparent background overlaid on the magnified video stream in the lens (Figure 2d) , using the intrinsic parameters of the real camera.

The implementation places the lens in the spatial proximity of the manipulation area, at approximately the same vergence depth

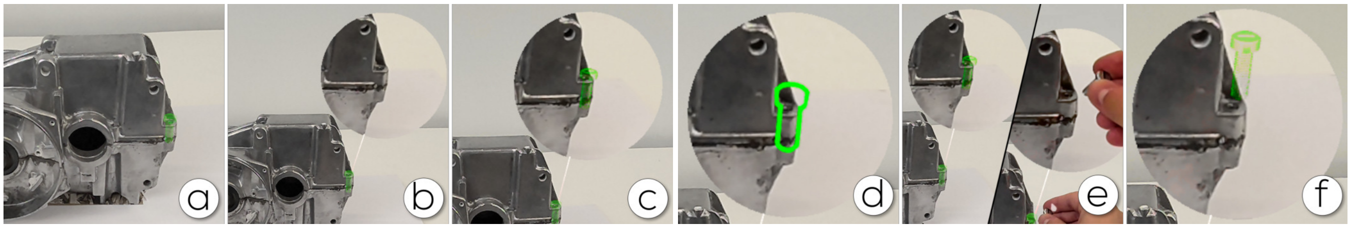


Figure 3: Overview of conditions in the first formative study. The study explored visualization styles for magnified instruction augmentations of a screw position on an engine block, within the AR lens. Conditions included: (a) lens *disabled*, (b) lens *enabled* (no augmentation), (c) semi-transparent mesh, (d) outline, (e) adaptive transparency, and (f) animation.

as the real part, allowing participants to approach the workspace as needed. This allows users to view both the in-situ augmentation and the magnification at the same time, similar to previous work on the placement of video instructions in AR [48]. Alternatively, the magnified view can be placed directly in front of the real object, effectively mimicking a physical magnification lens [24].

We implemented the magnification lens for the *Meta Quest 3*, a video-see-through (VST) headset, and the *MagicLeap 2*, an optical-see-through (OST) headset, using Unity3D v2022.3.60f1. To access the pass-through camera feed, *Meta Horizon OS* must be at least v74. We simplify the authoring of instructions for our evaluations with a JSON format to represent tasks. Each JSON snippet encodes the task definition, step order, and part metadata, including the visualization style and magnification parameters.

4 Formative Studies

We conducted two formative studies to iteratively inform the design of the AR magnification lens for assembly tasks involving small parts. We focused on identifying effective visualization strategies for the augmented magnification view and understanding how display technology influences the usefulness of the magnification, informing the design of the final system and its evaluation.

We recruited participants via flyers, online posts, and word-of-mouth. All studies were approved according to the guidelines of the ethics review board of *Graz University of Technology*.

4.1 Visualization style

In the first formative study, participants (N=6, ages 24–44, mean (M)=32.7, standard deviation (SD)=6.8) completed guided assembly tasks using in-situ instructions displayed on the *Meta Quest 3*, with and without a magnification lens. This study qualitatively explored how the different visualization styles (subsection 3.2) affect user preference during assembly tasks involving small objects. Participants inserted a series of screws into an engine block. We evaluated six visualization conditions for the magnification lens, including variations in rendering styles and transparency adaptations (Figure 3). After each condition, participants provided qualitative feedback in semi-structured interviews.

User feedback In general, users commented positively about following the magnified instructions. One user noted that the visualizations helped since "you have to be very precise to hit the right hole", while another used the lens to "get a detailed view of [a] more hidden position or trickier position". One participant particularly appreciated that the lens view is a live video magnification that changes with one's head pose rather than a static image, stating "I changed my head position to adjust the lens view, so I can see the zoom view clearly. It's much better to see it [in] the lens view".

The magnification view without augmented instructions (Figure 3a) was by far the least preferred option. While standard in-situ overlays were reportedly sufficient to locate the general target area, they seemed to lack the visual clarity needed to verify correct placement and component contact confidently. The magnification lens was consistently described as helpful, particularly for inspecting fine details and confirming correctness after an action was performed. Users struggled to follow the progress of the task using only the in-situ visualization, without the magnification lens. One participant noted that when the "screw is overlaid, [they could] not make out if there is a gap between the head of the screw and the machine". Another user having identified the same issue noted the benefit of the adaptive transparency as a solution in that "with the adaptive transparency, I can see this problem going away".

Participants strongly preferred magnified views, with adaptive transparency (Figure 3e) ranked highest, as it reduced occlusion of the target area during hand manipulations, while also maintaining the visibility of the instructional cues.

Limitations of the VST headset Observations and user feedback indicated that participants tended to naturally alternate their attention between the magnified view and the in-situ augmentation, using the lens as a complementary aid rather than a continuous primary view. Furthermore, we observed that the limited VST resolution and related image distortions reduced the visibility of small parts. According to one participant, "the resolution of the headset makes it a bit tough to actually see the hole", while another said they could "see the lens visualization helping with really small holes that [they] would not be able to make out with the [...] video see-through". These results indicate that the VST resolution of the *Meta Quest 3* aggravated the issue of interacting with small parts in AR, while the magnification lens provides a solution to improve visibility of smaller, low-resolution parts. This finding prompted a follow-up study comparing VST and OST headsets to assess robustness across display technologies. Participants also suggested that the lens would be more valuable for complex assemblies.

4.2 HMD comparison

In the second formative study, we investigated whether display technology influences the effectiveness of the magnification lens. Following feedback from the first formative study, we created a more challenging scenario. Participants (N=8, ages 23-56, M=31.6, SD=10.6) performed a more demanding wiring task that required inserting small jumper wires into closely spaced connectors (Figure 4), as closely spaced identical connector pins require high awareness of geometric alignment. The participants alternatively used a *Meta Quest 3* and a *MagicLeap 2* headset. We chose the *MagicLeap 2* because its OST display allows users to perceive real objects directly at full retinal resolution. The study followed a within-subject design with four tasks for each of the four conditions, $\{\text{VST, OST}\} \times \{\text{magnification, no magnification}\}$. For all tasks, we used in-lens visualization with adaptive transparency, which was the clear favorite in the first formative study. Participants again provided subjective ratings after each condition and shared qualitative feedback during interviews.

User feedback When asked about their preference, participants consistently preferred the conditions with "the zoom option",

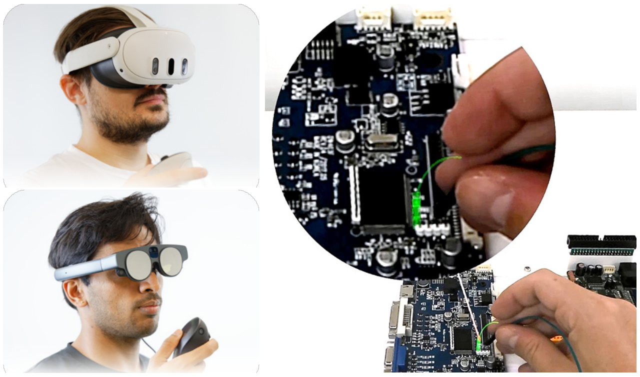


Figure 4: The small-scale object used in the second formative study (right), comparing different display technologies (left). Participants connected jumper wires between predefined pins on control boards and a small breadboard.

with one noting that "it's cooler, and a bit clearer". Most users preferred the *MagicLeap 2*, as it enabled better perception of fine details due to the unmediated optical view. In contrast, several criticized the *Meta Quest 3*'s video passthrough, remarking that "it is very hard to see a fine view" using the VST headset. As in the first formative study, one participant noted that the magnification lens compensated for these limitations, stating "now I have the window, which is nice, because it compensates the [video quality]". Participants also praised the *MagicLeap 2*'s camera, describing the magnification lens as "much sharper", while another said that the VST version was "a bit blurred". The narrower field of view of the OST headset was not reported as problematic. Overall, the OST headset received more positive feedback for both the real view and the magnification lens. In terms of display technology, five out of eight users preferred the OST headset over the VST headset.

Participants reported combining in-situ visualization with the magnification lens during task execution, switching their focus between the two as needed. Many reported using the magnification lens to distinguish details in the mounting position. Some reported using magnification to verify the correctness of completed actions, as one user stated, "I used it mostly to be sure that where [I was] putting it was correct", describing the lens and in-situ augmentation as complementary, as "one would confirm the other". Similarly, another participant said they used the lens to check for correctness, "because the details were clearer in the magnifying [lens]".

Users praised the effectiveness of the magnification lens for the more complex wiring task. The increased visual clarity provided was perceived as helpful in identifying small components and mounting points. One participant commented that "especially for more detailed tasks [...] where there are multiple small options where [they] could put the thing, it's easier to see the differences between the tiny details". Participants enjoyed the magnification, even if they did not use it at all times. One user explained, "I would probably enable it even if I didn't use it the entire way" and "it's more of a nice [option] to have and especially when it comes to such detailed, small, specific things, it's a bit easier".

4.3 Findings

Insights from the formative studies directly informed the design of the final magnification lens and the validation study.

Magnification benefits for unmediated view Across tasks using a VST headset, participants reported difficulty identifying small components due to the limitations of the video-mediated view. At the same time, participants emphasized the benefits of an OST display and consistently expressed a preference for the combination of an OST headset and the magnification lens, indicating that magnification can provide additional value even when natural vision is available. Based on these observations, we selected the *MagicLeap 2* for the final experiment to isolate the effects of magnification without being confounded by video passthrough quality.

Small-scale complexity Compared to earlier tasks with clearly defined mounting locations, the small-scale wiring task introduced multiple small target points in close proximity, increasing ambiguity and visual complexity. This task better reflects real-world precision assembly scenarios and was therefore retained for the final evaluation.

Adaptive semi-transparency Feedback of the participants further revealed the importance of keeping the augmented instructions into the view of the magnified lens, and one user stated that when "try to put the wire, the virtual object disappears". In response, we refined the adaptive transparency behavior so that, instead of becoming fully transparent as the user's hand approaches the target, the overlay now fades to 14% opacity to ensure visibility of the instruction and avoid full occlusion of the target area.

Focus shifts Users appeared to alternate their attention between the magnified view and target area depending on the task phase, using the lens primarily for inspection and verification rather than continuously. To capture these focus shifts, we tracked eye-tracking data to analyze gaze behavior and lens usage over time.

Flexible placement of magnification Finally, some users expressed a desire for control over the spatial placement of the magnification lens. This feedback motivated the exploration of different lens placement strategies, including positioning the lens adjacent to the target area and directly in front of it, analogous to magnification practices in medical and dental contexts.

5 User Study

While the formative studies provided insights into individual design parameters, they did not assess the combined effects of these design choices on task performance, usability, and user experience. We therefore conducted a within-subject experiment comparing three instructional conditions: performing the task without magnification support (Figure 5a), using a live magnification lens (Figure 5b), and using a magnification lens showing a head-tracked "virtual view" (Figure 5c). The virtual view resembles a virtual lens visualization [12, 13] of magnified content that has been prepared beforehand. The study was approved in accordance with the guidelines of the ethics review board of *Graz University of Technology*.

5.1 Study design

We defined the *Magnification* variable with three conditions:

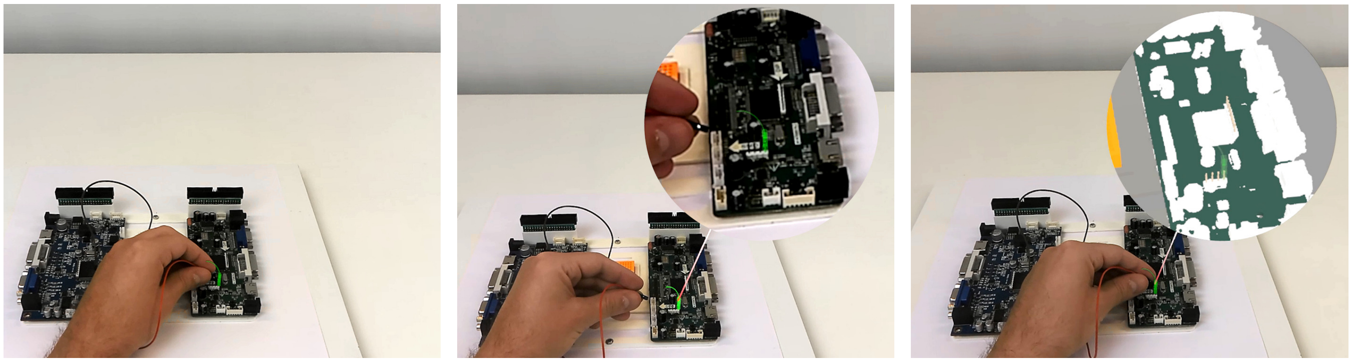
DL: magnification lens *disabled*, in-situ AR instructions only

EL: magnification lens *enabled*, showing the *live* headset camera view, including in-situ AR instructions

EV: magnification lens *enabled*, showing the *virtual* rendering, including in-situ AR instructions

The EL condition represents the final AR magnification design derived from the formative studies. It shows a live camera view with instructions rendered inside the lens and uses adaptive transparency to reduce occlusion as the user's hand approaches the target. The EV condition shows a magnified digital twin of the object, updated with head motion and using adaptive transparency, but does not display the user's hands or the manipulated physical object.

We used the task from the second formative study. Participants were instructed to complete four wire insertion tasks between control boards and a breadboard. Wire locations were selected such that previously placed wires did not provide placement cues.



(a) Condition DL (b) Condition EL (c) Condition EV

Figure 5: The three conditions of the final user study were (a) disabled lens (*DL*), (b) enabled magnification lens with live view (*EL*), and (c) enabled magnification lens with head-tracked virtual view (*EV*). Screenshots were captured from the video feed of the *MagicLeap 2* and adjusted for visual accuracy.

5.2 Hypotheses

Following insights gained from our formative studies, as well as prior literature on task assistance, we formulated the following hypotheses to guide the evaluation in our user study. These hypotheses address not only user preference but also behavioral measures, task performance, and subjective workload.

H1 Participants will prefer conditions with an enabled magnification lens (EL, EV) over no magnification (DL).

H2 Due to the zoomed view of the target, participants will move their view closer to the object without a lens (DL) than with either magnification lens (EL, EV).

H3 Task performance will improve, with fewer errors when either magnification lens (EL, EV) is used compared to DL.

H4 We expected better usability and lower task load when either magnification lens (EL, EV) is used compared to DL.

We measured objective performance as task completion time (TCT) for each assembly step and pin placement error rates. To assess behavioral effects, we recorded head movement and eye-tracking data using the headset's position and the built-in eye tracker of the *MagicLeap 2*, tracking fixations on the magnification lens, the task object, and the surrounding environment. As subjective data we measured task load (NASA-TLX) [22], usability (SUS) [8], and user experience (UEQ) [29] using standard questionnaires. After completing all conditions, we conducted a semi-structured interview.

5.3 Procedure

We recruited 24 participants who had not taken part in the formative studies through flyers, online posts, and word-of-mouth. Participants were between 21 and 55 years old (M=31.04, SD=8.68), with eight identifying as female and 16 identifying as male. 20 participants had normal or corrected-to-normal vision using contact lenses, and four participants wore glasses. Participants reported slight-to-moderate prior AR experience on average (M=2.46, SD=1.28 on a 5-point scale). All participants except one were right-handed, and none reported color vision deficiencies.

After filling out an informed consent, participants performed a familiarization task by placing two wire pins. For the study, the participants performed four wiring tasks per condition. We verified the registration of the virtual and real object before each condition using a removable ArUco [18] marker tracked by the headset. After each condition, participants completed the NASA-TLX, SUS, and UEQ questionnaires before proceeding to the next condition. Conditions were counterbalanced using a Latin Square. After all conditions, we conducted a semi-structured interview, and participants completed a demographic questionnaire. We collected 3 (conditions) $\times$ 4 (wiring tasks) = 12 data points per participant, for a total of 12$\times$24 (participants) = 288 data points over all participants.

5.4 Exploratory study

Following the experiment, we conducted an exploratory study motivated by users' feedback from the formative studies to gather qualitative insights into user preferences for magnification lens placement. Only the live magnification lens (EL) was used. In the exploratory study, participants manually positioned the lens using the controller before each task, as the system did not automatically update the lens placement. We asked participants to use certain placement options for each step, which allowed us to collect feedback on the manipulation and perception of the lens:

Top: Magnification lens placed above the real object

Side: Lens placed next to the real object

Front: Lens placed overlaid in front of the real object

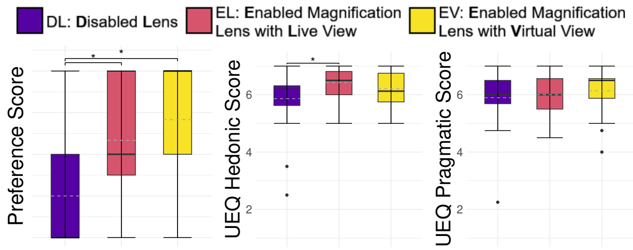
Free: Free lens placement by the user

Participants placed four wires using four placement options: Top (above the object), Side, Front, and Free (user-defined placement). Placement order and wire locations were counterbalanced. After completing all conditions, they ranked the placements and participated in a semi-structured interview on placement preference.

6 Results

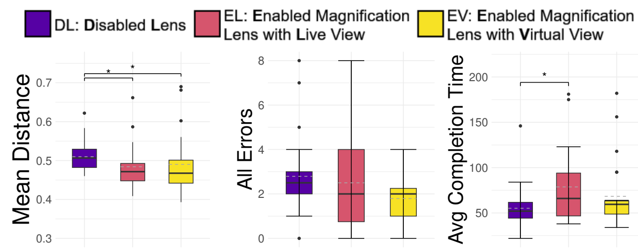
We calculated mean TCT, error rate, head distance, gaze fixations, and questionnaire scores per participant and condition. As objective measures (TCT, error rate, mean distance) violated assumptions of normality, tested with Shapiro-Wilk tests [41], and homogeneity of variances, tested with Levene's test [31], we used nonparametric Friedman tests [16] with post-hoc pairwise comparisons using Nemenyi tests [36]. For qualitative data (preferences and questionnaire data), we used the same nonparametric analysis. Analysis was done in R, and we set the significance level at $\alpha = 0.05$ for all tests.

Friedman tests revealed statistically significant differences for TCT ($\chi^2(2)$=12.25, p=.002), mean distance ($\chi^2(2)$=11.565, p=.003), preference ($\chi^2(2)$=11.55, p=.003), hedonic UEQ score ($\chi^2(2)$=10.03, p=.01), and frustration ($\chi^2(2)$=9.029, p=.01).



(a) User preference ↑ (b) Hedonic quality ↑ (c) Pragmatic quality ↑

Figure 6: Subjective preference results for each condition include (a) the average preference of the users, (b) the hedonic user experience results, and (c) the pragmatic user experience results.



(a) Head-object distance (b) All user errors ↓ (c) Completion time ↓

Figure 7: Objective performance results for each condition include (a) average user errors and (b) average completion time. (c) The mean distance between the users' heads and the real object.

Pairwise post-hoc Nemenyi tests revealed statistically significant differences for TCT between DL and EL (p=0.002), for mean distance between DL and EL (p=0.033) and DL and EV (p=0.003), for preference between DL and EL (p=0.045) and DL and EV (p=0.003), for hedonic UEQ score between DL and EL (p=0.025), for frustration between DL and EV (p=0.038).

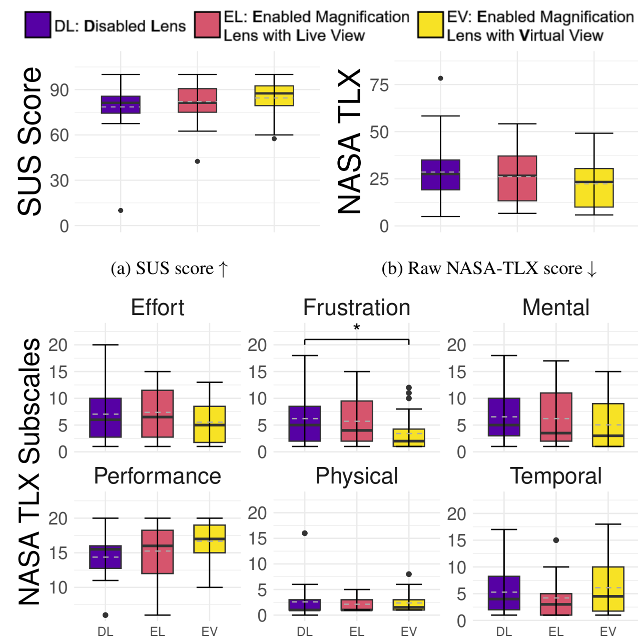
6.1 Preference

Participants significantly preferred both lens conditions (EL, EV) over no magnification (DL), **supporting H1** (Figure 6a). The live AR lens (EL) received the highest hedonic UEQ ratings (Figure 6b), indicating that the participants found EL more enjoyable or engaging. This is supported by qualitative feedback from the participants; one participant stated that the live view in the lens is "better than fake renderings", another described the virtual lens as feeling "like a LEGO instruction". One user commented on the live view lens that "at every point [they] knew how to use the lens to precisely [pinpoint the right spot]". The clarity of the virtual lens was also praised, with users stating "[they] used it less often than [live view lens], but it was very helpful". While pragmatic UEQ scores were higher for both lens conditions, differences were not significant.

Qualitative feedback emphasized the value of hand visibility in the live lens. One user noted about the EL condition that "you can see more precisely where your hands are". Another participant stated that "[the instruction] was clearer [in EV], but it was helpful to see my hands [in EL]". Participants described the virtual lens as clearer for counting and orientation, but the live lens as more natural and easier to relate to the physical task. One user said that the rendering was "actually harder to compare to the real thing, since you have to think around". Three participants, medical doctors who consented to disclosing their profession, selected the live magnification lens as their favorite. One noted that it would be a "good alternative to optical lenses in surgery", highlighting its potential relevance for applications that demand close-up visualizations.

6.2 Distance to object

Interestingly, **contrary to our original hypothesis H2**, participants moved significantly closer to the object when using magnification lenses (EL, EV) compared to DL (Figure 7a). Head-tracking data and user feedback indicate that users approached the object intentionally to increase the effective zoom of the lens. In contrast, when using no lens (DL), participants tended to maintain a greater distance from the object. Moving the head closer to the lens is akin to increasing the zoom level seen through the lens, allowing users to make out more details. Inspection of the data over time revealed that, in both lens conditions (EL, EV), users moved their heads closer to the object early in the task. Note that, while the difference in head distance was significant, the motion represents only small head movements (2–2.6 cm) to zoom the lens contents.



(a) SUS score ↑ (b) Raw NASA-TLX score ↓

(c) NASA-TLX subscales

Figure 8: Subjective results of our study: (a) The combined SUS scores, (b) the combined NASA-TLX, and (c) the TLX subscales.

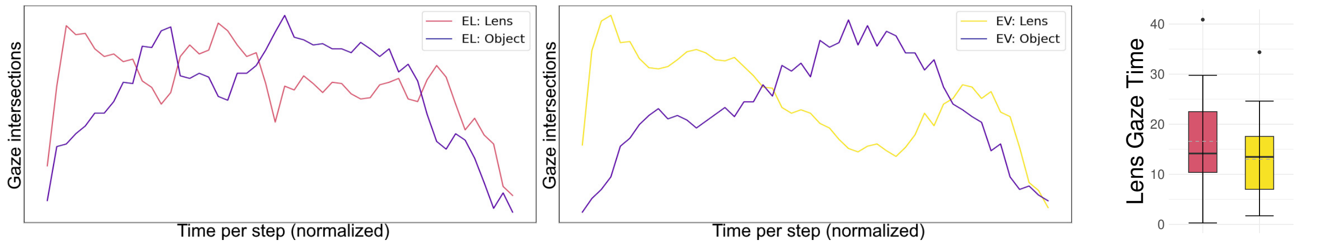
6.3 Task performance

Analysis of performance data revealed only limited differences between conditions. A statistically significant effect was found for TCT: Participants were slower with the live lens (EL) than with no lens (DL) (Figure 7c). The results showed that the participants made fewer errors in both lens conditions (EL, EV); however, this effect was not significant (Figure 7b), leading us to **reject H3**.

Qualitative feedback suggests that the increased completion time reflects verification behavior, with multiple users deliberately using the magnified view to confirm correct placement. For example, one participant noted that they "could confirm whether or not [they were] correct" using the live magnification lens, while another remarked that, in the DL condition, the lack of magnification "made it hard to hit the correct pin".

6.4 Task load and usability

Overall task load scores were lower for magnification conditions, but differences were not significant (Figure 8b). Analysis of in-



(a) Count of gaze intersections with task object and magnification lens averaged per instruction step in condition EL.

(b) Count of gaze intersections with task object and magnification lens averaged per instruction step in condition EV.

(c) Gaze time directed at the lens in EL and EV conditions.

Figure 9: Gaze patterns across conditions EL and EV. (a) Plot of average gaze intersections with different target types over the course of a step in condition EL and (b) in condition EV. (c) Time users spent looking at the magnification lens with the live view and the virtual view.

dividual subscales following the method of Hart [21] revealed a significant reduction in frustration for the virtual lens (Figure 8c) compared to no magnification (DL). Usability scores (Figure 8a) were higher for both magnification conditions, corresponding to an improvement in usability grade from C (DL) to B (EL, EV) according to Bangor et al. [3], although differences were not statistically significant. Consequently, **we reject H4**, as task load and usability were not significantly higher for lens conditions.

While participants could complete the task using only the in-situ visualization without magnification (DL), the small components increased frustration due to limited visibility. Participants clearly perceived less frustration when details were easily visible in the virtual lens (EV) magnification. As one user pointed out, "it was easy to count the pins on the 3D model" using the virtual lens. Participant feedback was also generally positive for the live AR lens (EL), with one user stating it was "clearly easier to see" using the live lens. Since all motions are amplified in the magnification lens, small movements are also exaggerated. One participant commented that "[the magnified view] jiggles around with [their] movements".

6.5 Gaze patterns

We analyzed fixation data for the magnification lenses used in the EL and EV conditions. Of the 24 participants, four who wore glasses were excluded from gaze analysis due to interference with the eye tracker. Figure 9 shows the distribution of fixations in the task for each lens. Visual inspection suggests that users fixated more frequently on the live magnification lens than the virtual lens (Figure 9c); however, statistical analysis tests did not reveal a significant difference between the two eye-fixation conditions.

Gaze data reveals distinct usage patterns between lenses. Analyzing the virtual lens (EV) gaze patterns in Figure 9b for a task, users tended to fixate on the lens at the beginning of the step to understand the instruction from the magnified view, then shifted focus to the object to perform the action. One user said that they "used the virtual lens to count [the pins] and the in-place [augmentation] to find the area on the breadboard". In contrast, gaze patterns for the live lens (EL) in Figure 9a show that users distributed their attention more evenly between the lens and the object. One participant stated that they "switched [my] view between the real object and the [live] lens". This suggests that the live lens integrates more naturally into the workflow of participants, encouraging them to move back and forth between magnified and direct views, as it supported both placement and verification. As one participant noted, the live magnification "gives an easier-to-read feedback" than DL.

6.6 Exploratory study results

The exploratory study was completed by 23 participants, as one participant stopped after the main experiment due to eye strain.

Participants overwhelmingly valued manual lens placement; 16 participants chose *Free* placement as their favorite. The condition received the best average ranking (M = 1.35). Among the fixed placement options, *Top* was preferred by nine participants, followed by *Side*, which was preferred by six participants. One user explained that "above is better than to the side, since it's more in the focus area, so I see both the object and the lens".

Participants consistently reported that *Front* placement was their least favorite, and many participants found placing the lens overlaid in front of the target object "confusing" or "obstructive". Since the magnified view is rendered from the camera stream in 2D, one participant again remarked that it was "difficult for depth perception". Another frequent comment was that placing the lens in front of the target object impaired the view of the users' hands during interaction. The participants preferred to see their fingers in their natural view, in addition to a spatially separate magnification lens. As one user stated, "[I] would rather see my own fingers". This observation questions related work that places magnification widgets directly over the task area [13] and suggests that the magnified view should instead be positioned slightly offset from the object. In Free placement, users mainly positioned the lens slightly above and diagonally offset from the target, closely matching the experimental configuration (Figure 5b).

7 Discussion

Building on the results of our studies, we reflect on user behavior and results collected across conditions. We derive a set of design guidelines that inform the development of future AR instructional systems targeting small-object scenarios. Finally, we outline future work opportunities that extend beyond the present study, identifying possible directions for magnification strategies, broadening use cases, and addressing limitations of current AR hardware.

7.1 Design guidelines for small-scale augmentation

We collect insights on user preferences, task performance, gaze behavior, and interaction strategies, and we extract guidelines that provide practical recommendations for effectively integrating magnification lenses and in-situ augmentations.

Magnification as a feature Most participants appreciated having the option to view instructions through a magnification lens, even when they preferred in-situ instructions without magnification. This suggests that optional, more detailed visualizations can enhance the user experience, particularly for tasks involving small components.

Live view improves user experience While both virtual and live magnification were well received, live camera-based magnification achieved higher hedonic experience scores and appeared to integrate more naturally into users' workflows when understanding and verification are required. Contrary to our initial hypothesis, the lens did not reduce users' need to approach the object, but instead encouraged closer inspection and interaction.

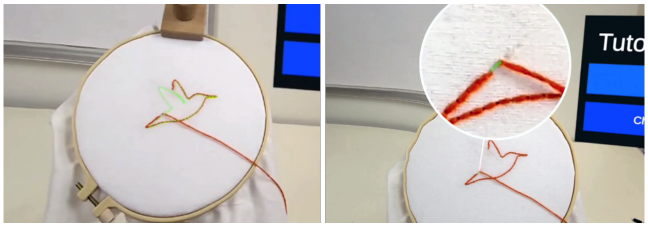


Figure 10: Applications of the proposed lens may also focus on more dynamic, complex instructions. (left) An AR embroidery pattern showing augmented instructions overlaid on the fabric as the sewing outline. (right) The AR magnification lens focuses on a single stitch.

Spatial separation to avoid interference Our findings indicate that users prefer the magnified lens to be spatially separated from the real-world target. The exploratory study shows a preference for positioning the lens slightly above the augmented region rather than directly in front of it, as in related work [13, 24]. This likely preserves consistent scale and depth perception, avoiding the sudden enlargement of the user's hands within the lens.

Adaptive transparency to reduce occlusion Users commented that in-situ AR instructions can occlude small parts, an issue also noted by Henderson and Feiner [23] and Wiethüchter et al. [47]. We rendered in-situ visualizations semi-transparently and faded the magnified view to near transparency as the user's hands approached the target. Participants responded positively, reporting reduced occlusion without lacking instructional cues.

Ensure precise tracking and visual stability For guidance to be effective, especially when magnifying small parts, the augmented instructions must remain precisely aligned with the real object at all times. High-resolution visuals, stable tracking, and accurate registration are critically important, as even small offsets or jitter become highly noticeable in magnified instructions.

Manual control of lens Users should also be allowed to manually adjust its position. Most participants preferred the ability to freely move the magnification lens, which offered additional flexibility as placement could be adapted to a given situation. Participants also addressed the possible improvement of having a feature to toggle the lens on or off.

7.2 Limitations and future work

While this work demonstrates the benefits of magnification lenses for AR instructions in small-scale tasks, several promising directions remain for future exploration. Our work is the first to investigate live AR magnification in an interactive, bi-manual instructional setting. Future work could extend this to more dynamic actions such as stitching, sewing, or soldering, where guidance also includes the use of tools. We implemented an embroidery scenario for the proposed magnification (Figure 10) and plan to explore whether live magnification better supports more complex tasks compared to the localization and placement tasks explored in this paper.

Magnification strategies should be validated across a wider range of tasks and environments. While we mitigated novelty effects through familiarization, users' enthusiasm for the lens and its manipulation may still be partially influenced by novelty, as suggested by the high hedonic quality results. Providing customization options such as adjustable zoom levels, lens shapes, or dynamic lens behaviors could further improve usability across tasks and user preferences. Evaluating different magnification levels may also reveal how the user experience is affected by reduced workspace context and potentially amplified perceived image motion.

In terms of lens position, placements above the target area were generally preferred. In the exploratory study, the participants frequently used manual lens adjustments, indicating a need for task- and context-dependent placement. Further analysis could inform automated or context-sensitive lens positioning strategies [20, 46].

Some participants reported that in-situ augmentations occasionally appeared blurry when inspecting targets at close distances, reflecting a known limitation of current HMDs. Similar effects have been reported on the *MagicLeap* and *MagicLeap 2*, stemming from the vergence–accommodation conflict [37]. As users inspect small components, their eyes accommodate to the object depth, while augmentations remain fixed at the display focal plane, causing either the real object or the virtual content to appear out of focus. This issue is particularly problematic in small-scale tasks. While varifocal displays address this limitation [1, 14], digital magnification lenses can partially mitigate it by rendering magnified views at a comfortable focal distance while preserving detail.

While our implementation relies on the built-in headset camera, not tackling sub-milimiter scale, future HMDs may overcome current hardware limitations through improvements in camera resolution and optical quality, increasing the fidelity of the live view lens by improving detail visibility. Future research could also examine the limits of tracking stability, registration accuracy, and jitter tolerance in small-scale AR tasks. In our studies, we ensured that the registration between real and virtual elements was precise by careful calibration of the setup for each participant. In the future, automatic image stabilization techniques to reduce the amount of jitter in the magnified view may further improve the user experience.

8 Conclusion

We designed and implemented a live AR magnification approach for instructional systems targeting small-scale tasks, enabled by a live view of the AR HMD camera. Through a series of formative studies, a controlled user study, and an exploratory follow-up, we demonstrated that magnification enhances the usability of AR instructions for precise work on small components. Our findings show that users consistently value magnification, even when provided as an optional feature, and tend to engage more frequently with live, camera-based magnification over purely virtual alternatives. Our findings further suggest that live magnification can be integrated more naturally into users' workflows and encourage closer inspection rather than disengagement from the physical task.

- Users value magnification, even as an optional feature.
- A live magnified view improves the user experience.
- Lens placements should not obstruct the users' view of their own hands or the object.
- Adaptive transparency can reduce occlusion without removing instructional cues.
- High stability and accurate registration are necessary for achieving good usability.
- Users value positional control of the visualization.

These insights lead to practical design guidelines, contributing to a broader understanding of how AR systems can support precision work in small-scale work areas. We see magnification lenses as a promising step toward more effective and flexible AR guidance, with applications in domains such as industrial assembly, medical procedures, and other contexts involving precision at a small scale.

Acknowledgments

This work was supported by the Alexander von Humboldt Foundation funded by the German Federal Ministry of Education and Research, and by Snap, Inc.

REFERENCES

[1] K. Akşit, W. Lopes, J. Kim, P. Shirley, and D. Luebke. Near-eye varifocal augmented reality display using see-through screens. *ACM Transactions on Graphics (TOG)*, 36(6):1–13, 2017. doi: 10.1145/3130800.3130892 9

[2] M. A. Aldosari. Dental magnification loupes: an update of the evidence. *The Journal of Contemporary Dental Practice*, 22(3):310–315, 2021. doi: 10.5005/jp-journals-10024-3057 2

[3] A. Bangor, P. Kortum, and J. Miller. An Empirical Evaluation of the System Usability Scale. *International Journal of Human–Computer Interaction*, 24(6):574–594, 2008. doi: 10.1080/10447310802205776 8

[4] E. A. Bier, M. C. Stone, K. Pier, W. Buxton, and T. D. DeRose. Toolglass and magic lenses: the see-through interface. In *Proc. Conference on Computer Graphics and Interactive Techniques (Siggraph)*, pp. 73–80, 1993. doi: 10.1145/166117.166126 2

[5] J. Blattgerste, P. Renner, B. Strenge, and T. Pfeiffer. In-Situ Instructions Exceed Side-by-Side Instructions in Augmented Reality Assisted Assembly. In *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*, pp. 133–140, 2018. doi: 10.1145/3197768.3197778 2

[6] J. Blattgerste, B. Strenge, P. Renner, T. Pfeiffer, and K. Essig. Comparing conventional and augmented reality instructions for manual assembly tasks. In *Proceedings of the 10th International Conference on Pervasive Technologies Related to Assistive Environments*, PETRA '17, p. 75–82. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3056540.3056547 1

[7] B. G. Branson, R. Abnos, M. L. Simmer-Beck, G. W. King, and S. F. Siddicky. Using motion capture technology to measure the effects of magnification loupes on dental operator posture: A pilot study. *Work*, 59(1):131–139, 2018. doi: 10.3233/WOR-172681 2

[8] J. Brooke. SUS: A quick and dirty usability scale. *Usability Evaluation in Industry*, 189(194):4–7, 1996. doi: 10.1201/9781498710411-35 6

[9] S. Büttner, M. Prilla, and C. Röcker. Augmented reality training for industrial assembly work - are projection-based ar assistive systems an appropriate tool for assembly training? In *Proc. ACM Conference on Human Factors in Computing Systems (CHI)*, CHI '20, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3313831.3376720 2

[10] C. Chen, Z. Tian, D. Li, L. Pang, T. Wang, and J. Hong. Projection-based augmented reality system for assembly guidance and monitoring. *Assembly Automation*, 41(1):10–23, 11 2020. doi: 10.1108/AA-02-2019-0028 2

[11] Z. Choudhary, J. Ugarte, G. Bruder, and G. Welch. Real-time magnification in augmented reality. pp. 1–2. Association for Computing Machinery, New York, NY, USA, 2021. doi: 10.1145/3485279.3488286 2

[12] K. Čopič Pucihar and P. Coulton. Enhanced virtual transparency in handheld AR: digital magnifying glass. In *Proceedings of the 15th International Conference on Human-computer Interaction with Mobile Devices and Services*, pp. 452–455, 2013. doi: 10.1145/2493190.2494654 1, 2, 5

[13] M. Dastan, M. Fiorentino, E. D. Walter, C. Diegritz, A. E. Uva, U. Eck, and N. Navab. Co-designing dynamic mixed reality drill positioning widgets: A collaborative approach with dentists in a realistic setup. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 2024. doi: 10.1109/TVCG.2024.3456149 1, 2, 5, 8, 9

[14] C. Ebner, S. Mori, P. Mohr, Y. Peng, D. Schmalstieg, G. Wetzstein, and D. Kalkofen. Video see-through mixed reality with focus cues. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 28(5):2256–2266, 2022. doi: 10.1109/TVCG.2022.3150504 9

[15] S. Feiner, B. MacIntyre, and D. Seligmann. Knowledge-based augmented reality. *Communications of the ACM*, 36(7):53–62, 1993. doi: 10.1145/159544.159587 2

[16] M. Friedman. The use of ranks to avoid the assumption of normality implicit in the analysis of variance. *Journal of the American Statistical Association*, 32(200):675–701, 1937. doi: 10.1080/01621459.1937.10503522 6

[17] T. B. Garland and C. A. Sanchez. Rotational perspective and learning procedural tasks from dynamic media. *Computers & Education*, 69:31–37, 2013. doi: 10.1016/j.compedu.2013.06.014 3

[18] S. Garrido-Jurado, R. Muñoz-Salinas, F. Madrid-Cuevas, and M. Marín-Jiménez. Automatic generation and detection of highly reliable fiducial markers under occlusion. *Pattern Recognition*, 47:2280–2292, 06 2014. doi: 10.1016/j.patcog.2014.01.005 6

[19] M. Gattullo, A. Evangelista, A. E. Uva, M. Fiorentino, and J. L. Gabbard. What, how, and why are visual assets used in industrial augmented reality? a systematic review and classification in maintenance, assembly, and training (from 1997 to 2019). *IEEE Transactions on Visualization and Computer Graphics*, 28(2):1443–1456, 2022. doi: 10.1109/TVCG.2020.3014614 2

[20] R. Grasset, T. Langlotz, D. Kalkofen, M. Tatzgern, and D. Schmalstieg. Image-driven view management for augmented reality browsers. In *2012 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 177–186, 2012. doi: 10.1109/ISMAR.2012.6402555 9

[21] S. G. Hart. Nasa-Task Load Index (NASA-TLX); 20 Years Later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 50(9):904–908, 2006. doi: 10.1177/154193120605000909 8

[22] S. G. Hart and L. E. Staveland. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Human Mental Workload*, vol. 52 of *Advances in Psychology*, pp. 139–183. North-Holland, 1988. doi: 10.1016/S0166-4115(08)62386-9 6

[23] S. Henderson and S. Feiner. Exploring the benefits of augmented reality documentation for maintenance and repair. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 17(10):1355–1368, 2010. doi: 10.1109/TVCG.2010.245 1, 2, 9

[24] C. Ilo, W. Zheng, and D. A. Bowman. Virtual loupes: An augmented reality aid for microsurgery. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 617–618. IEEE, 2021. doi: 10.1109/VRW52623.2021.00191 1, 2, 4, 9

[25] F. Jasche, S. Hoffmann, T. Ludwig, and V. Wulf. Comparison of different types of augmented reality visualizations for instructions. In *Proc. ACM Conference on Human Factors in Computing Systems (CHI)*, pp. 1–13, 2021. doi: 10.1145/3411764.3445724 2

[26] D. Kalkofen, E. Mendez, and D. Schmalstieg. Interactive focus and context visualization for augmented reality. In *2007 6th IEEE and ACM International Symposium on Mixed and Augmented Reality*, pp. 191–201. IEEE, 2007. doi: 10.1109/ISMAR.2007.4538846 2

[27] B. M. Khuong, K. Kiyokawa, A. Miller, J. J. La Viola, T. Mashita, and H. Takemura. The effectiveness of an AR-based context-aware assembly support system in object assembly. In *Proc. IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 57–62. IEEE, 2014. doi: 10.1109/VR.2014.6802051 1, 2

[28] F. Kiss, P. W. Woźniak, V. Biener, P. Knierim, and A. Schmidt. Vum: Understanding requirements for a virtual ubiquitous microscope. In *Proceedings of the 19th International Conference on Mobile and Ubiquitous Multimedia*, MUM '20, p. 259–266. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3428361.3428386 2

[29] B. Laugwitz, T. Held, and M. Schrepp. Construction and evaluation of a user experience questionnaire. In A. Holzinger, ed., *HCI and Usability for Education and Work*, pp. 63–76. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008. doi: 10.1007/978-3-540-89350-9_6 6

[30] E. Laviola, M. Gattullo, A. Evangelista, M. Fiorentino, and A. E. Uva. In-situ or side-by-side? a user study on augmented reality maintenance instructions in blind areas. *Computers in Industry*, 144:103795, 2023. 1, 2

[31] H. Levene. Robust tests for equality of variances. *Contributions to Probability and Statistics*, pp. 278–292, 1960. 6

[32] J. Looser, M. Billinghurst, and A. Cockburn. Through the looking glass: the use of lenses as an interface tool for augmented reality interfaces. In *Proceedings of the 2nd International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia*, pp. 204–211, 2004. doi: 10.1145/988834.988870 2

[33] J. Looser, R. Grasset, and M. Billinghurst. A 3d flexible and tangible magic lens in augmented reality. In *2007 6th IEEE and ACM Interna-*

tional Symposium on Mixed and Augmented Reality, pp. 51–54, 2007. doi: 10.1109/ISMAR.2007.4538825 2

[34] A. Martin-Gonzalez, S.-M. Heining, and N. Navab. Head-mounted virtual loupe with sight-based activation for surgical applications. In *Proc. International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 207–208. IEEE, 2009. doi: 10.1109/ISMAR.2009.5336459 1, 2

[35] P. Mohr, B. Kerbl, M. Donoser, D. Schmalstieg, and D. Kalkofen. Retargeting technical documentation to augmented reality. In *Proc. ACM Conference on Human Factors in Computing Systems (CHI)*, CHI '15, p. 3337–3346. Association for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2702123.2702490 2

[36] P. B. Nemenyi. *Distribution-free multiple comparisons.* Princeton University, 1963. 6

[37] L. Qian, T. Song, M. Unberath, and P. Kazanzides. Ar-loupe: Magnified augmented reality by combining an optical see-through head-mounted display and a loupe. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 28(7):2550–2562, 2020. doi: 10.1109/TVCG.2020.3037284 2, 9

[38] R. Radkowski, J. Herrema, and J. Oliver. Augmented reality-based manual assembly support with visual features for different degrees of difficulty. *International Journal of Human-Computer Interaction*, 31(5):337–349, 2015. doi: 10.1080/10447318.2014.994194 1

[39] R. Sato, T. Yamaguchi, T. Shibahara, K. Honda, M. Choi, and B. Shizuki. Gazescope: Gaze target selection with a magnifier in vr environments. In *Proceedings of the Augmented Humans International Conference 2025*, pp. 65–78, 2025. doi: 10.1145/3745900.3746095 3

[40] R. Schubert, G. Bruder, and G. Welch. Intuitive user interfaces for real-time magnification in augmented reality. In *Proc. ACM Symposium on Virtual Reality Software and Technology (VRST)*, VRST '23. Association for Computing Machinery, New York, NY, USA, 2023. doi: 10.1145/3611659.3615694 2, 3

[41] S. S. Shapiro and M. B. Wilk. An analysis of variance test for normality (complete samples). *Biometrika*, 52(3-4):591–611, 1965. 6

[42] A. Stanescu, P. Mohr, D. Schmalstieg, and D. Kalkofen. Model-free authoring by demonstration of assembly instructions in augmented reality. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 28(11):3821–3831, 2022. doi: 10.1109/TVCG.2022.3203104 1

[43] L. Stearns, V. DeSouza, J. Yin, L. Findlater, and J. E. Froehlich. Augmented reality magnification for low vision users with the microsoft hololens and a finger-worn camera. In *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility*, pp. 361–362, 2017. doi: 10.1145/3132525.3134812 1, 2

[44] L. Stearns, L. Findlater, and J. E. Froehlich. Design of an augmented reality magnification aid for low vision users. In *Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility*, pp. 28–39, 2018. doi: 10.1145/3234695.3236361 2

[45] A. Tang, C. Owen, F. Biocca, and W. Mou. Comparative effectiveness of augmented reality in object assembly. In *Proc. ACM Conference on Human Factors in Computing Systems (CHI)*, pp. 73–80, 2003. doi: 10.1145/642611.642626 2

[46] M. Tatzgern, D. Kalkofen, R. Grasset, and D. Schmalstieg. Hedgehog labeling: View management techniques for external labels in 3d space. In *Proc. IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 27–32. IEEE, 2014. doi: 10.1109/VR.2014.6802046 9

[47] R. Wiethüchter, S. Kalloori, and D. Lindlbauer. Side-by-side might win: Occlusion negatively affects the performance of augmented reality task instructions. In *2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 913–914. IEEE, 2024. doi: 10.1109/VRW62533.2024.00253 9

[48] M. Yamaguchi, S. Mori, P. Mohr, M. Tatzgern, A. Stanescu, H. Saito, and D. Kalkofen. Video-annotated augmented reality assembly tutorials. In *Proc. ACM Symposium on User Interface Software and Technology (UIST)*, pp. 1010–1022, 2020. doi: 10.1145/3379337.3415819 2, 4

[49] Z. Yang, J. Shi, W. Jiang, Y. Sui, Y. Wu, S. Ma, C. Kang, and H. Li. Influences of augmented reality assistance on performance and cognitive loads in different stages of assembly task. *Frontiers in Psychology*, Volume 10 - 2019, 2019. doi: 10.3389/fpsyg.2019.01703 2

[50] F. Zhu, L. Sidenmark, M. Sousa, and T. Grossman. Pinchlens: Applying spatial magnification and adaptive control-display gain for precise selection in virtual reality. In *Proc. International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 1221–1230. Institute of Electrical and Electronics Engineers Inc., 2023. doi: 10.1109/ISMAR59233.2023.00139 3