Arrow, Bézier Curve, or Halos? – Comparing 3D Out-of-View Object Visualization Techniques for Handheld Augmented Reality

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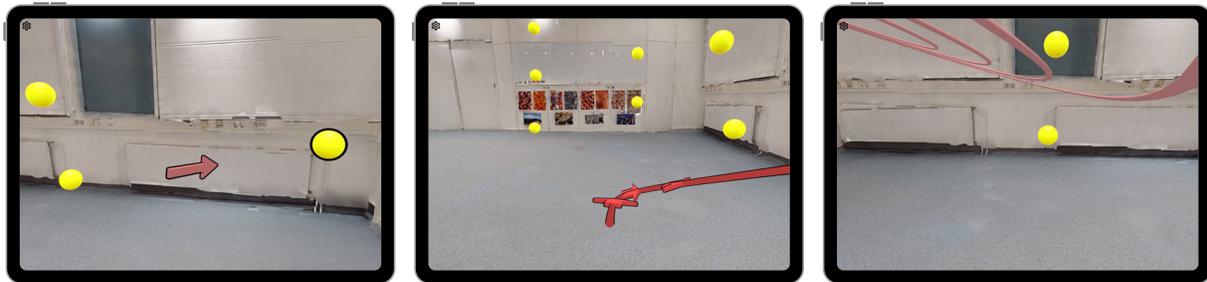[2]Aarhus University, Denmark

Figure 1: We compared different 3D out-of-view object visualizations for handheld AR displays: A 3D arrow pointing towards the POI *(left)*, a Bézier curve leading to the POI *(middle)*, and pulsing 3D halos starting at the POI's position *(right)*.

ABSTRACT

Handheld augmented reality (AR) applications allow users to interact with their virtually augmented environment on the screen of their tablet or smartphone by simply pointing its camera at nearby objects or "points of interest" (POIs). However, this often requires users to carefully scan their surroundings in search of POIs that are out of view. Proposed 2D guides for out-of-view POIs can, unfortunately, be ambiguous due to the projection of a 3D position to 2D screen space. We address this by using 3D visualizations that directly encode the POI's 3D direction and distance. Based on related work, we implemented three such visualization techniques: (1) *3D Arrow*, (2) *3D Bézier Curve*, and (3) *3D Halos*. We confirmed the applicability of these three techniques in a case study and then compared them in a user study, evaluating performance, workload, and user experience. Participants performed best using *3D Arrow*, while surprisingly, *3D Halos* led to poor results. We discuss the design implications of these results that can inform future 3D out-of-view object visualization techniques.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / Augmented Reality; Human-centered computing—Visualization—Visualization techniques

1 INTRODUCTION

Augmented reality (AR) applications allow to seamlessly integrate virtual 3D objects into the users' physical environment [1] and have found application in various application domains like education, architecture, and marketing [3]. Further, there is an increased research interest in using this technology for enhancing co-located and remote collaboration [3, 4, 42]. With recent advances in software and hardware, handheld AR displays (i.e., smartphones and tablets) have become the most prevalent AR devices to date [17, 39].

Tasks in handheld AR often require users to interact with points of interest (POIs) in close vicinity [31], such as searching for AR content in an interactive exhibition or calling a collaborator's attention to a specific object. However, due to the device cameras' limited field of view (FOV), handheld AR displays can be compared to movable peepholes that only show a small portion of the AR content. Consequently, the POIs are often off-screen, and users need to carefully scan their surroundings to find them [31]. Various out-of-view object visualizations have been introduced (e. g., [21, 30, 44]) to facilitate this process. However, proposed 2D visualizations anchored in the device's 2D screen space are often insufficient to convey both – the POI's 3D position and distance. As a solution, a wide range of 3D visualizations has been proposed in prior research, demonstrating their benefits for desktop-based virtual environments (e. g., [8, 10]) and head-mounted AR and virtual reality (VR) displays (e. g., [35, 50]). However, only few studies have explored 3D out-of-view visualizations for handheld AR displays and those focused exclusively on 3D arrows [27, 38]. Hence, we are not aware of any work that compares different 3D out-of-view object visualizations for handheld AR displays, which are the most prevalent AR devices to date [17, 39].

To address this research gap, we implemented three 3D out-of-view object visualizations for handheld AR that are based on related work and encode both the POI's 3D position and distance: (1) A *3D Arrow* pointing towards the POI, (2) a *3D Bézier Curve* leading to the POI, and (3) pulsing *3D Halos* originating from the POI's position. We evaluated our visualizations in a two-step approach, aiming to answer the following research questions:

RQ1 Can the proposed 3D out-of-view object visualizations be applied in a realistic handheld AR scenario?

RQ2 How do the 3D out-of-view object visualizations differ in terms of (a) performance, (b) subjectively perceived workload, and (c) user experience?

Based on findings from a case study, we contribute a more profound understanding of the *Applicability* (RQ1) of the implemented

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cues in an interactive exhibition (museum) scenario and derive design considerations from the collected feedback. Further, results from a user study offer insights into how these cues compare in terms of *Performance* (RQ2, a), perceived *Workload* (RQ2, b), and *User Experience* (RQ2, c) in the lab. Additionally, we provide implications for future research and the design of 3D out-of-view object visualizations for handheld AR.

2 RELATED WORK

We first cover traditional off-screen visualizations for 2D information landscapes as they inspired our 3D visualization techniques. Afterward, we focus on out-of-view object visualization techniques for AR and VR devices. Here, we follow the classification by Kristensen et al. [28] and categorize them into 2D and 3D visualizations. Additionally, we discuss works that compare both approaches.

2.1 Off-screen Visualizations

Visualization techniques for displaying large 2D information spaces on 2D displays are typically categorized into overview+detail views, focus+context views, and contextual views [11, 24, 31]. While overview+detail techniques use a second view (e.g., a miniature map [13]) to give an overview of the complete information landscape, focus+context techniques and contextual views visualize the information relative to the users' view. While focus+context techniques distort the information landscape (e. g., fisheye-views [37]), contextual views use proxies (e. g., arrows) pointing at off-screen POIs. We focus on the latter, as they are distortion-free [20] and do not induce additional mental effort for integrating distinct overview+detail views [11]. Commonly used and studied shapes for proxies in contextual views are arrows [9], arcs [2, 9], and wedges [24].

Simple arrow-based visualizations only encode the direction to off-screen POIs but not their distance. To additionally convey the distance information, works added textual annotations [2, 9] or used differently sized or stretched arrows [9]. As an alternative to arrow-based visualizations, Baudisch and Rosenholtz [2] introduced Halo as an off-screen visualization that directly encodes the distance information in the visualization itself. It relies on circles having the POIs in their center and being just large enough that a part of them (i. e., an arc) is visible in the user's view of the information landscape. The visualization makes use of amodal completion [24, 41], which is the ability of the human visual system to complete parts of an object that are occluded. When completed to the full circles, the arcs lead to the POIs, and their curvature conveys the POIs' distance.

In an experimental comparison, Baudisch and Rosenholtz [2] showed that Halo can outperform arrow-based visualizations with textual distance annotations. Burigat et al. [9] compared Halo with two arrow-based techniques that scale or stretch the arrows to convey the POIs' distance. The results of their study showed that with the stretched and scaled arrow-based visualizations participants were not only faster but also more accurate according to the off-screen POIs' distance. However, with Halo, participants could better "*identify the current location of off-screen objects.*" Complementary, the results of a study by Henze et al. [26] suggest that visualizations using scaled and stretched arrows only outperform Halo when having a large number of off-screen POIs and that users perform better with Halo for a small number of off-screen POIs. The reason for that could be that when a large number of off-screen POIs needs to be visualized, Halo results in overlapping, cluttered arcs that are hard to interpret [24]. As a solution to this problem, Gonçalves et al. [18, 19] introduced HaloDot, which aggregates the arcs of off-screen POIs that are close to each other into a single arc.

By introducing Wedge, Gustafson et al. [24] proposed a different solution to reduce Halo's clutter. Instead of arcs, Wedge uses isosceles triangles as proxies with the base visible on-screen and the legs converging at the off-screen POIs. These triangles are then rotated around their tip to avoid overlapping. In an experimental

comparison, Gustafson et al. [24] showed that Wedge has higher accuracy than Halo and a similar distance error. However, participants were better with Halo in distinguishing between close and distant objects due to the large visual difference between the halos. They did not find differences regarding task completion time. Ens et al. [14] compared Wedge with an overview+detail technique and showed in a study that with Wedge, participants were generally more accurate and, at close ranges, also faster.

2.2 2D Out-of-View Object Visualizations

Works we discuss in this section directly adopt the above-described off-screen visualization techniques to AR environments. Since proxies are still anchored in the device's 2D screen space, "*information conveyance [. . .] is limited to a left-or-right and above-or-below discrimination*" [7] and additional visual [15, 30, 31, 44] or auditory [5] features need to be introduced to provide information about the objects 3D distance or allow for front-or-rear discrimination [27].

For example, in SidebARs [44] textual annotations were added to the arrows in their handheld AR visualization to convey the distance to the out-of-view objects. However, since the arrows are positioned at and point towards the left and the right screen border, the technique does not support above-or-below and front-or-rear discrimination. Perea et al. [30, 31] adopted Halo for handheld AR with Halo3D and investigated the color, transparency, and thickness of the arc as additional visual features to convey the objects' distance. Initial user feedback suggests that transparency is the preferred visual feature since it minimizes visual intrusion on the screen. However, front-or-rear discrimination is not supported. Fan et al. [15] used an arrow-based technique for video-see-through head-mounted AR in which the size of the arrow indicates how much the head has to be turned. But again, no information for front-or-rear and above-or-below discrimination is conveyed. Gruenefeld et al. [21] adopted Arrow, Halo, and Wedge to head-mounted video-see-through AR and showed that Halo and Wedge performed better than the arrow-based visualization. However, their techniques can only visualize out-of-view objects located in a 90-degree area in front of the user.

2.3 3D Out-of-View Object Visualizations

Proposed 2D visualizations are insufficient to convey the information about the location of objects in 3D environments [7]. Therefore, a number of techniques have been introduced that utilize 3D proxies for guiding users to out-of-view objects to convey the objects' 3D position. Commonly studied shapes for these proxies are 3D variants of the originally used arrows [40], arcs [20, 35], and wedges [20].

For example, for head-mounted AR and VR displays, Gruenefeld et al. [20] project Halo and Wedge on an imaginary sphere around the user and showed that both techniques can perform similarly well. However, due to the fixed positing of the proxies, the authors report that it was not possible to look at them from different angles, which reduced 3D perception.

Other works for head-mounted AR displays also use curves and funnels [16, 34] to guide users to out-of-view objects. For example, Feiner et al. [16] used a rubber-band leading line in a printer repair scenario, and Bocca et al. [6] used a series of linked rectangles to construct an attention funnel drawing users' attention to objects in the scene that outperformed simple highlighting and verbal descriptions. Schwerdtfeger and Klinker [40] compared different variants of such attention funnels with a technique that combines rubber-band lines and 3D arrows, showing that both visualization techniques can perform similarly. Renner and Pfeiffer [34, 35] introduced SWAVE, which uses moving waves projected to a sphere around the user that propagate to the target. The sphere's radius is constantly updated to match and encode the distance to the target. Simulating AR in VR, Renner et al. [34] compared simple highlighting with SWAVE and a curve-based approach to visualize occluded objects, with the curve-based approach outperforming simple highlighting.

2.4 2D vs. 3D Out-of-View Object Visualizations

Comparisons of 2D and 3D out-of-view object visualizations have demonstrated benefits of using 3D over 2D proxies for desktop-based virtual environments [8, 10], heads-up AR displays [45, 46], handheld AR displays [27, 38], as well as for head-mounted AR and VR displays [35, 36, 50].

Chittaro and Burigat [8, 10] compared 3D arrows, 2D arrows, and an overview+detail visualization based on a radar metaphor for finding targets in a desktop-based VE and showed, that their 3D visualizations can be at least as effective as the 2D visualizations or even outperform them for some tasks. Consistently, Tönnis et al. [45, 46] showed that for heads-up AR displays, 3D arrows outperform a bird's eye schematic map for alerting car drivers of hazards.

Trapp et al. [47, 48] investigated different adaptions of the original Halo technique for identifying buildings in a virtual 3D city rendered on a mobile phone. The authors introduced 3D Halo Circle, 3D Halo Sphere, and 3D Halo Billboard as 3D visualizations directly anchored in the scene. 3D Halo Circle draws two horizontal circles around the buildings, 3D Halo Sphere uses a semi-transparent sphere with the buildings in the center, and 3D Halo Billboard uses vertical circles always facing the user. Additionally, they propose 3D Halo Projection, which projects a circle on an imaginary plane hovering in front of the user. However, they only conducted a preliminary user study comparing 3D Halo Billboard with 3D Halo Sphere and showed that both techniques have different advantages in terms of different factors related to accuracy.

For handheld AR, Schinke et al. [38] compared 3D arrows with a 2D top-down mini-map as overview+detail visualization. To convey the distance to the out-of-view objects with the 3D arrow-based visualization, the authors scaled the arrows in length. Results of their study show that participants were faster with 3D arrow-based visualization and also could interpret the position of the out-of-view objects more precisely than with the mini-map. Similarly, Jo et al. [27] compared 3D arrow clusters with a focus+context and an overview+detail visualization based on a radar metaphor. Using the 3D arrow cluster, participants performed similarly as with the focus+context technique, which outperformed the overview+detail visualization. However, for a higher number of items (i.e., 50), participants were less accurate with the 3D arrow cluster than with the focus+context technique. The authors mainly attribute this to arrows occluding each other, which led to confusion.

One solution to the occlusion problem could be using semi-transparent proxies, as Yu et al. [50] proposed for head-mounted VR displays. Their 3DWedge technique is based on semi-transparent pyramids that are centered around a reference in front of the user. Each pyramid's base points towards an out-of-view target and its height is scaled based on the target's distance. A comparison with 3D arrow clusters, a 3D and 2D overview+detail visualization based on a radar metaphor showed that 3DWedge and the 3D arrow cluster outperformed the overview+detail visualizations. As an improved version of 3DWedge, they finally proposed 3DWedge+, which combines 3DWedge with 3D arrows and led to increased accuracy of the technique for high-density configurations. Simulating head-mounted AR in VR, Renner and Pfeifer [35] compared their SWAVE technique with a 2D arrow, a 3D Attention Funnel, and a simple image showing the object that the user needs to find. Here, the SWAVE technique and the 2D arrow outperformed the other techniques. In a second study [36], they compared the 2D arrow with simple highlighting and a 3D line-based visualization, with the latter outperforming the other techniques.

2.5 Conclusions from Related Work

Our analysis of related work revealed that proposed 2D visualizations are often insufficient to convey both – the target's 3D position and its distance. As a solution, numerous works introduced out-of-view object visualizations that rely on 3D proxies and also demon-

strated the benefits of these visualizations. However, only Schinke et al. [38] and Jo et al. [27] considered 3D out-of-view visualizations for handheld AR displays. However, they focused solely on 3D arrow-based visualizations and showed that they can outperform more traditional 2D visualizations. Since they only studied arrows as 3D proxies, there is, to the best of our knowledge, no experimental comparison of different 3D out-of-view object visualizations in handheld AR displays, being the most prevalent AR devices to date [17, 39]. We address this research gap by studying different 3D out-of-view object visualizations using commonly studied proxies i.e., arrows, arcs, and lines.

3 DESIGN OF THE VISUALIZATION TECHNIQUES

Based on related work, we designed three 3D out-of-view object visualizations: (1) A *3D Arrow* pointing towards the object, (2) a *3D Bézier Curve* leading to the object, and (3) pulsing *3D Halos* starting at the object's position. Since we rely on 3D proxies, our visualizations convey the target's complete 3D position (i.e., left-or-right, front-or-rear, and above-or-below). To additionally also encode the target's distance, we color-coded our visualizations based on a warm-cold analogy [18, 43]. Therefore, we first define a max distance based on the furthest target. We map a linear color gradient along this distance that progressively transitions from red for close objects, through white for mid-distance objects, to blue for distant objects. In each frame, the color of the visualization is updated according to the ratio of target distance to max distance.

We chose our techniques as they utilize commonly studied proxies and also cover different aspects of the classification by Kristensen et al. [28]: *3D Halos* and *3D Bézier Curve* are leading visualizations attached in the world view. On the contrary, *3D Arrow* is a directing visualization that is attached to the user's view. Based on our scenarios of being guided to an interactive exhibit in a museum or having a collaborator calling one's attention to a specific object, we decided to focus on single out-of-view objects and to use non-persistent cues, i.e., cues that disappear as soon as the target is found. In the following, we describe our out-of-view object visualizations in greater detail and explain how related work informed their design. For the implementation we used Unity 2021.1.2f1 [49] together with Vuforia Engine 9.8.5 [32] and Vuforia Area Targets [33].

3.1 3D Arrow

Similar to previous works (e.g., [27, 38, 40]), this technique presents a head-fixed *3D Arrow* in the users' view that always points towards the out-of-view object (cf. Fig. 1 (left)). We positioned our arrow 0.5 meters in front of the mobile device and 5 centimeters below the screen's center. With that, users look at the arrow from slightly above, which helps in conveying its 3D shape.

These particular design parameters resulted from findings during a case study (cf. Sect. 4) where the arrow was initially vertically centered on the screen, leading to difficulties in interpreting the pointing direction as the arrow was seen directly from the front. The downward offset leads to a better perspective of the 3D arrow, thereby better supporting orientation disambiguation. Further, the arrow received a black outline to improve visibility.

3.2 3D Bézier Curve

Similar to previous work [16, 34] we use a 3D path as second visualization that guides the user to the out-of-view object (cf. Fig. 1, middle). To construct the path, we use a quadratic Bézier curve defined by a start point, an end point, and one control point. As start point we use a point 0.25 meters below and 0.7 meters in front of the tablet position in tracked space, and set the position of the out-of-view object as end point. The control point, positioned on an imaginary horizontal line 0.5 meters away from the tablet in viewing direction, defines the bending of the curve. On this horizontal line, the point can shift towards the left or to the right side of the screen,

Figure 2: As part of our iterative design approach we evaluated our 3D out-of-view object visualizations through an exploratory case study using an ongoing handheld AR-based exhibition in a museum.

making the curve bend smoothly towards the target while avoiding overlaps when the target is directly behind the user. To improve visibility and further clarify the direction of the curve, small 3D arrows are visualized at predefined intervals along the path. Again the case study (Sect. 4) informed the design of this cue, such as supporting interpretation of the 3D direction of the curved line with 3D arrows and defining the between-arrow intervals to prevent overlaps. Further, a black outline was added to the line to improve visibility.

3.3 3D Halos

Previous handheld AR implementations of Halo used 2D halos projected to the 2D screen space and with that did not convey the information needed for front-or-rear discrimination [30, 31]. To address this issue, our implementation relies on pulsing *3D Halos* with the geometrical form of a torus. Similar to Renner and Peiffer [34, 35], we utilize the metaphor of a stone thrown into the water: The halos or tori constantly originate from the position of the out-of-view object and, as their size increases, they move towards the user's device like ripples on the water's surface (cf. Fig. 1 (right)). The halos move towards a point 0.5 meters in front of the tablet (in viewing direction) and slightly above or below the screen center, depending on whether the object is located above or below the tablet position. With that the user is always looking at the visualization from slightly above or slightly below, which helps to better convey its 3D shape. After they become visible on the device screen, each halo continues to grow for two seconds before disappearing. Similar to the original Halo [2] technique, we make use of amodal completion. This means, when completed to the full torus, the halos lead to the position of the out-of-view object, additionally supported by the direction from which the animated halos propagate into the field of view. Finally, the curvature of the halos conveys the distance to the target.

Findings from the case study (Sect. 4) helped refine the initial size, growth rate, and number of presented halos. This ensured instant and clear visibility of 3D halos, with a smoothly growing animation.

4 EXPLORING APPLICABILITY IN AN EXHIBITION SCENARIO

In designing our 3D out-of-view object visualizations, we pursued an iterative approach. A particular objective was to ensure the applicability of our techniques in a realistic scenario and their usability. Hence, we conducted an exploratory case study in a museum with an ongoing handheld AR-based exhibition. At the entrance, visitors were equipped with a tablet that allowed them to explore different AR-based interactive exhibits distributed throughout the museum. We had the opportunity to directly integrate our 3D out-of-view object visualizations into the AR app of the exhibition and to recruit actual visitors as participants.

4.1 Participants

At the exhibition, we recruited 6 volunteers (4 female, 2 male) between 19 and 25 years ($M = 22.5$, $SD = 2.51$) as study participants. Overall, participants rated their prior AR experience as medium ($M = 2.5$, $SD = 0.55$), VR experience as low ($M = 1.5$, $SD = 1.17$), and experience with 3D video games as moderately

high ($M = 3$, $SD = 1.7$), using a scale from 1 (never used) to 5 (regular use). We expected at least some AR experience, as participants were recruited at the end of their visit to the museum and had already been using the handheld AR system throughout the exhibit. Importantly, half of the participants stated that they had seen or used out-of-view object visualizations before.

4.2 Task

We instructed participants to locate five AR-based interactive exhibits in a predefined order using each of our out-of-view object visualizations (within-groups design) in counterbalanced order. All participants started the task at the same position and with the same orientation. They then followed the out-of-view object visualization to locate the first interactive exhibit in the room. As soon as the exhibit was within the camera's field of view it was visually highlighted for two seconds, and then the system proceeded to direct the participant to the next interactive exhibit. The process was repeated until participants found the last exhibit.

4.3 Procedure

Participants filled out a short demographic questionnaire first. Afterward, participants completed the target-finding: in each of the conditions, they had to locate the same 5 exhibits but in different order. Sessions ended with a semi-structured interview in which we asked participants to rank the visualizations by their general preference. Additionally, we asked them to list advantages and disadvantages of each technique, whether and where these would have been helpful in the exhibition, and whether they could imagine other use cases for the presented visualizations. Sessions took approximately 10 minutes and participants were not compensated for their time. We followed all ethical and sanitary guidelines provided by our institution and the museum at the time of the study.

4.4 Apparatus

Participants used an 11" Apple iPad Pro (2021, 466 grams) with a screen resolution of 2388×1668 pixels (264 pixels per inch) to perform the study task. For generating the AR experience, we used the rear-facing camera (12 MP resolution) together with the tablet's integrated LiDAR scanner. The exhibition room (cf. Fig. 2) measured approximately 7.97×4.85 meters, with one interactive exhibit (i. e., out-of-view objects) being located at each wall and another one in the center of the room.

4.5 Case Study Findings

We clustered users' feedback using affinity diagramming to extract common themes. First, we report the results related to the *Applicability (RQ1)* of our techniques for our exhibition scenario. Further, participants' visualization preferences and general feedback informed the design of each visualization, as described in Sect. 3.

Overall, participants agreed with the applicability of all three visualizations for the handheld AR-based exhibition. They particularly valued that the visualizations helped to find the exhibits ($n = 4$) and ensured that they would not overlook them ($n = 2$). Closely related to that, participants expressed the wish for such visualization techniques to be used for providing a guided tour through the exhibition ($n = 4$). Additionally, one participant said that the visualizations might be helpful for interacting with the exhibits themselves, as some of these involved wall-sized AR content that exceeded provided field-of-view and therefore required looking around.

Participants were then asked to rank the visualizations by their subjective preference, whereby *3D Arrow* ($Mdn = 1$) was liked better than both *3D Halos* ($Mdn = 2.5$) and *3D Bézier Curve* ($Mdn = 2.5$), with four participants indicating *3D Arrow* as their first preference.

Participants' reflections about the advantages and disadvantages of each visualization reveal important factors to consider in the design of such cues: Participants ($n = 5$) liked the simplicity of the *3D*

Arrow, which they described as *"simple"* (#5), *"clear"* (#3), and *"intuitive"* (#2). They further liked that *3D Arrow* was always visible and constantly in front of the user. Two participants explicitly commented on the performance of *3D Arrow* being positive, while one had difficulties interpreting the direction when the interaction point was next to or behind them. The *3D Bézier Curve* was described as effective by one participant, and another valued the guidance of the curve, as it instantly told them where they needed to turn to. However, half of the participants ($n = 3$) did not like the design of the curve, as it was not aesthetic or took up to much space on the screen and two participants found the number of arrows shown along the curve too high, as these were overlapping. One participant commented that a better viewing angle was necessary to be able to interpret the 3D direction of the curve. Finally, one participant liked that *3D Halos* are integrated into the space, and another commented that they knew quickly when they had to turn around when using *3D Halos*. However, participants ($n = 3$) had problems locating the halos in the first place.

5 COMPARING 3D ARROW, BÉZIER CURVE AND HALOS

We evaluated the three implemented visualizations in a controlled lab study, aiming to explore how they compare in terms of (a) *Performance*, (b) *Workload*, and (c) *User Experience* (RQ2). In each of the three conditions, (1) *3D Arrow*, (2) *3D Bézier Curve*, (3) *3D Halos*, participants were instructed to perform a *search task* and an *estimation task*, as described below. The conditions were presented in counterbalanced order.

5.1 Participants

We recruited 24 participants (17 male, 7 female), with age ranging from 19 to 33 years ($M = 23.96$, $SD = 3.41$), from our two local universities. Twenty-two identified as students, one as PhD student, and one as employee, from a wide range of different fields (e. g., computer science, biology, psychology, economy, chemistry, or law). All participants had either normal or corrected-to-normal eyesight. On a scale from 1 to 5 ("none" to "very much"), participants on average reported low AR experience ($M = 1.75$, $SD = 0.94$), moderate to low VR experience ($M = 2.04$, $SD = 1.12$), and moderate to high experience with 3D video games ($M = 3.83$, $SD = 1.4$).

5.2 Tasks

In line with previous research, we compare our three visualizations in a search task (e. g., [20,27,38]) and an estimation task (e. g., [20,23]).

Search Task For the search task, we distributed 20 virtual yellow spheres with a diameter of 20 centimeters in mid-air throughout our physical lab (cf. Fig. 1) and then tasked participants to sequentially located these spheres in a predefined order, with the help of our three out-of-view visualizations. Before the task started, participants were positioned at a predefined location in the center of our lab. We instructed participants not to leave this position and to just turn on the spot following the directions of the visualization technique to locate the correct sphere. This was highlighted by a black outline and could be selected by tapping on the display, whereupon the next target was highlighted. The spheres were distributed evenly throughout the room, at various distances, altitudes, and directions, thereby requiring repeated changes of orientation. This procedure was repeated until they located all 20 spheres. Participants were instructed to complete this task as *quickly* as possible. The search task was followed by an estimation task.

Estimation Task In this task, participants were asked to estimate and mark the position indicated by the respective 3D out-of-view object visualizations (no target spheres were shown). Again, participants assumed a stationary position in the middle of our lab, and were asked not to move away from this and only turn on the spot. To start the task, participants needed to point the device in

a predefined starting direction. Then the visualization appeared, indicating a specific target position in the room and conveying the target distance through color-coding. The visualization disappeared as soon as participants started to turn in the indicated direction to initiate the estimation task. A virtual 3D sphere casting a shadow on the floor (depth cue) was attached to the tablet 0.5 meters in front of the user and could thereby be moved around. It could also be moved closer or further away by swiping up or down on the touchscreen. We tasked participants to place this sphere at the position indicated by the visualization, by tapping on a button once they were satisfied with its location. This procedure was repeated for 10 different positions distributed at various distances across the room and covering different rotation angles from the participant's starting orientation. Participants were asked to solve this task as *accurately* as possible.

5.3 Dependent Variables and Operationalization

Performance (RQ2, a) was evaluated based on task completion time and efficiency for the *search task*, and accuracy for the *estimation task*. *Task completion time* is defined as the overall search time participants needed to locate all spheres. To measure *efficiency*, we computed the overall tablet movement angles in degrees (cf. [35]). For *accuracy*, we measured the euclidean distance between participants' estimated position and the actual target position indicated by the visualization. To evaluate subjectively perceived *workload* (RQ2, b), we used the raw, unweighted NASA Task Load Index (NASA TLX) [25]. Further, we assessed *User Experience* (RQ2, c) with the User Experience Questionnaire (UEQ) [29] and additionally conducted a semi-structured interview. Here, we asked participants to rank the visualizations according to their general preference, list advantages and disadvantages of each technique, and also to think about possible use cases. We transcribed all interviews and clustered participants' answers thematically using affinity diagramming.

5.4 Procedure

Participants were welcomed and provided with introductory documents explaining the study's purpose and procedure. After offering a chance to ask questions, we asked them to sign a consent form and fill out a demographic questionnaire. In a training session, the examiner then introduced participants to the three out-of-view object visualization techniques. Then, participants started the training phase with the first visualization technique (according to counterbalanced order of conditions) guiding them to three virtual spheres distributed in the lab. As soon as they felt comfortable in using the technique, the study trial began and they were tasked to find the 20 spheres as quickly as possible. After the trial, participants filled out the NASA TLX. The examiner then explained the *estimation task* (in the same condition), and participants could again practice in a short training phase before they completed the estimation task trial. They then again filled the NASA TLX for this trial and answered the UEQ reflecting on the particular visualization technique used in both tasks. The whole procedure was then repeated for the other two conditions. Each session ended with a final semi-structured interview. Sessions took approximately one hour and participants were financially compensated for their time. We followed all ethical and hygiene guidelines provided by our institution at the time of the study.

5.5 Apparatus

Participants used the same 11" Apple iPad Pro (2021) as during the case study, again relying on its rear-facing camera and the built-in LiDAR scanner for creating the AR experience. This tablet was also used for questionnaire responses. For the study, we allotted an area of approximately 4.0×7.0 meters in our lab. Further, we attached landscape posters to the white walls to provide additional features for stable tracking.
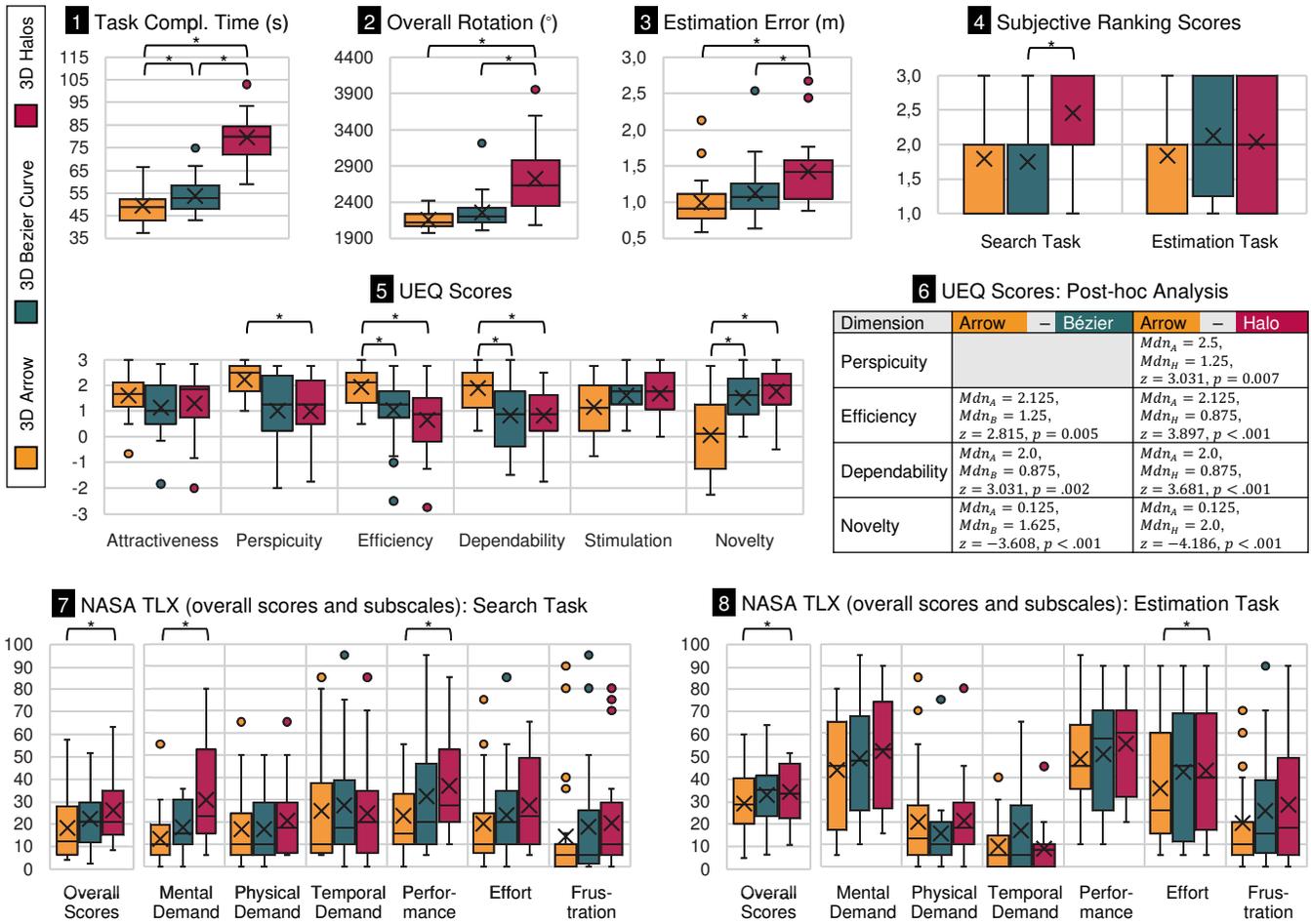
Figure 3: (1-3) Boxplots for performance related measures: (1) task completion time in seconds, (2) performed rotations in degree, and (3) estimation error in meters. (4-5) Boxplots for UX related measures: (4) subjective fractional rankings for search and estimation task, and (5) UEQ scores. (6) Detailed post-hoc analysis results for the UEQ scores with only significant results being listed. (7-8) Boxplots for workload related measures: the overall scores of the NASA TLX, and its scores broken down into subscales for the (7) search task and the (8) estimation task.

6 MAIN STUDY FINDINGS

In this section, we present the main findings of our lab study. To ensure good readability when indicating medians, means, and standard deviation, we use subscript $_A$ for *3D Arrow*, subscript $_B$ for *3D Bézier Curve*, and subscript $_H$ for *3D Halos*. For statistical significance we assume $\alpha = 0.05$, which was adjusted for number of comparisons in post-hoc tests (Bonferroni correction; $\alpha = 0.05/3 \approx .016$).

6.1 Performance

Task Completion Times The task completion times for the *search task* are visualized in Fig. 3.1. A Shapiro-Wilk test confirmed homogeneity of variances. A repeated measures ANOVA revealed significant differences between the three conditions ($F(2,46) = 230.90, p < .001$). Pairwise comparisons show that task completion times for *3D Arrow* ($M_A = 49.45, SD_A = 7.64$) were significantly lower than for *3D Bézier Curve* ($M_B = 53.73, SD_B = 7.59, p = .003$) and *3D Halos* ($M_H = 79.43, SD_H = 10.02, p < .001$). Further, participants were also significantly faster with *3D Bézier Curve* compared to *3D Halos* ($p < .001$).

Efficiency Efficiency measures based on accumulated tablet rotation angles in the *search task* are shown in Fig. 3.2. The minimal overall rotation needed to find all spheres was 1850 degrees. As homogeneity of variances was violated (Shapiro-Wilk test), we

performed a Friedman's ANOVA, which revealed significant differences between the conditions ($\chi^2(2) = 24.25, p < .001$). Post-hoc pairwise comparisons using Dunn's Test showed that participants rotated the tablet significantly less when using both *3D Arrow* ($Mdn_A = 2117.58, z = -4.76, p < .001$) and *3D Bézier Curve* ($Mdn_B = 2202.69, z = -3.46, p < .001$) compared to *3D Halos* ($Mdn_H = 263.66$). No significant difference was found between *3D Arrow* and *3D Bézier Curve*.

Accuracy The positioning accuracy measured as euclidean distance between the indicated and estimated position in the *estimation task* are visualized in Fig. 3.3. As homogeneity of variances was violated (Shapiro-Wilk test) we performed a Friedman's ANOVA. This shows significant differences between the three conditions ($\chi^2(2) = 30.08, p < .001$). Post-hoc analysis with Dunn's Test revealed that participants' estimations were significantly less accurate using *3D Halos* ($Mdn_H = 1.42$) compared to both *3D Arrow* ($Mdn_A = 0.91, z = -5.34, p < .001$) and *3D Bézier Curve* ($Mdn_B = 1.07, z = 3.75, p < .001$). Again, no significant difference was found between *3D Arrow* and *3D Bézier Curve*.

6.2 Workload

We assessed workload via the NASA TLX for both tasks separately.

For the *search task*, Friedman's ANOVA revealed significant differences between conditions for the overall scores ($\chi^2(2) = 11.389$,

$p = .003$), as illustrated in Fig. 3.7. Dunn's Test indicates significantly lower scores for *3D Arrow* ($Mdn_A = 12.5$) compared to *3D Halos* ($Mdn_H = 21.25, z = -3.32, p < .001$). Analysis of the subscales revealed statistically significant effects for *Mental Demand* ($\chi^2(2) = 14.308, p < .001$) and *Performance* ($\chi^2(2) = 10.894, p = .004$). A post-hoc Dunn's Test shows that participants rated *Mental Demand* to be significantly lower for *3D Arrow* ($Mdn_A = 10$) than *3D Halos* ($Mdn_H = 22.5, z = -3.681, p < .001$). In terms of *Performance*, *3D Arrow* ($Mdn_A = 15.00$) was also rated significantly better than *3D Halos* ($Mdn_H = 27.50, z = -3.103, p = .002$). No significant effects were found for any of the other dimensions.

Also for the *estimation task*, Friedman's ANOVA revealed significant differences between conditions in overall scores ($\chi^2(2) = 10.903, p = .004$), as shown in Fig. 3.8. Dunn's Test indicates significantly lower scores for *3D Arrow* ($Mdn_A = 28.75$) compared to *3D Halos* ($Mdn_H = 33.75, z = -2.815, p = .005$). In the subscales, significant effects were found only for *Effort* ($\chi^2(2) = 8.175, p = .017$), where pairwise comparisons reveal *3D Arrow* ($Mdn_A = 25.00, z = -2.598, p = .009$) as less demanding than *3D Halos* ($Mdn_H = 40.0$). No further significant effects were found.

6.3 User Experience

User experience was assessed through the UEQ and a final semi-structured interview, in which participants were asked to rank the visualizations by preference. Further, we asked them to list advantages and disadvantages of each technique, and also think about possible use cases for our 3D out-of-view object visualizations.

User Experience Questionnaire (UEQ)   The results of the UEQ are visualized in Fig. 3.5. Friedman's ANOVA revealed statistically significant differences for the dimensions *Perspicuity* ($\chi^2(2) = 10.63, p = .005$), *Efficiency* ($\chi^2(2) = 17.66, p < .001$), *Dependability* ($\chi^2(2) = 16.29, p < .001$), and *Novelty* ($\chi^2(2) = 21.71, p < .001$). The results of the post-hoc Dunn's Tests that showed significant differences are listed in Fig. 3.6. In terms of *Perspicuity*, participants scored *3D Arrow* significantly better than *3D Halos*. For the dimensions *Efficiency* and *Novelty*, *3D Arrow* was scored significantly better than both *3D Bézier Curve* and *3D Halos*. Only in terms of *Novelty* *3D Arrow* performed significantly worse than *3D Bézier Curve* and *3D Halos*.

Subjective Ranking   We asked participants to rank the visualizations according to their general preference in the *search task* and the *estimation task* (cf. Fig. 3.4). Rankings only differed significantly for the search task (Friedman's ANOVA: $\chi^2(2) = 7.583, p = .023$), where *3D Bézier Curve* ($Mdn_B = 2$, Dunn's Test: $z = -2.45, p = .014$) was preferred over *3D Halos* ($Mdn_H = 3$).

Concluding Interview   We asked participants to list the advantages and disadvantages of each technique. In the following, we summarize their answers clustered thematically.

Concerning positive aspects of *3D Arrow*, most participants ($n = 20$) valued the visualization for its simplicity, e. g., describing it as "*clear*", "*simple*", and "*intuitive.*" Further, participants positively commented on the technique's performance for locating out-of-view objects ($n = 8$) and estimating their position ($n = 6$). They also liked that *3D Arrow* was always visible and constantly located at the same position in front of the user. Regarding negative aspects, some participants ($n = 4$) mentioned that in some situations (e. g., with the out-of-view object behind the user), it was difficult to perceive the arrow's 3D shape on a 2D display. As further general negative sensations, they ($n = 2$) stated that *3D Arrow* only provides rough directions ($n = 6$) and is not novel ($n = 2$).

3D Bézier Curve was particularly appreciated for its guiding character ($n = 10$), e. g., "*You don't have to think much and just follow the curve*" (#18). Also, participants valued that it very clearly visualized the out-of-view object's position ($n = 12$), was always visible ($n = 4$), and well suited for the search task. Some participants

($n = 12$) mentioned that compared to *3D Arrow*, its 3D shape was better perceptible. Finally, participants ($n = 7$) expressed general positive sensations, describing the visualization e. g., as "*exciting*", "*cool*", and "*fun.*" Regarding negative aspects, they mainly criticized aesthetic aspects since, in some constellations, the arrows overlapped ($n = 7$), and the visualization was hard to interpret from specific angels ($n = 7$). Further, they perceived it as overloaded ($n = 10$), and some ($n = 4$) stated that sometimes the bending behaved unexpectedly.

Asked about *3D Halos*, participants ($n = 8$) mainly valued that the arcs' curvature additionally conveyed the distance to the target, e. g., "*the distance is better depicted, more visual and intuitive*" (#17). Regarding performance, participants ($n = 8$) also appreciated that it conveyed the target's direction very well. Further, they ($n = 3$) liked how the *3D Halos* are integrated in 3D space and described it as being intuitive ($n = 6$), e. g., "*it is intuitive because it's as if the object is sending a signal*" (#20). Finally, participants valued the visualization's novelty ($n = 3$) and expressed general positive sensations ($n = 7$), e. g., describing it as being "*fun*", "*cool*", and "*having a game character.*" However, some participants perceived *3D Halos* as distracting ($n = 5$), requiring a lot of screen space ($n = 4$), and being slow ($n = 4$). Related to that, participants ($n = 9$) faulted that the *3D Halos* took some time to become completely visible. They further stated that it was difficult to estimate the target's direction ($n = 7$) and altitude ($n = 8$).

7 DISCUSSION

In the following, we discuss our research questions with regards to the findings from our case study and user study.

7.1 Applicability of the Visualization Techniques

The preliminary case study was conducted explicitly for the purpose of exploring the applicability of the proposed 3D visualization techniques in a realistic scenario (RQ1). Our findings support that such visualizations may be helpful, effective, and desirable in an exhibition context. Participants reasoned that they could thereby be guided through the exhibition and avoid overlooking an exhibit. Further, guidance was desired when the content of an interactive exhibit did not fit entirely in the FOV. Here, visualizations for out-of-view objects could enhance the users' awareness of additional, yet unseen, AR content. Another exciting use case mentioned in the interviews was intelligent guidance: "*For avoiding contact with other visitors [during the Covid-19 pandemic] the system could tell you which interactive exhibit you should do next.*"(#5). The most preferred visualization in this context was *3D Arrow*.

The interviews with our user study participants contribute further insights on applicability based on the additional potential use cases that were mentioned. Here preference ratings were in line with the case study in that *3D Arrow* was superior to *3D Halos*. However, it appears our improvements to the *3D Bézier Curve* visualization were successful, as this was now rated similarly to *3D Arrow* and also preferred over *3D Halos*. This highlights *3D Bézier Curve* as an attractive alternative, which may be particularly beneficial in scenarios where occlusion of the target object may hinder its discovery with *3D Arrow* alone, as the continuous line may provide more effective guidance.

7.2 Differences between Arrow, Bézier Curve and Halos

Based on our lab study findings, we can reflect on the main differences between the compared techniques (RQ2).

a) Performance: The difference between techniques is perhaps most pronounced for *Performance*, where *3D Halos* are clearly less effective than both other techniques. In the *search task*, this led to task completion times that were about 1.5 times longer, as well as a greater overall amount of viewpoint rotation. This indicates that users performed more visual searches instead of being effectively

guided to the target, which may be attributed to the animation of *3D Halos* that caused them to only gradually appear on the users' screen. Further, interpretation of the direction from which these "ripples" were expanding requires time and the limited field of view arguably poses a challenge, in that at most times only small parts of the halos are visible. Similarly, in the *estimation task*, *3D Halos* led to less accurate position estimates. This again may be attributed to the limited screen space hindering the user from viewing most of the circles and thereby hindering their ability to estimate the circles' center. Further, due to the perspective distortion, these concentric circles were perceived as ellipses of varying minor axis, which may further complicate the matter. However, it should be noted that the *3D Halos* are presented relative to the object position, in contrast to *3D Arrow* and *3D Bézier Curve*, which are both screen-fixed. So, while *3D Halos* appear to be inferior in these performance measures, they may present benefits in terms of occluding screen space in scenarios where some degree of visual search is desired.

Remarkably, it appears that *3D Bézier Curve* may be an effective alternative to the traditional *3D Arrow* technique, as it differed only in terms of task completion time (approx. 1.1 times longer with *3D Bézier Curve*). This may be explained by the greater familiarity of the more traditional *3D Arrow*, or perhaps its simplicity that offers clear directional instruction. The latter notion is supported by information volunteered in interviews, which suggests that some participants felt confused by the arrows along the curve. Future work could explore alternative implementations of the *3D Bézier Curve*, e.g., with more subtle animation to indicate direction, or textures designed to better highlight the three-dimensionality of the curve.

b) Workload: Differences with respect to *Workload* were evaluated separately for the *search task* and *estimation task* based on subjective ratings (NASA TLX). For both tasks, the overall workload was perceived to be significantly higher for *3D Halos* compared to *3D Arrow*. In the search task, this appears to be mainly attributed to a significantly higher rated *Mental Demand* and a significantly lower rated *Performance* when searching for targets with 3D Halos compared to 3D Arrow. This is in line with participants' performance results in the search task (cf. Fig. 3.1+2). For the *estimation task*, the higher overall perceived workload of *3D Halos* compared to *3D Arrow* appears to be attributed mainly to *Effort* needed to achieve their level of performance. According to the measured estimation error (cf. Fig. 3.3), the level of performance was significantly lower for *3D Arrow* compared to *3D Halos*, which reflects a similar pattern.

Overall, these findings support that the interpretation and use of *3D Halos* was more challenging. Finally, the overall low ratings across all subscales for the *search task* reflect its low complexity compared to the slightly more demanding *estimation task*.

c) User Experience: The results of the UEQ further highlight the superiority of *3D Arrow* compared to *3D Halos*, as it was perceived as having higher *Perspicuity*, *Efficiency*, and *Dependability*. Further, *Novelty* was rated lower for *3D Arrow*, which we interpret as beneficial, as it indicates a higher degree of familiarity and, hence, better interpretability of this cue. These findings are not surprising, given the performance and task load scores. *3D Arrow* also scored better than *3D Bézier Curve* in *Efficiency* and *Dependability*. The first is also objectively supported by the measures of task completion time, while the second indicates that users may have perceived the behavior of *3D Bézier Curve* as less predictable. A factor that likely plays into this is the comparable *Novelty* participants attributed to the *3D Bézier Curve* visualization.

Interestingly, the preference rankings do not clearly coincide with the UEQ, performance, or task load measures, which would make us expect a clear preference for *3D Arrow*. Instead, in the *search task*, where participants were instructed to prioritize speed, we merely see a clear preference for *3D Bézier Curve* over *3D Halos*. *3D Arrow* might tentatively be ranked second, but the high variance makes this result inconclusive. In the *estimation task*, where the main aim was

accuracy and we might therefore expect a correlation with estimation error or perceived dependability, we can identify no clear preference.

The interview offers a few more insights on user experience concerning distance estimation. A notable example: 20/24 participants found the color mapping for distance helpful. However, some had difficulties distinguishing the intermediate colors, e. g., light blue or light red, suggesting that a fade directly from red to blue (without transition through white) may be more effective. In addition to the color-coding, *3D Halos* encode distance information through their curvature, which 17/24 participants reported to have used. Nevertheless, this redundant distance encoding did not lead to improved performance in the study tasks. It is, however, important to consider that it gets more difficult to accurately interpret larger distances due to bigger halos being only partially visible on the small screen.

8 LIMITATIONS AND FUTURE WORK

While our exploratory case study in the exhibition attests to the applicability of our cues in more complex scenarios, we perceive a limitation in that it involves purely subjective opinions of only 6 participants and a single selected use case. Further, our lab study was relatively simple and future work should explore the generalizability of our results to varying visual components and scenarios:

Firstly, we decided to focus on visualizing a single out-of-view object at a time, thereby sequentially guiding the user from one object to the next [20] following the narrative of the exhibition. However, other scenarios may need cues to multiple out-of-view objects simultaneously, which may require adaptation of our proposed 3D out-of-view object visualizations. For example, we could extend our implementation of *3D Arrow* to a 3D arrow cluster, as proposed by Jo et al. [27], who found it suitable for visualizing dozens of objects. Also, for *3D Bézier Curve* and *3D Halos* a strategy would need to be developed for minimizing overlap, for example, by aggregating the visualization of object clusters (cf. [18, 19]) e. g., encoded in the thickness of *3D Bézier Curve*. Secondly, instead of out-of-view objects in terms of the FOV, future work could investigate using 3D visualizations for indicating occluded objects, e. g., as previous works for head-mounted AR did in an assembly [34] and repair scenario [16]. Here, the *3D Bézier Curve*, with its guiding character, might prove useful to direct the users around occluding obstacles (cf. [34]). Further, a combination of *3D Bézier Curve* and *3D Arrow* could be promising for such scenarios. Finally, as we merely considered static objects, future work should investigate scenarios that require visualizing moving out-of-view objects (e. g., avatars in a remote scenario). This was explored by Gruenefeld et al. [22] for overview+detail and focus+context visualizations on head-mounted VR displays, not however for 3D out-of-view object visualizations.

Beyond this, the validity of our findings is limited by the sample size and should be interpreted respectively. Finally, the effect of gender [12] may represent a potential confound, as our sample was not balanced. These aspects will need to be explored by future work.

9 CONCLUSION

While out-of-view object visualizations have been abundantly explored in HCI, we present a first comparison of *3D Arrow*, *3D Bézier Curve*, and *3D Halos* for handheld AR. A small case study allows initial conclusions about the applicability of these cues in a realistic scenario. Further comparison in a lab study reconfirms the benefits of the traditional *3D Arrow*, but also reveals *3D Bézier Curve* as an effective alternative, while our design of *3D Halos* was less successful. Our results may serve to inform the design of such cues to support different scenarios and inspire future research.

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