# Design and Evaluation of Off-Screen Visualization Techniques for Mixed Reality Head-mounted Displays

Bachelor Thesis

submitted by

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# Abstract

Currently, augmented reality head-mounted displays provide only a small field of view. Therefore, objects that are out of view are not perceived by the user, which makes spatial cognition tasks harder to accomplish [1]. Off-screen visualization techniques provide a solution. Many different off-screen visualization techniques were developed and each technique has individual strengths and weaknesses. Additionally, most of the current off-screen techniques are continuously visible and occupy much space in the field of view. Therefore in this thesis, the three off-screen visualization techniques 1) *Map*, 2) *Halo*, and 3) *Combination of Map and Halo* were developed to investigate off-screen visualization techniques for augmented reality.

This thesis presents the development and evaluation of the three approaches. First, the foundations and related work are presented. Next, the study prototype, including the requirements and the design concept for the visualization techniques are shown. Thereby, *Map* includes an on-demand 3D overview map, *Halo* is based on the original Halo technique but adapted for augmented reality, and *Combination of Map and Halo* combines both individual techniques. The evaluation of the techniques was guided by the question of how the visualization techniques influence the *Performance* (RQ1), *Spatial Cognition* (RQ2), *Cognitive Load* (RQ3), and *User Experience* (RQ4). Furthermore, the conducted user study is discussed in detail in this thesis. Objectively, the user study data showed no statistically significant differences between the conditions, except for a learning effect in condition *Halo*. Additionally, *Map* was subjectively preferred. Moreover, it was shown that adding an additional technique might be beneficial to compensate for disadvantages or supplement with additional strengths. However, the current implementation of *Combination of Map and Halo* does not outperform the individual techniques.

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# 1 Introduction

Many electronic devices, like smartphones or personal computers, are used daily. Augmented reality (AR) is also becoming more prominent in this context. All devices, as different as they are, have one thing in common: their display size is limited. This can lead to information not being perceived when content is outside the display. For example, when viewing three-dimensional environments through displays, the entire environment can never be shown at once.

Objects that are not visible on displays are called *off-screen objects* or *out-of-view objects* for head-mounted displays. In the following, the term *off-screen objects* will also be used for head-mounted displays to provide better readability. Without additional hints, there is no information about the existence of the off-screen content, which can lead to impaired spatial cognition and makes tasks that require spatial knowledge harder to achieve [1].

A solution to draw attention to the off-screen content are off-screen visualization techniques. They give hints about the properties of the off-screen object, like the location, direction, or distance. Thereby, they improve the awareness of those objects and support spatial cognition [1]. There are many proposals for diverse off-screen visualization techniques with different strengths and weaknesses. While they are helpful tools that provide essential information, most existing techniques take away much space in the field of view. They are continuously visible and possibly distract the user when the technique is not needed [2]. However, the unique advantages and disadvantages differ for the individual techniques.

Research in off-screen visualization techniques is especially interesting for augmented reality head-mounted displays. They allow viewing the real environment while also adding virtual content. Additionally, the head-mounted display allows users to keep their hands unoccupied and use them to interact directly with the system or the real environment. Since augmented reality head-mounted displays provide a relatively small field of view, off-screen content gets a special meaning because the content is more likely to be outside of the displays range, e.g., the HoloLens 2 has a horizontal field of view of 43° and 29° vertically [3]. This gives off-screen visualization techniques a unique chance to enhance spatial perception when wearing augmented reality head-mounted displays.

In this thesis, three different off-screen visualization techniques were developed to investigate the strengths and weaknesses of different techniques for augmented reality head-mounted displays. The techniques include 1) *Map*: an on-demand 3D overview map, 2) *Halo*: a halo-based technique adapted for AR, and 3) *Combination of Map and Halo*: a technique that unites the individual techniques *Map* and *Halo*. The techniques *Map* and *Halo* are two very different approaches with unique strengths. For example, *Halo* is in line with the users' point of view. The halos indicate the distance and direction between the user and the object and *Halo* has an advantage when searching for close objects [4]. *Map*, on the other hand, provides an overview of the surroundings, gives information about the whole environment, and shows the objects and the users' position in relation to each other. However, halos do not give any depth information and maps provide an exo-centric view, while our vision through a head-mounted display is ego-centric. Switching between those views leads to a high cognitive load [2]. Nevertheless, both techniques were found to be helpful tools for head-mounted displays. The individual strengths and weaknesses of *Map* and *Halo* make it promising to investigate a combination of the two techniques. There is only little research in combining several techniques [5, 6]. Additionally, to the best of my knowledge, there is no research on combining an overview map with a second technique. Due to the individual strengths and weaknesses mentioned above, one assumption is that combining multiple techniques can alleviate individual drawbacks of one technique with the benefits of the other. Furthermore, providing two techniques gives freedom to the user to decide which technique they want to use and gives additional hints about the user preference.

A user study with 18 participants was conducted to investigate the properties of the three visualization techniques *Map*, *Halo*, and *Combination of Map and Halo*. In the study, the participants had to search for virtual objects in augmented reality with the help of different off-screen visualization techniques. Afterwards, they were asked to place the objects at the positions where they were found earlier. The aim of the study was to find out how the different techniques influence the participants' *performance* (RQ1), *Spatial Memory* (RQ2), *Cognitive Load* (RQ3), and *User Experience* (RQ4).

This thesis presents the prototype's development and evaluation. In the next chapter, the theoretical foundations will be shown, including an explanation of the mixed reality spectrum and the field of views of different devices. Afterwards, the related work, which includes different visualization techniques like Arrows, Halo, or Wedge is analyzed. Next, the design of the prototype, derived from the requirements, is shown in detail. As a central part of this thesis, a user study was conducted. This thesis describes the preparation, conduction, and evaluation of the study. Finally, the thesis finishes with a discussion that includes implications for future research and a conclusion.

# 2 Theoretical Background

This chapter presents the theoretical background, which serves as a foundation for the subsequent chapters. In the following, the classification of mixed reality devices is elaborated. Additionally, the different fields of views (FOV) of various head-mounted displays are discussed.

## 2.1 Mixed Reality

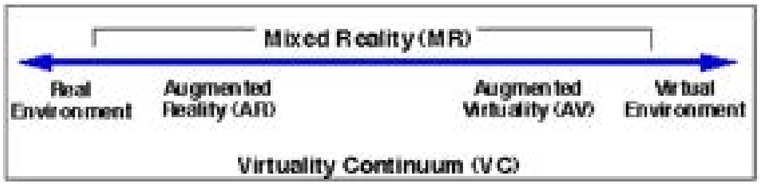


**Figure 2.1:** Simplified representation of the proposed "Virtuality Continuum" (taken from [7]).

One classification for Mixed Reality displays was proposed by Paul Milgram and Fumio Kishino in 1994 [7]. They use the term Mixed Reality (MR) for technologies that merge the real world with virtual ones. *Real Environments* are located on the left end of their proposed virtuality continuum (see Figure 2.1). They contain only physical objects. On the other end, the *Virtual Environment* is positioned and contains only virtual objects. In between those two extremes, two more categories are positioned. On the right of *Real Environment* is *Augmented Reality* located. It refers to real environments that also include virtual objects, whereas *Augmented Virtuality*, which is located right from *Augmented Reality* and left of *Virtual Environment* and refers to completely graphic environments that are immersive or partially immersive but add video reality.

## 2.2 Limited Field of View

Humans can perceive information in a nearly 180 degrees environment [8]. In comparison, the field of view of augmented reality head-mounted displays is a lot smaller. The original HoloLens has a field of view of 30° horizontally and 17.5° vertically [9]. The HoloLens was used to implement the off-screen visualization techniques *HaloAR* and *WedgeAR*, which were developed by Gruenefeld et al. [2]. They identified the small field of view as challenging since much space was needed for their visualization technique and only a little space remained unoccupied in the field of view. The HoloLens 2 has a more extensive field of view compared to its predecessor, with a horizontal field of view of 43° and 29° vertically [9]. Although the field of view is twice as big compared to the HoloLens, it is still significantly smaller than our human vision. On the other hand, the Varjo XR-3 [10] is an approach for a mixed reality head-mounted display that provides an even bigger field of view compared to the HoloLens 2. It claims to have the widest field of view with 115° horizontally.

In comparison, the field of views of virtual reality head-mounted displays will be elaborated in the following. The Oculus Quest 2, for example, has a field of view of 85°-93° horizontally and 88°-98° vertically [11]. This is noticeably bigger compared to the HoloLens 2 [3], which is currently state of the art for AR head-mounted displays. However, the Pimax vision 8K [12] with a diagonal field of view of 200° provides an even bigger field of view than the Oculus Quest 2 [11].

In summary, the field of view on head-mounted displays increased significantly over time. For example, this can be seen when comparing the HoloLens and HoloLens 2 [9] but there is still room for improvement, especially for augmented reality head-mounted displays. Moreover, the field of view of mixed reality head-mounted displays is still much smaller than our human vision's capabilities. Additionally, the field of view on AR head-mounted displays is also noticeably smaller than the field of view of VR devices. The small field of views lead to content being more likely to be off-screen and not being perceived by the user. Thereby, the limited field of views of mixed reality head-mounted displays show the importance of off-screen visualization techniques, especially for augmented reality head-mounted displays.

# 3 Related Work

In this chapter, different existing proposals for off-screen visualization techniques are elaborated. Parts of this chapter were already described in the seminar [13] and were adopted or revised for the following section. There are many proposals for off-screen visualization techniques with very distinct approaches. For example, some techniques use 2D hints, while others use three-dimensional hints. There are also approaches that focus only on visualizing one object, while others are capable of visualizing many objects or complete environments. Finally, the techniques were also developed for different devices and environments positioned all over the mixed reality spectrum. One approach to classifying off-screen visualization techniques is dividing them into the categories *Contextual Views*, *Focus+Context*, and *Overview+Detail* [4]. *Contextual Views* present off-screen objects with the help of abstract shapes. *Focus+Context* approaches use distortion and smooth transitions to present the objects in the surrounding. Furthermore, Visualization techniques that belong to *Overview+Detail* approaches show a miniature view of the environment. The following sections present an overview of different proposals for each category. Additionally, combinations of several techniques are discussed.

## 3.1 Contextual Views

There are many proposals for *Contextual Views*. However, there are too many to present every proposed approach in this section. Therefore in the following, four very different approaches and further development of them is shown to give a broad overview. The discussed techniques include: radar approaches [14], arrow approaches [15] halo approaches [1], and wedge approaches [4].

### 3.1.1 Radar Techniques

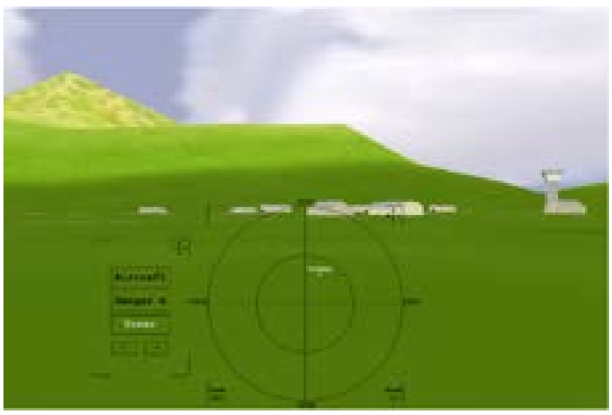

**Figure 3.1:** The "2D radar" navigation aid that visualizes an off-screen object in the upper right of the radar (taken from [14]).

The 2D radar technique implemented by Burigat and Chittaro [14] was developed for desktop VE and uses a radar metaphor that is shown on the screen. Additionally, the user is located in the center of the radar (see Figure 3.1). The target is indicated as a colored point inside the radar region and annotated with the object's name. Furthermore, the distance between the user and the target can be approximately derived. Thereby, the targets' location is indicated in relation to the viewers' position. For example, a target on the right side of the radar stands for a target located right of the current view.

Burigat and Chittaro [14] conducted a study to compare the radar technique with a control condition (containing no additional aid) and two arrow-based approaches, which will be discussed in the next section. They tested the aids in two different environments and differentiated between users with experience in navigation in 3D virtual environments and users without experience. Under the different conditions, the radar technique never outperformed any arrow-based technique. Only for experienced users, the radar technique was as effective as arrows. Further details about the arrow-based approaches will be elaborated in the next section.

### 3.1.2 Arrow Techniques

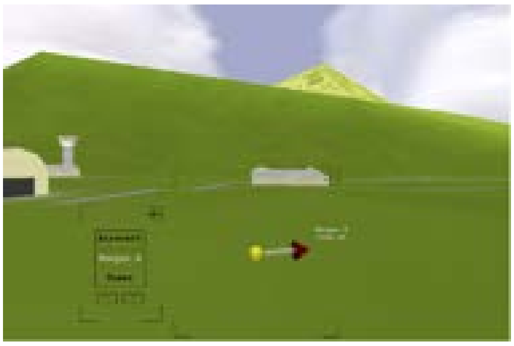

**Figure 3.2:** The "3D arrows" navigation aid, pointing to an off-screen objects with a 3D arrow (taken from [14]).

**Figure 3.3:** The "2D arrows" navigation aid, pointing to an off-screen objects with a 2D arrow (taken from [14]).


**Figure 3.4:** A Mock up of the interface of SidebARs is shown. Arrows with different types of off-screen objects are visualized on the sidebars. They are annotated with the closest distance and the amount of targets combined in one arrow (taken from [15]).

Arrow-based techniques were developed for different environments. One implementation was proposed by Burigat and Chittaro [14] who compared dynamic 2D arrows (see Figure 3.3), 3D arrows (see Figure 3.2) and a radar technique (see Figure 3.1) in a geographic desktop VE, and an abstract desktop VE. The radar technique was already introduced above. The 3D arrow technique was inspired by people pointing at targets with their hands, while road signs inspired the 2D arrow technique. Thereby, for both techniques, an arrow pointing to the right indicates a target positioned right of the current view. Additionally, the arrows are labeled with the distance and the target's name in both techniques.

Burigat and Chittaro [14] found that all techniques (2D arrows, 3D arrows, and radar) were significantly faster compared to having no aid. Furthermore, experienced users were faster with all techniques, while the inexperienced users were significantly faster with 3D arrows compared to the other conditions, probably because no mental translation was needed. Experienced users were also faster with 3D arrows in the abstract VE. Additionally, subjective preference correlates with these results.

Another example of an arrow-based technique is SibebARs [15]. Unlike the previous example, it was developed for mobile augmented reality. The application is aimed at firefighters and uses arrows to indicate points of interest (POIs), like fire hydrants or fire companies. The arrows are placed on transparent bars on each side of the screen and are annotated with the distance to the off-screen targets (see Figure 3.4). The targets that are visible on the screen are shown in speech bubbles.

SidebARs [15] contains several unique properties to reduce clutter and to find the best fitting target quickly. First, all POIs of the same type and within a sidebar are merged into one arrow. The amount of targets is written on the arrow and the distance to the closest POI is also annotated. The user can select which types should be shown, which decreases clutter even more. Another property to reduce clutter and irrelevant information is the possibility of determining the radius in which POIs should be shown.

The authors claim that their prototype seems promising and that the results of their evaluation were generally good [15]. The main problem mentioned in their evaluation is that no different roles were implemented, which would be helpful in this particular use case.

To conclude, there are different proposals for off-screen visualization techniques that use arrows. Their performance depends on the applied environment and the experience of the user [14]. For example, inexperienced users can benefit from 3D arrows compared to 2D approaches [14]. Moreover, it can be beneficial to group off-screen objects by their type and allow selecting a radius in which targets should be shown. Thereby, clutter can be reduced [15]. Finally, arrow-based visualization techniques can be helpful but are only sufficient in particular use cases. Ekman and Lankoski [16] claim that any technique using arrows is enough for wayfinding and to guide a user to their target but arrows do not give enough context as a navigational aid. The drawbacks of arrows are that they only indicate the direction, but not the distance when no distance is explicitly added [1].

### 3.1.3 Halo Techniques

In this section Halo will be explained, and further development of the technique. Halo [1] was invented by Patrick Baudisch and Ruth Rosenholtz in 2003 and uses a single non-distorted view that indicates location and direction without explicit distance labeling. The technique uses arcs that are part of circles (see Figure 3.5). Thereby, a circle is placed around each off-screen object, resulting in the object's position being in the circle's center. The circle size is computed dynamically to only reach into a small area on the edges of the display and to occupy only a little screen space.

**Figure 3.5:** The figure visualizes five off-screen targets (a) and shows the circles that belong to the arcs (b) (taken from [1]).

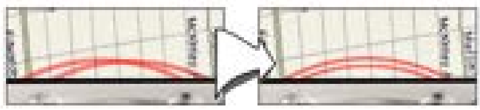

**Figure 3.6:** Overlapping arcs (left) are merged into a multi-arc (right) (taken from [1]).

Halo has an advantage when looking for closer targets [4]. However, when many off-screen locations need to be visualized, clutter occurs quickly due to increased overlap. A solution to reduce overlaps and clutter is to merge the arcs of heavily collocated targets into a single multi-arc consisting of 2-3 thinner arcs or a thick double ring for four or more merged targets (see Figure 3.6).

A study compared Halo with an arrow-based technique and showed that task completion was significantly faster with Halo [1]. Additionally, Halo was subjectively preferred. However, there were also some drawbacks of Halo. The distance awareness for targets that further away decrease faster with Halo compared to the arrow-based technique. Furthermore, the error rate in the corners is twice as high for Halo compared to the edges.

(a) *HaloVR.* (b) *WedgeVR.* (c) *HaloAR.* (d) *WedgeAR.*

**Figure 3.7:** The figure shows the HaloVR (a), WedgeVR (b), and HaloAR (c), WedgeAR (d) techniques that visualize one off-screen object (taken from [2]).

HaloAR and HaloVR were developed by Gruenefeld et al. [2] and are based on the original Halo technique but adapted for mixed reality head-mounted displays. Several steps were necessary to implement the technique and to allow placing off-screen targets at a 360-degree angle around the user's head. First, an imaginary sphere with a one-meter radius is generated around the user's head (see Figure 3.8 (a)). Next, an imaginary line is drawn from the user's head to the off-screen target (see Figure 3.8 (b)). The Halo is then computed from the point where the sphere and the imaginary line intersect until it reaches the user's field of view. In contrast to the original Halo technique [1], the target is not located in the middle of the circle but on the other end, to enable a 360-degree target placement. Additionally, transparency was added for less occlusion.

Gruenefeld et al. [2] conducted a study to compare and evaluate HaloAR, HaloVR and two techniques called WedgeAR and WedgeVR. Their study showed that all technique are usable for AR and VR. Overall, the only

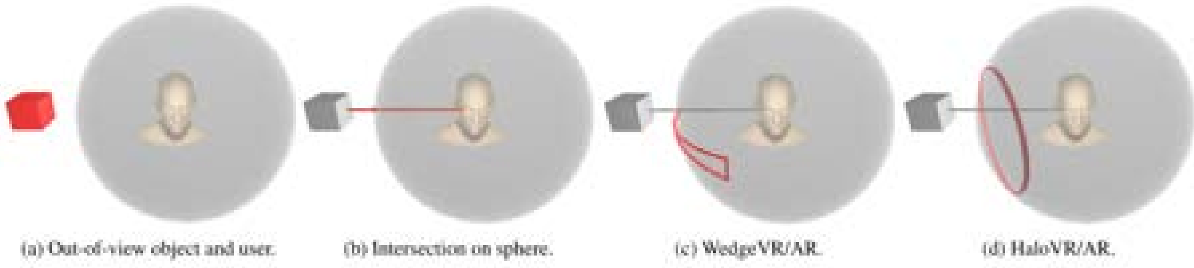


**Figure 3.8:** The figure shows the mapping of off-screen objects onto a sphere and the resulting HaloAR/VR and WedgeAR/VR visualization techniques. The user with an imaginary sphere and a cube as out-of-view objects is shown (a), next, the intersection with the sphere between the user and cube is shown (b), the out-of-view object is visualized with WedgeVR/AR (c), and HaloVR/AR (d) (taken from [2]).

significant difference between the techniques was that HaloAR was found to perform better regarding direction error than WedgeAR. Additionally, they found that more off-screen objects lead to worse performance of search time. Therefore, it is suggested to visualize as few objects simultaneously as possible.

To summarize, Halo was introduced almost two decades ago [1] and has been developed for various devices [1, 2]. Halo was found to be a useful off-screen visualization with many advantages and still some drawbacks. Halo provides information about the direction and distance of off-screen objects and was found to perform better than arrow-based techniques [1, 17]. Halo also shows advantages when looking for close targets [4]. However, one drawback is that Halo gets cluttered quickly.

### 3.1.4 Wedge Techniques

**Figure 3.9:** The Halo interface (a) and Wedge interface (b) are shown (taken from [4]).

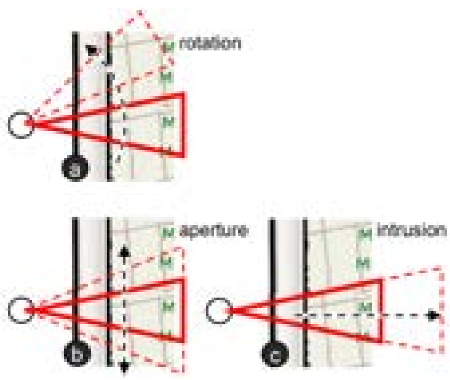


**Figure 3.10:** The three degrees of freedom of wedge are shown: rotation (a), aperture (b), and intrusion (c) (taken from [4]).

Wedge [4] was invented in 2008 by Gustafson et al. as an improvement of Halo (see Figure 3.9). They claim that Wedge indicates direction and distance without the clutter and overlap that occurs with Halo when many targets are shown. Wedge uses acute isosceles triangles to indicate off-screen locations. Two corners of the triangle are situated on the screen, and the tip is located off-screen, in the same spot as the off-screen target. Wedge uses the same location functionality as Halo. Thereby the wedges can be recreated from the fragments.

For the design of the wedges, several goals were specified. The goals are avoiding overlap, maximizing location accuracy, and serving as additional distance cues. The main focus lies on avoiding overlap and is achieved by rotating the wedges (see Figure 3.10 (a)), reducing aperture (see Figure 3.10 (b)), and reducing intrusion into the screen (see Figure 3.10 (c)). For the wedge design, a longer intrusion for longer distances and a shorter intrusion for shorter distances was chosen. This creates several advantages. First, it naturally reduces overlap, and second, it serves as an additional distance cue. It also increases the accuracy and gives the possibility for nested wedges. The second parameter aperture defines the angle separating the legs of the wedge (see Figure 3.10 (b)). It is calculated linear to the target distance and serves as a primary cue for the target distance. The rotation algorithm works clockwise for up to 5 overlapping wedges and rotates the overlapping wedges repeatedly.

Gustafson et al. [4] conducted a study to investigate whether Wedge outperforms Halo. They confirmed that Wedge is more accurate than Halo, especially for wedges or arcs located on the display's corners. However, for detecting the closest target Halo scored better.

Similar to Halo, the original Wedge technique was also transferred to other devices and environments. One example is WedgeAR [2] and WedgeVR [2]. They were developed for head-mounted displays (see Figure 3.8 (b),(d)). For WedgeVR and WedgeAR, a similar mapping to HaloAR and HaloVR was used (see Figure 3.8). Additionally, changes from the original Wedge technique were made. For example, the ability to rotate wedges was removed. The rotation is usually helpful to avoid clutter, but pilot studies showed that jumping wedges lead to losing track of specific objects.

In their study Gruenfeld et al. [2] compared WedgeAR with the above introduced HaloAR technique and the WedgeVR techniques with the above introduced HaloVR technique. All techniques showed a lower workload and were found to have acceptable usability in their applied environment (VR or AR head-mounted displays). The study showed that more off-screen objects led to worse search time performance with all techniques. Therefore, it is suggested to visualize as few objects simultaneously as possible. For the techniques applied in augmented reality, the limited field of view negatively affected user performance.

To conclude, Wedge was developed as an improvement for Halo. It was developed for different environments with different adjustments and is less likely to get cluttered compared to Halo [4].

## 3.2 Focus + Context

In the following, the *Focus+Context* technique Aroundplot [18] is shown. The approach uses distortion and maps 3D spherical coordinates to 2D rectangular fisheye. For the mapping process, an imaginary sphere is created and then mapped onto the device screen (see Figure 3.11). The orange parts indicate the part visible in the view frustum, and the gray areas represent the most compressed parts when mapped onto the 2D area. The dynamic magnification technique was introduced as a solution for the high degree of compression. The technique enlarges the content in the direction of the view movement, which correlates with the direction of the searched targets (see Figure 3.12). When the movement direction changes, the magnification is adapted, and when the movement stops, the current orientation becomes the new starting orientation after a certain time.

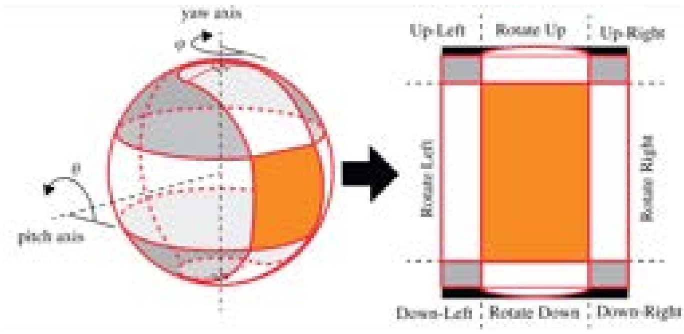


**Figure 3.11:** A mapping from 3D spherical coordinates (left) to 2D rectangular fisheye (right) is shown (taken from [18]).

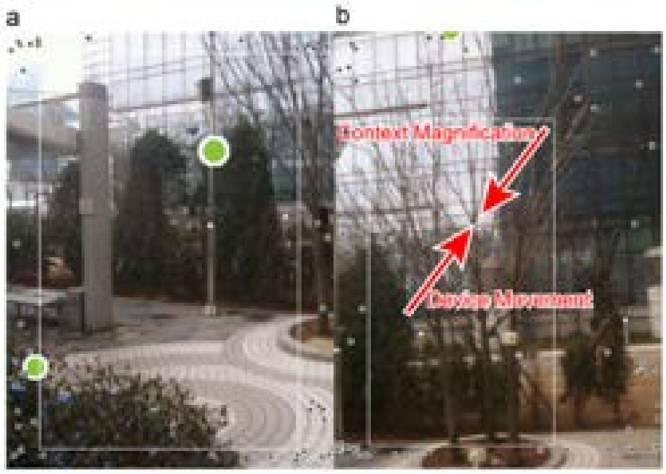


**Figure 3.12:** Th dynamic magnification method with 50 objects in a static state (a) and in a dynamic state (b) is shown (taken from [18]).

To evaluate Aroundplot [18], the technique was compared to a top-down 2D radar and a 3D arrow cluster. Aroundplot was found to be more accurate and faster than the 2D radar interface and more accurate than the 3D arrows when 50 objects were shown. The main drawback of the 2D radar interface is assumed to be the lack of height indication. The authors claim that Aroundplot gives intuitive direction cues while minimizing occlusion [18]. They also suggest further research to increase the performance by finding solutions for the problem of crowded corners.

## 3.3 Overview + Detail

*Overview+Detail* approaches use miniature maps of the environment. They can be two- or three-dimensional (see Figure 3.13. Especially, 3D Maps usually make use of the Worlds-in-Miniature (WiM) Metaphor. Stoakly et al. [22] were the first to mention WiMs in virtual reality. Since then, the definition of the WiM metaphor has been altered, and different proposals were made. Danyluk et al. [23] also came up with a new definition in 2021, which they claim is more inclusive: "A World-in-Miniature is a scale replica of an environment linked to the original space via interaction or virtual feedback - an interactive world within a world." [23]. This definition extends

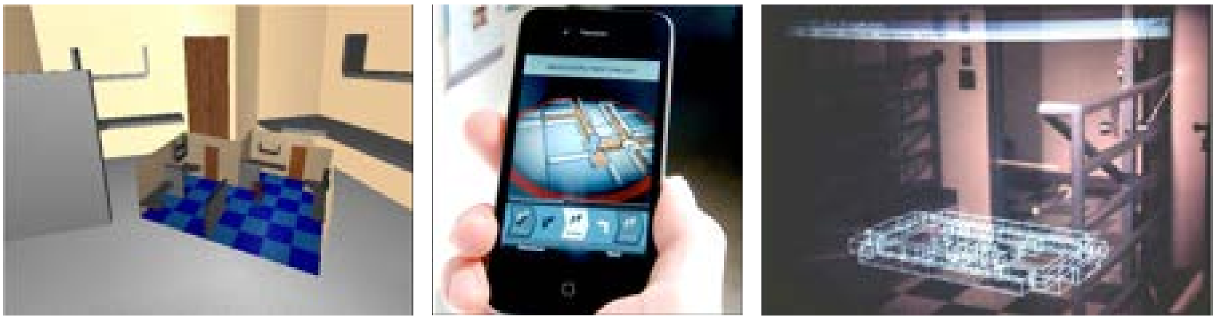

**Figure 3.13:** A WiM representing a room in VR [19] (left), a WiM on a smartphone [20] (middle), and a WiM in augmented reality [21] (right) is shown.

the original definition, which only included VR, over the entire mixed reality spectrum. Also, it includes object manipulation with the help of the replica, as well as interactions like navigation and IoT control. The definition also includes WiMs of different sizes.

Several design dimensions were proposed to distinguish and describe the WiMs by their different characteristics [23]. However, the dimensions do not include any interaction since the authors argue that interactions are a design space on their own. Danyluk et al. developed the proposed dimensions by analyzing 25 papers using the Worlds-in-Miniature Metaphor. The identified dimensions are shown in the following.

1. **Size-Scale-Scope** contains three related dimensions. The size refers to the physical dimensions of the replica. Hereby, replica refers to the overview map, which is seen as a replica of the environment. It can vary between only a few centimeters and or many meters. The scope describes the amount of represented space in the replica. An example could be a single object or a whole city. Additionally, the scale is derived from the size and scope and describes the relation between those two dimensions. In the examined papers, most large WiMs also had a broad scope.

2. **Abstraction** refers to transforming the referenced environment into a replica. It can be transformed into a perfect digital recreation, which is typical for VR environments, or the abstraction can simplify the scene and thereby reduce clutter. Typically, in AR a higher abstraction is used compared to virtual reality because it is easier to create a perfect copy of a virtual environment.

3. **Geometry** refers to the shape of the replica. This is especially important in large environments that need clipping to be usefully visualized. Replicas can be clipped to simple shapes like a cylinder or the measurements of a room, building, or workspace.

4. **Reference Frame** describes the position and orientation of the replica. The position can be pericutaneous, peripersonal, or extrapersonal. Pericutaneous describes a position directly on the viewer's body, e.g., as a virtual wristwatch. While a peripersonal position is concerning the viewer's position but not directly attached. The extrapersonal position has no fixed connection to the viewer's body. Typically, replicas close to the body tend to be small, while replicas in the extrapersonal space tend to be bigger.

5. **Links** establish a connection between the replica and the environment. Most of the examined replicas did not use links, but those that did mostly visualized the view frustum in the replica to indicate the position and orientation of the viewer.

6. **Multiples** refers to using more than one replica. If multiple replicas are used, they can differ in their properties, e.g., having a smaller replica and a bigger one. They can also be recursive, meaning one replica is placed within another.

7. **Virtuality** refers to the placement in the XR spectrum [7]. The placement ranges from VR devices over AR devices to the replica being an actual physical object.

The examined WiMs are very diverse concerning the introduced dimensions, but there were still gaps and challenges identified for some of them [23]. For example, links were found to be very rare, as well as pericutaneous WiMs with a large size, and WiMs containing several replicas. Additionally, creating truly realistic WiMs remains challenging, especially for augmented reality. Another challenge and a possible drawback is the cognitive load that is necessary to incorporate the different views in your mind [2].

Besides the seven proposed design dimensions, WiMs can be grouped by their application area. The first application area is **Wayfinding**. It describes identifying and following paths from one location to another. Typically the reference frame should be peripersonal or pericutaneous. This allows the WiM to move with the viewer. Additionally, small sizes and a constrained scope may be beneficial. Another application area is **Collaboration**. It involves several viewers that use the same WiM. A large size and extrapersonal reference frame is suggested to be the best choice. For **Visualization** applications, multiples and links are suggested to support exploring and analyzing the data. The **Navigation** area describes environments that use WiMs to change the position in the usually virtual environment. The focus lies on enabling precise navigation and should be considered when choosing the scale. The viewer can also profit from distorted geometries to make navigating occluded areas easier. The last application area **Control Space** refers to a replica that supports controlling elements of the environment. Here, abstraction is suggested to help increase the size and visibility of interactive elements.

To conclude, many aspects should be considered when developing an application involving WiMs. It was shown that it is important to choose the right dimensions with respect to the application area, to ease use [23]. The many possibilities also show how versatile WiMs can be used, and Danyluk et al. [23] claim WiMs as highly relevant for XR research. There are also remaining challenges, gaps, and drawbacks, like the cognitive demand [2].

## 3.4 Combining Techniques

There is only few research on combining several visualization techniques and the existing research focuses on particular combinations. Furthermore, the combinations include unique techniques that were not explained in the above sections. This is in line with the large number of proposals for off-screen visualization techniques that can not be elaborated completely in this thesis. However, the above introduced techniques give a good overview of existing approaches and the below-mentioned techniques are additionally roughly explained in the following.

One approach was developed by Gruenefeld et al. [5] (see Figure 3.14). Their approach compares a printed map with an in-view visualization, an out-of-view visualization, and a combination of in-view and out-of-view visualization. The study was conducted in AR using the HoloLens. For the in-view visualization technique, they chose a 3D representation of the object, and a wireframe of the visual cue when the object is occluded (see Figure 3.14 (b)). The decision to use this in view visualization technique was made after comparing four different approaches in a study. As out-of-view technique EyeSee360 [24] was chosen (see Figure 3.14 (c)). Gruenefeld et al. found the technique to work better compared to eight other techniques, with fastest search time and best usability. EyeSee360 [24] uses a radar-like visualization. The off-screen objects are mapped to a grid system that transforms the 3D information onto a 2D plane. A rectangle represents the users field of view and the area around the rectangle represents the off-screen space. Thereby, the height placement on the plane also indicates the height placement in the environment.

Their study showed that the in-view visualization technique reduces error rates for object selection accuracy. Additionally, the combination had a positive influence on the search time performance but also led to visual clutter. However, the visual clutter also appeared when only using the out-of-view visualization technique alone.

(a) Printed map. (b) In-view visualization. (c) Out-of-view visualization. (d) Combined.

**Figure 3.14:** The techniques printed map (a), in-view visualization (b), out-of-view visualization (c), and a combination of in-view and out-of-view visualization (d) are shown (taken from [5]).

Another approach to combine several techniques was developed by Hein et al. [6]. They compared different single visualization techniques with several approaches to combine them. Their techniques also use the HoloLens. In their study they compared five conditions. Two conditions used only a single technique. The techniques are called *omnidirectional attention funnel* (see Figure 3.15 (left)), and *spherical wave based guidance* (see Figure 3.15 (middle)). *Omnidirectional attention funnel* [25] consists of a funnel that decreases in size towards the desired object. On the other hand, *spherical wave based guidance* [26] consists of circles around the target object to lead the attention towards the objects. Additionally, there were three conditions that combined two techniques. This was done by dividing the search process into coarse navigation and fine navigation. Depending on the angular distance towards an object only coarse navigation or only fine navigation is shown. All combination conditions used a *2D arrow* pointing to the left or right for coarse navigation. After switching to fine navigation *attention funnel* or *spherical wave based guidance* was shown. Additionally, a combination was tested that uses the *2D arrow* pointing to the left or right for coarse navigation and the same *2D arrow* pointing directly to the target as fine navigation.

The study showed a positive effect for differentiating between fine and coarse navigation. The fastest search times were achieved for the combination of *2D arrow* with *attention funnel* and for the combination of *2D arrow* with *spherical wave based guidance*. For the combination of *2D arrow* with *attention funnel* significant improvement could be shown, including a higher pragmatic quality.

**Figure 3.15:** The techniques *attention funnel* (left), *spherical wave based guidance* (middle), and *2D arrow* (right) are shown (taken from [6]).

## 3.5 Summary

Above, several off-screen visualization techniques were analyzed. All techniques have benefits and drawbacks and were found to be usable under different circumstances. The usability depends on different factors. For example on the tasks that need to be accomplished, the environment in which the technique is applied, or which device is used. Furthermore, the number of objects that need to be visualized simultaneously [2] and the experience of the user [14] influences the choice which approach fits best.

For example, arrow-based techniques were found to be suitable only for guidance to a destination or wayfinding but not as single cue for navigational aids [16]. Additionally, 3D arrows outperformed the radar technique in desktop virtual environments [14], while Aroundplot outperformed a 2D radar interface in mobile augmented reality [18]. Wedge claims to outperform Halo concerning the tendency to get cluttered [4] but Halo has an advantage over Wedge when searching for close targets [4]. Both Halo and Wedge were found to be usable and perform better than arrows in augmented and virtual reality [17]. In the following, an overview of the techniques, including their advantages and disadvantages, is illustrated (see Table 3.1).

Additionally, it was shown that few research exists in combining several techniques. Moreover, the research that was done is only concerned with very specific use cases. For example showing coarse or fine navigation, depending on the angular distance towards an object [6]. Another approach uses in-view and out-of-view visualization techniques [5]. However, the existing research indicated that further research is promising and should be performed.

| **Technique** | **Benefits** | **Drawbacks** |
|---|---|---|
| **Radar** [14, 18] | Indicates direction [14] | Could not outperform arrows [14] or Aroundplot [18], Does not indicate height [18] |
| **Arrows** [14] | Sufficient to guide to a target [16] | Distance is not implicitly indicated [1], Only sufficient for specific tasks [16] |
| **Halo** [1, 27, 2] | No distance annotation needed [1], Outperforms arrow-based technique [1, 17], Suitable for AR and VR [17, 2], Advantage in detecting close targets [4] | Gets cluttered easily [4], Higher error rate on corners [1] |
| **Wedge** [4, 2] | No distance annotation needed [4], Suitable for AR and VR [2], Reduces clutter compared to Halo [4] | Rotation property omitted for WedgeAR [2] and WedgeVR [2] |
| **Aroundplot** [18] | Outperforms 2D radar [18] | Corners are more crowded [18] |
| **WiMs** [23] | Works also for occluded objects, Provides exo-centric overview | Higher Cognitive load [2] |

**Table 3.1:** Overview of advantages and disadvantages of off-screen visualization techniques are shown.

# 4 Study Prototype

This chapter presents the design concept of the three visualization techniques 1) *Map*, 2) *Halo*, and 3) *Combination of Map and Halo*. First, the used technologies are explained. Followed by, the three visualization techniques that are also used as conditions in the study. For each technique, it is explained why the technique was chosen, based on the findings from the related work. Additionally, the requirements and the derived design for each technique is shown.

## 4.1 Used Technologies

As Hardware, the **HoloLens 2** [3] was used. The head-mounted display is currently state of the art and not wired. Therefore it is suitable for a use case where walking through a room to search objects is required. An alternative augmented reality head-mounted display is the Varjo XR 3 [10]. It provides a bigger field of view but is also cable bound and restricts walking freely through a room. Therefore the HoloLens 2 was chosen over the Varjo XR3.

The study prototype was developed in C# with **Unity3D** [28]. The application was built for "Universal Windows Platform" (UWP) and Unity version 2020.3.11f1 was used.

The **Mixed Reality Toolkit (MRTK)** [29] was integrated into the project to make the application usable on the HoloLens 2. Additional features, like the HoloLens buttons, are also provided by the toolkit and were used in the application.

Vuforia's Image Targets from the **Vuforia Engine** [30] with version 10.8, were used as a marker in combination with the **RoomMarker plugin** [31], provided by the Human-Computer Interaction Group. It is used to adjust the scene contents' position and rotation to fit the measurements of the media room.

As **Models**, a replica of the media room [32] is used as a base to develop the map design. Additionally, an avatar provided by the Human-Computer Interaction Group is used on the map. Furthermore, additional models were used to serve as off-screen objects [33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46].

The off-screen visualization technique **HaloAR** developed by Gruenefeld et al. [47] for the original HoloLens, was used as a base for the *Halo* technique developed in the study prototype. Using their original proposal increases comparability.

## 4.2 Map

The first component of the study prototype is *Map*. Overview maps use the worlds-in-miniature metaphor. They are claimed to be promising and an extremely relevant area for XR research [23]. Moreover, they can be used in many different application areas, e.g., wayfinding or navigation [23]. While most off-screen visualization techniques only provide information about selected objects, maps provide an overview of the whole environment. Furthermore, overview maps can provide even more information, e.g., visualizing oneself in the room. These versatile advantages and their relevance for XR research lead to the decision to develop and investigate a 3D overview map.

The requirements for the map design are mainly derived from the seven design dimensions presented by Danyluk et al. [23]. Additional requirements to fit the use case are also included. Besides the requirements for the map, this also includes the design of additional features, e.g., the highlight capability or an avatar representing the users' position and orientation. The final design of *Map* can bee seen in Figure 4.1.

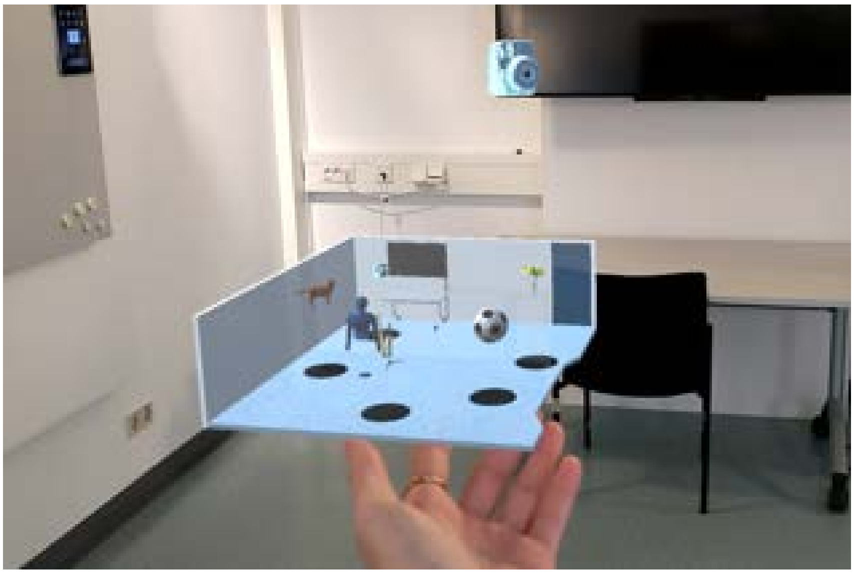

**Figure 4.1:** The off-screen visualization technique *Map* is shown. The map is placed on the non-dominant hand. The *camera* object is visible in the environment. The map shows an avatar representing the users' position and orientation, miniature objects representing the objects placed in the room (a saxophone, a football, a cat, yellow flowers and a camera), and a table and monitor that are placed as physical objects in the room.

- **Reference Frame:**

  The use case requires walking freely through the room to search for objects. Therefore, mobility is crucial, and the map must follow the user when needed. This requires a pericutaneous or peripersonal reference frame. Thus, the map is placed on the user's non-dominant hand and is only visible when the non-dominant hand is visible in the field of view. Since only one-handed interactions are required to interact with the application, the user's dominant hand remains usable for interacting with the system, e.g., by pressing buttons or moving objects. To make the map visible, the palm can face upwards, downwards, or anything in between. This allows the user to turn their wrist in the individually preferred angle, while the map always faces upwards. The on-demand aspect also leads to more space unoccupied in the field of view when the map is not needed.

- **Size-Scale-Scope:**

  The map's size is a trade-off between making it comfortable to lift the map and fitting it into the device's limited field of view while also representing the map in a big enough size to detect the desired information quickly. A good map size was found to be 14 cm by 11 cm. Thereby, the map size also correlates with the trend that maps with a reference frame near the body tend to be small in size.

The scope of the map must be as big as the space in which the objects (that serve as off-screen targets) are positioned. For the given use case, all objects are positioned in the media room, a lab facility of the HCI group.

The third dimension, the scale of the map, is derived from the dimensions size and scope. The optimal scope and map size were already determined above. However, the map size led to a too small object size. Therefore the scale of the objects must be adjusted to make it easier to identify the objects. At the same time, the magnification factor needs to be kept as small as possible to not deviate from the original scale more than necessary and remain the relations as precise as possible. An optimal object size was achieved by increasing the objects' size by a factor of 2.3.

- **Abstraction:**

  Due to technical limitations in augmented reality, the map design needs to be abstracted. This is typical in AR and can also reduce clutter and put more focus on key features in the surrounding.

  Therefore, the room is represented very clearly and minimally, e.g., walls and doors are shown using plain cubic game objects. The physical objects in the room, like the table and monitor, were rebuilt in unity and are very detailed, but some degree of abstraction can not be bypassed. Smaller furniture, like the chairs, were omitted entirely to reduce distraction.

  The virtual objects on the map are exact copies of the virtual objects in the room and only changed in scaled to fit the map's size. Additionally, black circles are placed underneath each object as a shadow. Thereby additional hints about the objects' placement in the room are given. For fair comparison, all shadows have the same size.

  Another important feature on the map is the avatar representing the users' position and orientation in the room. A picture of the avatar can be seen in Figure 4.2. The avatar uses a higher degree of abstraction, making it easy for every user to identify themselves with the avatar independent of their gender or other individual backgrounds. The abstracted design also sets the focus to the position and orientation of the avatar instead of the avatars appearance. These design decisions resulted in an avatar that only consists of the upper half of a body. Thereby, also no problems occur in the height adjustment due to different sized users, e.g., no floating feet occur. And the problem of having the avatar float over the map without moving its legs is bypassed. Additionally, a circle is placed underneath the avatar on the ground level, similar to a shadow. This makes it easier for the user to understand the avatar's exact position.

  Overall, the different abstraction levels lead to essential features remaining easily recognizable for good orientation and the focus being set to the virtual objects and the position of oneself in the room.

**Figure 4.2:** The avatar that is used on the map is shown. It consists only of the upper half of the body and is very abstracted. Additionally, a circle is placed on ground level as a shadow.

- **Geometry:**

  The map's geometry is similar to the geometry of the media room. The walls are shown to understand the objects' and avatars' position and to provide borders and background to detect the items quickly. However, the map should be designed to always show the inside of the miniature room. Therefore, the walls are required to become visible or invisible, depending on the users' rotation. This led to two different walls always being visible. Furthermore, the wall height on the map was changed to 6 cm, representing a height of 2 meters instead of the original room height of roughly 3 meters. This led to more space in the field of view, where the environment can be seen.

- **Links:**

  For the map itself, no links are required. However, *Combination of Map and Halo* requires highlighting the current target on the map and on the corresponding halo. This can be considered a link between the two techniques.

- **Multiples:**

  For the study prototype, only one map is required because the cues provided by the map are assumed to be sufficient. Furthermore, due to the relatively small scope in which the study prototype is applied, there is no need to use multiple maps.

- **Virtuality:**

  The application is applied on the HoloLens 2. One advantage of using augmented reality is the integration of the physical environment. The head-mounted display allows placing the map directly in the environment and does not limit the position to a small screen, e.g., when using a tablet AR. Additionally, head-mounted displays can be used without holding an extra device. Thereby, the hands remain unoccupied and can be used to interact with the map and objects directly.

- **Highlight capability:**

  An additional requirement for the map is the ability to indicate which object should be searched. This is done by adding a cylinder around the object that should be searched. Each cylinder for each object has the same size. Thereby, it is ensured that the highlights are comparable. The cylinders are colored in a transparent red to make it easy to see the highlight while still letting the object shine through. The highlight capability cann be seen in Figure 4.3.

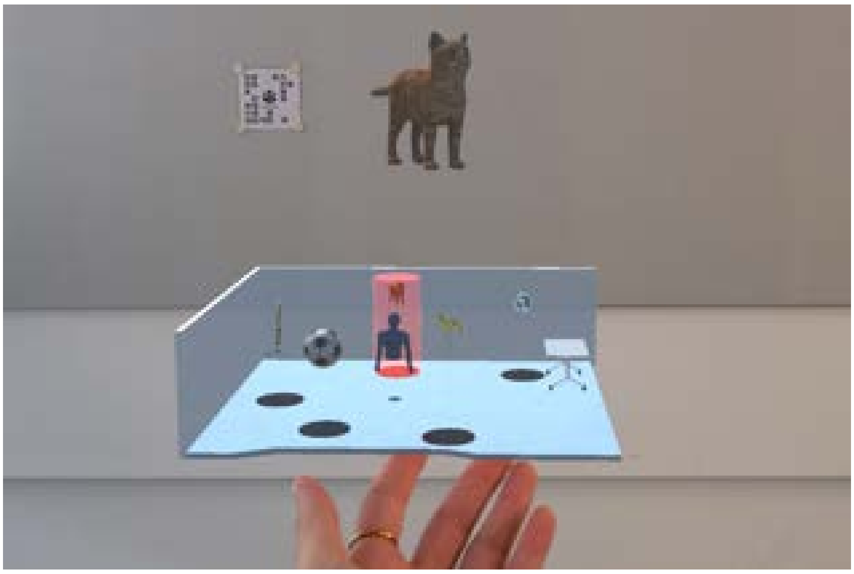

**Figure 4.3:** The off-screen visualization technique *Map* is shown. The *cat* object is highlighted with a cylinder on the map and also visible in the environment.

## 4.3 Halo

A halo-based technique was chosen as a second technique. The hints provided by Halo are in line with the users' point of view and distortion free. Additionally, the halos are dynamic, give hints about the direction towards the objects, and also about the amount of rotation needed until the object appears in the users' field of view. Gruenefeld et al. found Halo to work objectively best for Augmented Reality, compared to Arrows and Wedge [17]. Furthermore, for the techniques WedgeAR [2] and WedgeVR [2], rotating the wedges led to losing track of the objects. Therefore, the functionality was removed. Thereby, the main functionality to outperform Halo was removed. The positive properties of Halo techniques, and the proven usability for augmented reality head-mounted displays, led to the decision to compare the very different techniques *Halo* and *Map*, to get insights about their unique strengths and properties.

The *Halo* technique is based on the original Halo [1] technique and HaloAR [2]. The requirements for the developed Halo technique are mainly derived from HaloAR [2], but additional requirements are also added. The requirements and the derived design are explained in the following. The final design of *Halo* can be seen in Figure 4.4.

The code for HaloAR provided by Gruenefeld et al. [47] was used as a base *Halo*. An explanation of how HaloAR works in detail can be found above in the related work. The code provided by Gruenefeld at al. [47] already

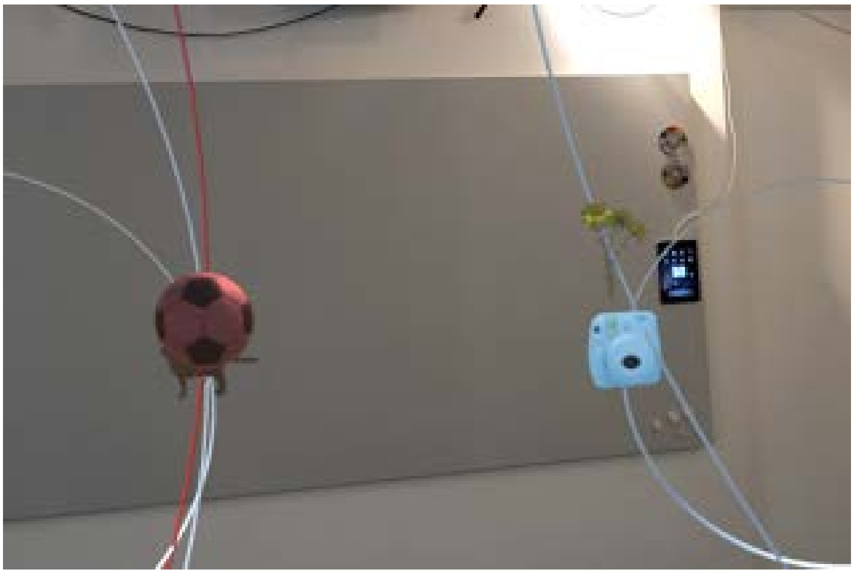

**Figure 4.4:** The off-screen visualization technique *Halo* is shown. Five halos are displayed. Each Halo indicates the corresponding object with an icon. The halos represent a saxophone, a football, and a cat on the left of the current view and yellow flowers, and a camera on the right of the current view. The football icon is visible on top of the other objects. The corresponding Halo and the icon are colored in red, representing that the football should be searched.

fulfills the requirement to visualize off-screen objects in a 360-degree placement. Using the key functionalities of their code increases comparability. Additionally, their study already showed, that the technique is suitable for augmented reality head-mounted displays [2]. However, their technique was developed for the original HoloLens. Therefore the code needs to be adjusted to fit the display of the HoloLens 2. This was done by changing the intrusion border of the halos from 5 degrees to 12 degrees, to fit the bigger field of view of the HoloLens 2. Besides moving the halos further to the borders of the display, the halos also needed to be moved downwards, to be positioned in the center of the display. This was necessary because the center of the HoloLens 2 is not placed in the middle of the display but in the upper half of the display, which led to the halos disappearing on the top of the display and leaving additional space on the bottom of the display.

Additionally, *Halo* should be Comparable to *Map* and *Combination of Map and Halo*. Therefore, icons that represent the corresponding objects were added to the halos. This is required because the map also indicates which object is placed at the represented position. To prevent the icons from overlapping, distributing them on the halos was considered. However, when Gruenefeld et al. developed WedgeAR, they found that rotating the wedges was distracting and not helpful [2]. It is assumed, that moving the icons around would lead to the same distraction. Therefore, the icons are positioned on the position of the halo that reaches furthest into the display. The position on the opposite side of this point on the halo is the position where the virtual object is placed in the room. Moving the icons on the Halo would possibly lead to inconsistencies in the mental model and make it harder to understand the position of the object in the room. Therefore, priorities were assigned to the icons instead. Thereby, the icon representing the currently searched object has the highest priority and is always placed on top. The item that was searched prior to the current one has the lowest priority and is placed behind the other objects. The other objects are placed in between. Unfortunately, in the current implementation, the icons still overlap slightly from some viewpoints, but the item that is currently searched for is always more than 50% visible.

The Halos are also required to indicate which object is currently searched. This was done by coloring the current halo red and also adding a red tint over the corresponding icon.

## 4.4 Combination of Map and Halo

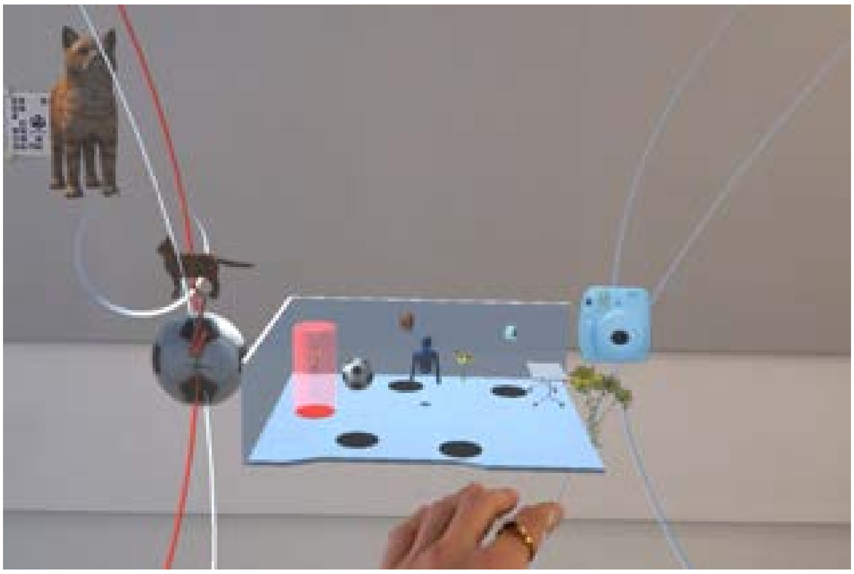

**Figure 4.5:** The off-screen visualization technique *Combination of Map and Halo* is shown. The map is placed on the hand and the halos are also visualized. The saxophone is highlighted with a red cylinder on the map and also with a red halo and red saxophone icon on the halo. On the upper left a cat is visible in the environment.

Additionally, a third technique that unites *Map* and *Halo* was developed. There are many proposals for off-screen visualization techniques that use a single method. However, only few research in combining techniques could be found so far. The existing research uses very specific use cases but the findings were also promising for further research in combining several techniques. The existing research only combines in-view visualization and out-of view visualization [5], or uses combinations that use a different method for coarse and fine navigation but not two techniques simultaneously. To the best of my knowledge, there is no research for maps that use an additional visualization technique. Furthermore, there are several reasons to investigate a combination of *Map* and *Halo*. A technique that combines *Map* and *Halo* is a more general approach that focuses on combining very different techniques in general. In this case *Map* is an *overview+detail* approach compared to *Halo* which belongs to *contextual views*. Research in a combination of those two techniques might give insights how the users interact when two very different approaches are presented to them. Additionally, each technique has benefits and drawbacks. Combining multiple techniques could alleviate individual drawbacks of one technique with the benefits of the other. For example, Halo indicates the target's distance and direction and has an advantage when searching for close targets [4]. However, *Halo* does not give any depth information [1] and tends to get cluttered quickly when many objects need to be visualized [4]. Furthermore, *Halo* does not work when the objects are occluded. Maps, on the other hand, give an overview of the surroundings and thereby can provide additional information, like the position of oneself in the environment. Maps also work for occluded objects. However, maps also provide an exo-centric view, while our vision through a head-mounted display is ego-centric. Switching between those views leads to a high cognitive load [2].

Due to the individual strengths and weaknesses mentioned above, one assumption is that combining multiple techniques can alleviate individual drawbacks of one technique with the benefits of the other. Additionally, it gives freedom to the user to decide which technique they want to use and gives additional hints about the user preference.

The requirements for the combination are directly taken from the individual requirements for *Map* and *Halo*. Therefore the combination includes the Halo technique as well as the on-demand map. The requirements for the individual techniques were already chosen to also fit the combination. For the currently searched objects both individual techniques highlight the represented object.

# 5 User Study

To compare the above-presented visualization techniques, a study was conducted. The study was conducted as a completely counterbalanced within-subjects study with the three techniques *Map*, *Halo*, and *Combination of Map and Halo* being the conditions. The research questions that led to the study design are explained in the following. Afterwards, the study setting, task, and procedure are presented. Followed by a description of the participants.

## 5.1 Research Questions

The research questions are influenced by previous findings from related work. It is assumed that *Halo* might have shorter search times because the hints given by the halos are immediately shown and no mental translation is needed compared to *Map*. Additionally, *Halo* has an advantage when searching for targets near the current field of view. The mental translation needed to switch between the ego- and exo-centric view with *Map* might also lead to a higher cognitive load with *Map* compared to *Halo*. On the other side, *Map* also provides an overview of the whole room, which might lead to better spatial cognition. Finally, all three techniques use very different approaches. Therefore it is also interesting to investigate how the participants liked the techniques and whether the quantitative data is in line with the subjective perception. These considerations led to the following research questions, that guided the study:

**RQ1**: How does the visualization technique affect performance?

**RQ2**: How does the visualization technique affect spatial memory?

**RQ3**: How does the visualization technique affect cognitive load?

**RQ4**: How does the visualization technique affect user experience?

## 5.2 Setting

The study was conducted in the Media room of the department HCI at the University of Konstanz. In the following a schematic illustration of the media room can be seen (see Figure 5.1). The room size is $7.06m$ x $5.8m$. However all object were place in a space of $5.5m$ x $4.5m$. During the study all blinds were closed and artificial light sources were used, to provide similar conditions for each participant. Otherwise, different light settings could lead to participants having trouble to see the virtual content well. Another possible disruptive factor are prominent features in the room. They could impact how easy it is to find an object or remember the objects' position. Additionally, they could distract the participants from accomplishing the task. Therefore, as many objects as possible were removed from the media room, to eliminate interfering factors that could influence the study outcome. This lead to the room containing no furniture, except for one table and two chairs that were needed to fill out the questionnaires and perform the interview. The table was placed with the longer side to the wall. This way less space is occupied in the center of the room. Additionally, by placing the chairs on the short ends of the table, more space was created as measurement due to the corona pandemic. By positioning the table on the wall, it was also easier to make sure that no virtual content overlaps with the table and the table itself is less prominent in the room for less distraction. Additionally, a monitor that was attached to a wall could not be removed.

The HoloLens 2 was used to run the application. Before each participant, the device was disinfected. The application also required a marker to adjust the virtual scene content.

**Figure 5.1:** A picture of the media room during a study is shown. On the left, the participant is looking at the marker to adjust the application to fit the measurements of the media room. On the right, the room is shown from the other side, while another participant fills out questionnaires.

## 5.3 Tasks

The participants had to perform a search task and a memory task in each of the three conditions. After each memory task, they had to fill out several questionnaires. The different tasks are explained in the following.

### 5.3.1 Search task

In the search task, the participants had to find different objects with the help of the different visualization techniques. The objects that needed to be searched, were divided into three different object sets. Each object set had one object from each of the categories *music instruments*, *animals*, *flowers*, *technology*, and *sport objects*. The objects for each object set can be seen in Figure 5.2, Figure 5.3, and Figure 5.4. *Object Set 1* was always used in the first condition, *Object Set 2* in the second condition, and *Object Set 3* in the third condition. For fair comparison, the order of the visualization techniques was counterbalanced to create six unique versions, where each visualization technique is paired with every object set. Thereby, it is prevented that one technique outperforms another one. This could happen if the participants are biased due to the order in which they use the techniques, or due to a learning effect that may occur when the participants get used to the application.

In all object sets, the objects were distributed similarly. A schematic distribution of the objects can be seen in Figure 5.5, Figure 5.6, and Figure 5.7. Only the rotation around the rooms center differed for each object set, to assure that the distances toward the objects were the same for every object set. *Object set 1* was rotated $0$ degrees, *Object set 2* was rotated $-50$ degrees, and *Object set 3* was rotated $-240$ degrees. The rotation was determined after several iterations to make sure that no object is hidden by a wall or overlapping with any other content in the room. Additionally, the search order was changed. All objects were placed on the same height. However, the

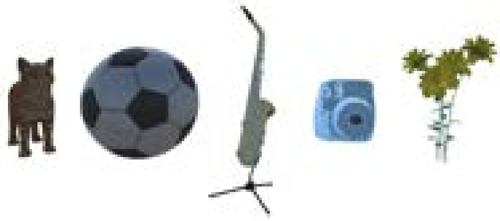

**Figure 5.2:** Object Set 1 is shown. It includes a cat, a football, a saxophone, a camera, and yellow flowers.

**Figure 5.3:** Object Set 2 is shown. It includes a basketball, a laptop, a cow, a rose, and a guitar.

**Figure 5.4:** Object Set 3 is shown. It includes a smartphone, a trumpet, violet flowers, a dog, and a tennis racket.

height differed for each participant, since the objects are placed in relation to the camera height of the HoloLens 2. The objects were placed 10 cm below the camera, leading to an objects' placement at about eye level.

To accomplish the search task, the participants had to search each of the five object three times, resulting in three passes, in which the five objects were searched for in the same order. The three passes were implemented due to the rather small number of objects in each object set. Furthermore, the small amount of objects resulted from *Halo*, which only allows a small amount of objects to be visualized at the same time. By performing the three passes, the participants have enough time to get used to the technique, and additionally, possible learning effects can be investigated.

During the search task, the participants had to press a button to highlight an object on the visualization technique. Then the corresponding object in the room should be found. The button was placed in the middle of the room, to make sure that the search paths are comparable and each individual search starts at the same position. To select an object, the participants had to move it slightly by grabbing it with their hand. After an object was selected, the highlight disappeared and the button to highlight the next target appeared in the middle of the room.

The search task served as main indicator for *Performance* (RQ1). Therefore, during the search task, the task completion time was tracked, and whether the objects were found correctly. Additionally, the search task served as reference to evaluate the *Cognitive Load* (RQ3) and *User Experience* (RQ4). It was also logged whether the map was visible in the field of view.

### 5.3.2 Memory task

In the memory task, the participants had to place the objects from the search task at the position where they found them previously. The participants also completed this task in augmented reality. Similarly to the search task, the participants had to press a button in the room middle but instead of highlighting a target, one of the

**Figure 5.5:** Positions of *Object Set 1* are shown.

**Figure 5.6:** Positions of *Object Set 2* are shown.

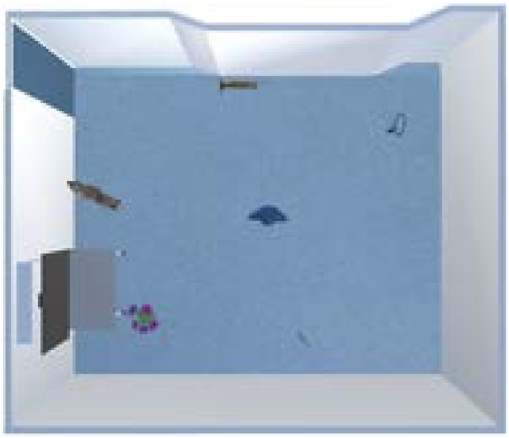

**Figure 5.7:** Positions of *Object Set 3* are shown.

previously searched object would appear next to the button. After the participant placed the object at the desired place, the button to spawn the next object would become visible again. Thereby, the objects appeared in the same order as the participant searched them in the previous task. By placing the objects one after another in a given order, the participants are guided through the task and the procedure is similar for each participant and therefore more comparable.

The memory task was performed as main indicator for *Spatial Memory* (RQ2). Thereby, the task completion time to place all objects was tracked. Additionally, the distance between the object's placement in the memory task and the object's placement in the search task was calculated. In an additional questionnaire after the memory task, it was asked how easy it was to place the objects. With the help of the questionnaire, it can be investigated whether the quantitative data is in line with the subjective perception. However, to include questions about the memory task in the questionnaires, the participants had to fill out the questionnaires after the memory task. Thereby, the possibility cannot be excluded, that the memory task also influences how the questions about the visualization technique itself are answered.

### 5.3.3 Evaluation

After the memory task, the participants were asked to fill out several questionnaires. For this purpose, the participants should lift the visor of the HoloLens 2. However, the participants were not prompted to put the whole device down. Thereby possible sources of error are reduced, e.g., having trouble with shifted scene content due to lost tracking of the environment. However, if the participant put down the device anyway, it was made sure that the application was not affected by it. This could easily be seen by observing the participant's position when interacting with the buttons and by the height in which the participant interacted with the objects. In the following the individual questionnaires are explained.

**Cognitive Load**

The first questionnaire that was handed to the participants was the NASA-TLX Questionnaire [48] to measure the *Cognitive Load* (RQ3). It was used without weighting but still provides valid results. The questionnaire was handed out first because it should be filled out directly after the task if possible.

**User Experience**

After the NASA-TLX, the participants had to fill out the User-Experience-Questionnaire (UEQ) [49] to asses their *User Experience* (RQ4). The questionnaire was handed out after the NASA-TLX due to the larger scope of the UEQ.

**Additional Questionnaire**

After the UEQ, an additional questionnaire was handed to the participants. It included questions about *how easy it was to understand the technique* (Question 1) and *how helpful the technique was* (Question 2). Additionally, the questionnaire also included questions about *how easy it was to identify which object is highlighted* (Question 3), *how easy it was to find the object* (Question 4), and *how easy it was to remember the objects' position* (Question 5). All questions were answered on a likert scale with 5 possible answers. Depending on the questions, the answers ranged from "very easy" to "very hard", or "easily recognizable" to "difficult to recognize". The main reason to use the additional questionnaire was to compare the quantitative data with the subjectively perceived *Performance* (RQ1) and subjectively perceived *Spatial Memory* (RQ2).

## 5.4 Procedure

In the following, the study procedure is elaborated. First, the participants were welcomed. Next, they had to fill out a consent form and a demographic questionnaire. Afterwards, they put on HoloLens 2, had time to get used to the device, and to ensure it fits correctly. After starting the application, the user had to look at a maker that adjusts the position of the application's content to fit the media room and the user's height. Finally, the participants had to report whether the marker was scanned correctly. If this was not the case, the application was restarted.

Before the actual tasks started, participants had to do a training phase to get used to the interaction techniques that were used in the application. In the training phase, they had to press buttons to interact with the system. Additionally, the participants had to search for two spheres located behind them, and had to lift them by grabbing them with their hand. Afterwards, the spheres disappeared, and reappeared one after another, with the instruction to place them at the previously found position. Thereby, the participants could get used to the system and AR in general. Additionally, the participants learned how to press a virtual button and how to move objects.

After the training phase, the participants had to select whether they are left or right handed. This information was needed to determine on which hand the map had to be placed. Furthermore, the participants were prompted to ask the examiner which version from one to six they should choose and had to press the corresponding button. To make sure that the participants chose the correct button, the selected version was logged. Afterwards, each condition went as follows:

1. Tutorial to test the visualization technique
2. Search task
3. Memory task
4. Questionnaires

In each tutorial, a short text was shown that roughly explained the current visualization technique. Next, the user had to search two different colored spheres that where located at the same positions behind the participants in each tutorial. An illustration of the tutorial for *Combination of Map and Halo* can be seen in Figure 5.8.

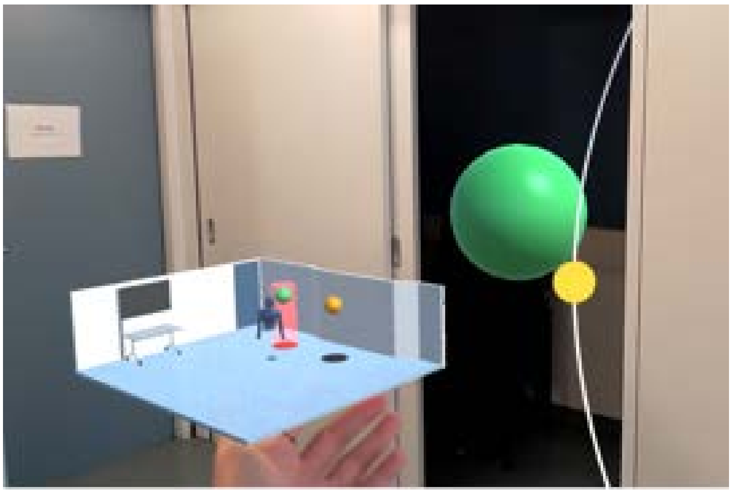

**Figure 5.8:** Tutorial for *Combination of Map and Halo*. The map is placed on the hand and the green sphere is highlighted an the map. The green sphere is also visible in the room. On the right, a Halo with a yellow circle is shown, indicating the yellow sphere on the right of the users' current field of view.

After the participant completed all conditions, the study was finished with a semi-structured interview.

## 5.5 Participants

The study was conducted with 18 participants (10 female, 8 male) between 19 and 27 (M = 22.56, SD = 2.01). All participants studied at the University of Konstanz or the HTWG Konstanz; two of them were PhD students. They had different backgrounds (e.g., education, computer science, biology, physics). Four participants wore glasses, one participant wore contact lenses, and one usually wore glasses but did not wear them during the study. Additionally, there were two participants with dyschromatopsia. All participants were right-handed. Only two had experience with AR HMDs in advance, and three had experience with AR applications.

# 6 Study Results

This chapter presents the study results in the order of the research questions. To indicate the conditions, subscript $_m$ is used for *Map*, subscript $_h$ for *Halo*, and subscript $_c$ for *Combination of Map and Halo*. To indicate the passes, subscript $_1$ is used for the first pass, subscript $_2$ for the second pass, and subscript $_3$ for the third pass. In this context, "pass" refers to the three passes performed in each condition. In all figures, *Map* is visualized in yellow, *Halo* in blue, and *Combination of Map and Halo* in green.

To evaluate interval-scaled data, the Shapiro-Wilk test was used to test for normal distribution. If the data was normally distributed, One-Way Repeated Measures ANOVA was performed and in case of violated sphericity, a Greenhouse-Geisser correction was applied. However, for data that was not normally distributed, Friedman's ANOVA was used. Furthermore, if the data did not satisfy the definition of being interval-scaled, Friedman test was used without performing the Shapiro-Wilk test. If Friedmann's ANOVA was significant, post hoc analysis was performed with Dunn-Bonferroni-Test. Thereby, an alpha level of 0.05 was assumed for all statistical tests. Additionally, the Bonferroni correction was used to adjust the alpha level to $(.05/3) \approx .016$ for pairwise comparisons. Sign test was used for ordinal data that compared two dependent data sets. Moreover, for not normally distributed data and ordinal-scaled but not interval-scale data, medians ($Mdn$) are reported. On the other hand, for normally distributed data, means ($M$) were reported. For the User-Experience-Questionnaire also means were reported since they are used in the official UEQ data analysis tool [49].

## 6.1 Performance (RQ1)

To study the *Performance*, task completion times and error rates were measured. Thereby, task completion time is defined as the sum of the time duration between pressing the button to highlight an object until the first object is moved. Since each of the five objects were searched three times, this makes up 15 individual search times. The different passes also allow comparing the search times of the three passes between each condition and within each condition. This could reveal intended learning effects. The error rate is defined with values of zero or one. If the first object moved after a new object is highlighted is also the intended target, the object is determined as being found correctly and the value 1 was assigned. Otherwise, the wrong object was selected and the value 0 was assigned.

### 6.1.1 Task completion times

The task completion times for the three conditions *Map*, *Halo*, and *Combination of Map and Halo* are shown in Figure 6.1. There was no statistically significant difference in task completion time for the three conditions ($F(2, 34) = 1.317$, $p = .281$). The means were $M_m = 84.074s$, $M_h = 93.788s$, $M_c = 93.053s$.

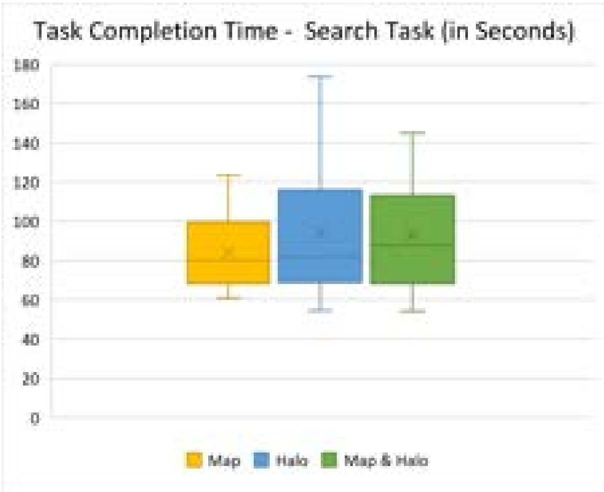


**Figure 6.1:** The task completion times of the search tasks in seconds are shown for the conditions *Map* (left), *Halo* (middle), and *Combination of Map and Halo* (right). Medians are shown as horizontal lines inside each box, and means are represented by crosses.

The task completion times, grouped by each pass are shown in Figure 6.2. There were no statistically significant differences in task completion times for the three different passes. In the *first pass* ($\chi^2(2) = 2.111$, $p = .348$) the medians were $Mdn_m = 31.377s$, $Mdn_h = 31.902s$, and $Mdn_c = 37.768s$. In the *second pass* ($\chi^2(2) = 1.444$, $p = .486$) the medians were $Mdn_m = 26.327s$, $Mdn_h = 29.075s$, and $Mdn_c = 26.962s$. And in the *third pass* ($\chi^2(2) = 0.778$, $p = .678$) the medians were $Mdn_m = 22.307s$, $Mdn_h = 23.128s$, and $Mdn_c = 23.578s$.


**Figure 6.2:** The task completion times of the search task in seconds are shown for the *first pass* (left), for the *second pass* (middle), and for the *third pass* (right). Medians are shown as horizontal lines inside each box and the means are represented by crosses.

The task completion times for each pass, grouped by visualization technique are shown in Figure 6.3. There were statistically significant differences in each condition.

For *Map* ($\chi^2(2) = 20.333$, $p < .001$), the task completion time in the *first pass* ($Mdn_1 = 31.377s$) was significantly longer compared to the *second pass* ($Mdn_2 = 26.327s, z = 1.500, p < .001$) and compared to the *third pass* ($Mdn_3 = 22.307s, z = 0.833, p = .037$).

For *Halo* ($\chi^2(2) = 30.333$, $p < .001$), the task completion time in the *first pass* ($Mdn_1 = 31.902s$) was significantly longer compared to the *second pass* ($Mdn_2 = 29.075s, z = 0.833, p = .037$) and compared to the *third pass* ($Mdn_3 = 23.128s, z = 1.833, p < .001$). Additionally, the *second pass* was significantly longer compared to the *third pass* ($z = 1.000, p < .008$).

For *Combination of Map and Halo* ($\chi^2(2) = 27.444, p < .001$), the task completion time in the *first pass* ($Mdn_1 = 37.768s$) was significantly longer compared to the*second pass* ($Mdn_2 = 26.962s, z = 1.722, p < .001$) and compared to the *third pass* ($Mdn_3 = 23.578s, z = 1.111, p = .003$).

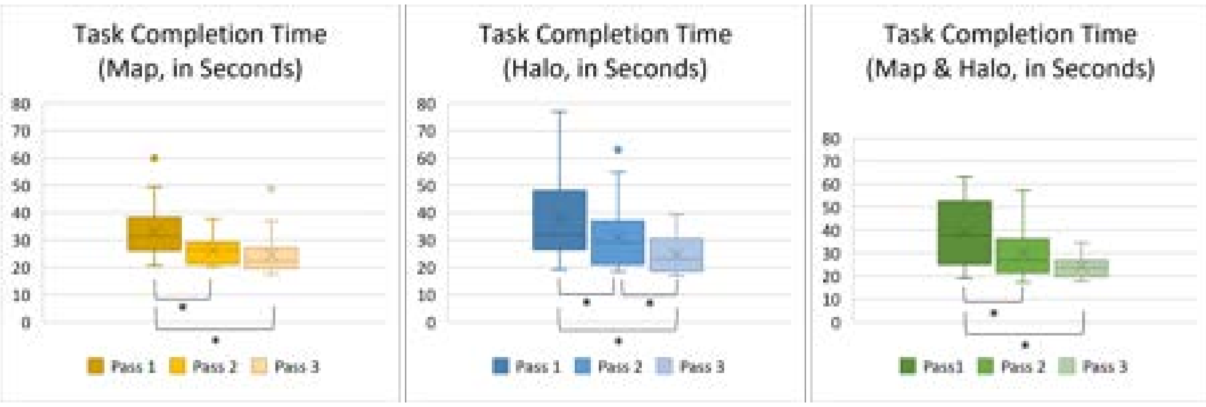


**Figure 6.3:** The task completion times of the search tasks for each pass for *Map* (left) , *Halo* (middle), and *Combination of Map and Halo* (right) are shown. Medians are shown as horizontal lines inside each box and means are represented by crosses. Significant differences are indicated by brackets with an asterisk next to it.

### 6.1.2 Error Rate

There were no significant differences in error rates between the conditions ($\chi^2(2) = 4.500$, $p = .105$). The error rates for each condition can be seen in Figure 6.4. Overall, 1.36% of the targets were not identified correctly. For *Map*, 0% of the targets were not identified correctly, for *Halo*, 1.75% were not identified correctly, and for *Combination of Map and Halo*, 2.22% were not identified correctly.

In the first object set $2.22\%$ of the objects were not identified correctly. In the second object set $1.11\%$ were not identified correctly, and in the third object set $0.74\%$ were not identified correctly.

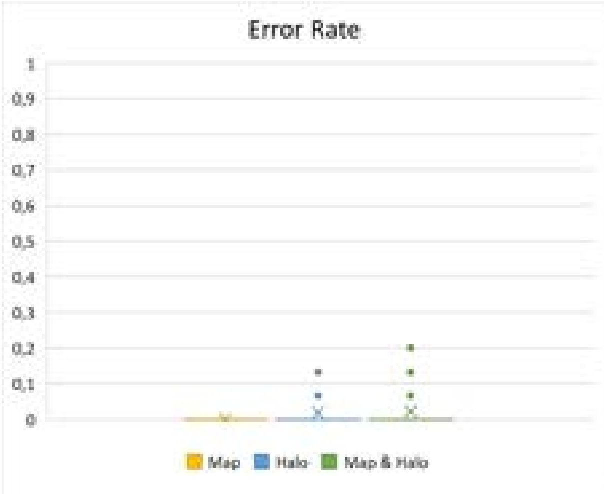


**Figure 6.4:** Error rates for the conditions *Map* (left), *Halo* (middle), and *Combination of Map and Halo* (right) are shown. Medians are shown as horizontal lines inside each box, and means are represented by crosses.

## 6.2 Spatial Memory (RQ2)

As aspects of *Spatial Memory*, distance and task completion time of the memory task was measured. Distance is defined as the distance in meter between the object's placement in the memory task and the object's placement in the search task. Task completion time is defined as the time to perform one memory condition, starting with pressing the button to make the first object visible, until the final movement of the last object.

### 6.2.1 Distance

The distances for all three conditions are shown in Figure 6.5. There were no statistically significant difference between the conditions ($\chi^2(2) = 2.111$, $p < .348$). The medians for each condition were $Mdn_m = .262m$, $Mdn_h = .272m$, and $Mdn_c = .278m$.

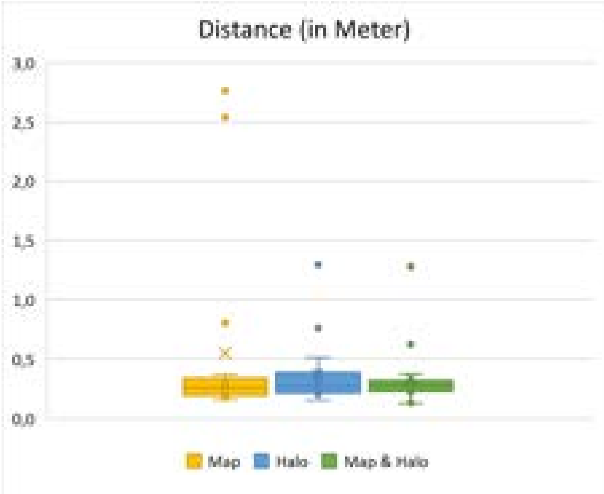


**Figure 6.5:** The distances between the object's placement in the search and memory task for the conditions *Map* (left), *Halo* (middle), and *Combination of Map and Halo* (right) are shown. Medians are shown as horizontal lines inside each box and means are represented by crosses.

### 6.2.2 Task Completion Time

The task completion times of the memory task for all three conditions are shown in Figure 6.6. There were no statistically significant differences between the conditions *Map*, *Halo*, and *Combination of Map and Halo* ($\chi^2(2) = .444$, $p = .801$). The medians for each condition were $Mdn_m = 59.077s$, $Mdn_h = 59.599s$, and $Mdn_c = 59.797s$.

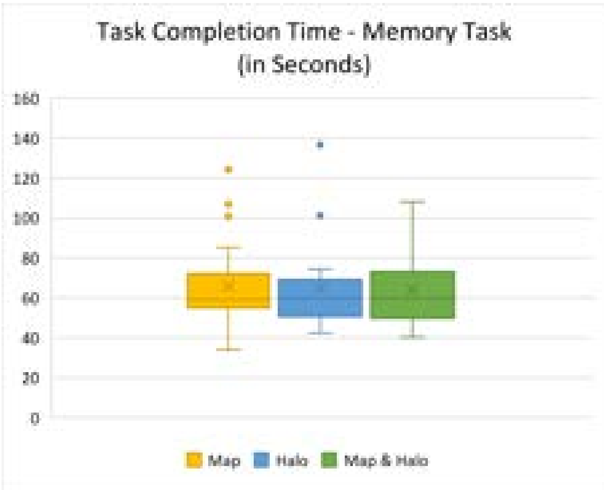


**Figure 6.6:** The task completion times of the memory tasks for the conditions *Map* (left), *Halo* (middle), and *Combination of Map and Halo* (right) are shown. Medians are shown as horizontal lines inside each box and means are represented by crosses.

## 6.3 Cognitive Load (RQ3)

To evaluate the *Cognitive load*, the NASA-TLX [48] was used without weighting. The scores can range from 0 to 100, with lower numbers indicating a lower task load. The overall scores can be seen in Figure 6.7. There was a statistically significant difference for the overall scores ($F(1.468, 24.954) = .488, p = .028$). However, the pairwise comparisons revealed no further statistically significant differences. The means were $M_m = 25.880$, $M_h = 28.704$, and $M_b = 28.148$.

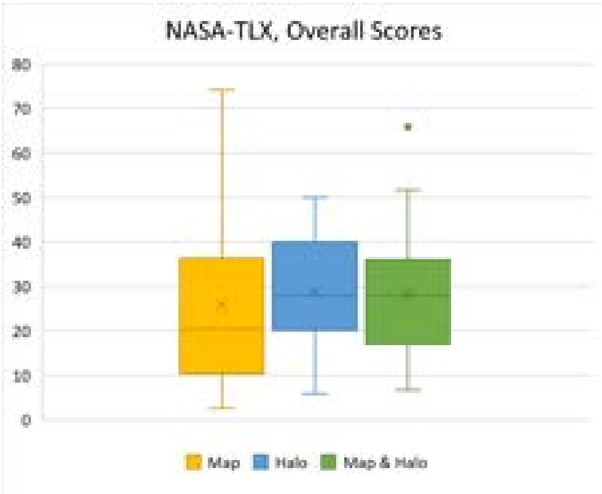


**Figure 6.7:** The overall scores of the NASA-TLX [48] for the conditions *Map* (left), *Halo* (middle), and *Combination of Map and Halo* (right) are shown. Medians are shown as horizontal lines inside each box and means are represented by crosses.

The individual dimensions of the NASA-TLX can be seen in Figure 6.8. There were also no significant difference for the individual dimensions.

For the dimension *Mental Demand* ($\chi^2(2) = 1.164$, $p = .559$) the medians were $Mdn_m = 25$, $Mdn_h = 35$, and $Mdn_c = 32.5$.

For the dimension *Physical Demand* ($\chi^2(2) = 4.978$, $p = .083$) the medians were $Mdn_m = 12.5$, $Mdn_h = 10$, and $Mdn_c = 10$.

For the dimension *Temporal Demand* ($\chi^2(2) = 0.441$, $p = .802$) the medians were $Mdn_m = 17.5$, $Mdn_h = 27.5$, and $Mdn_c = 25$.

For the dimension *Performance* ($\chi^2(2) = 3.633$, $p = .163$) the medians were $Mdn_m = 20$, $Mdn_h = 32.5$, and $Mdn_c = 25$.

For the dimension *Effort* ($\chi^2(2) = 3.46$, $p = .177$) the medians were $Mdn_m = 30$, $Mdn_h = 37.5$, and $Mdn_c = 25$.

Finally, for the dimension *Frustration* ($\chi^2(2) = 3.492$, $p = .175$) the medians were $Mdn_m = 10$, $Mdn_h = 22.5$, and $Mdn_c = 12.5$.

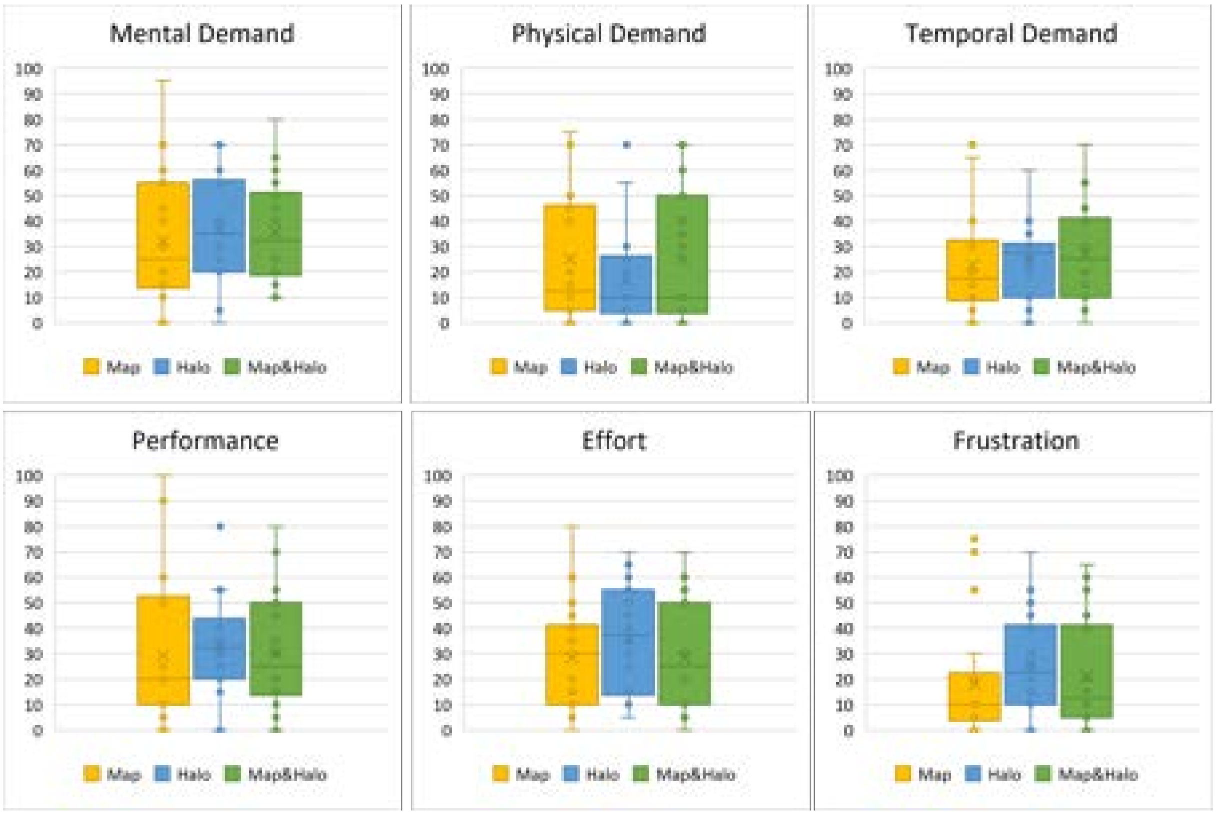


**Figure 6.8:** The NASA-TLX [48] scores for each dimension and grouped by condition are shown. Medians are shown as horizontal lines inside each box and means are represented by crosses.

## 6.4 User Experience (RQ4)

To assess the *User Experience*, the participants were asked to fill out the User-Experience-Questionnaire [49] (UEQ), as well as an additional questionnaire after each condition. Furthermore, after the third condition the participants were asked several questions in a semi-structured interview. All questions and questionnaires were answered and asked in German and translated to English for this thesis.

### 6.4.1 User-Experience-Questionnaire

The scores for the individual dimensions of the UEQ [49] can be seen in Figure 6.9. The scores can reach from $-3$ to 3, with higher values indicating a better user experience.

There was no statistically significant differences for *Attractiveness* ($\chi^2(2) = 1.284$, $p = .526$) with the means $M_m = 1.791$, and $M_h = 1.306$, $M_c = 1.398$.

There was no statistically significant differences for *Efficiency* ($\chi^2(2) = .925$, $p = .630$) with the means $M_m = 1.389$, $M_h = 1.042$, and $M_c = 1.042$.

There was no statistically significant differences for *Stimulation* ($\chi^2(2) = 1.733$, $p = .420$) with the means $M_m = 1.819$, $M_h = 1.681$, and $M_c = 1.681$.

There was no statistically significant differences for *Novelty* ($\chi^2(2) = 3.493$, $p = .174$) with the means $M_m = 1.056$, $M_h = 1.819$, and $M_c = 1.634$.

However, there were statistically significant differences for *Perspicuity* ($\chi^2(2) = 12.265$, $p = .002$). The value was significantly higher for *Map* ($M_m = 2.319$), compared to *Combination of Map and Halo* ($M_c = 1.208, z = 1.083, p = .003$) and *Halo* ($M_h = 1.125, z = 0.833, p = .037$).

There were also statistically significant differences for *Dependability* ($\chi^2(2) = 8.273, p = .016$). The values for *Map* ($M_m = 1.750$) were significantly higher than for *Combination of Map and Halo* ($M_c = 1.264 z = 0.917, p = .018$). The mean for Halo was $M_h = 1.083$.

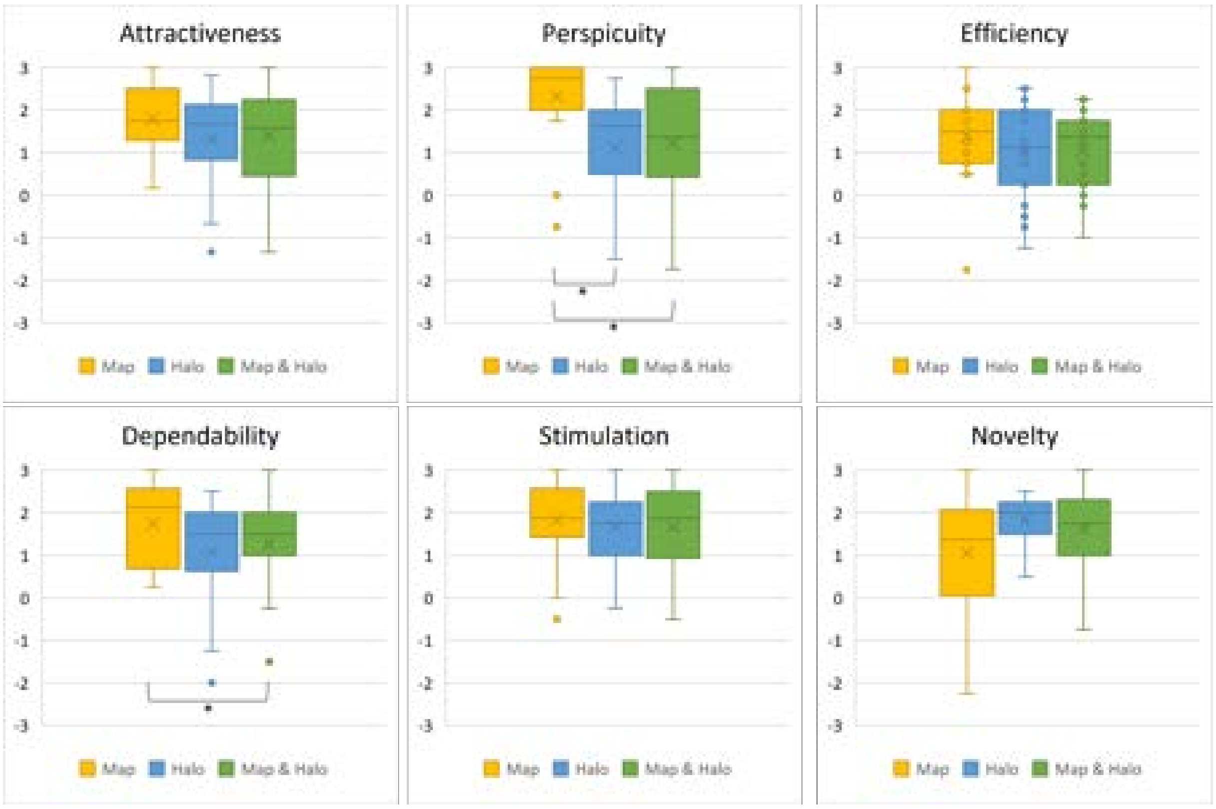


**Figure 6.9:** The UEQ scores for each dimension are shown. Medians are shown as horizontal lines inside each box and means are represented by the crosses. Significant differences are indicated by brackets with an asterisk next to it.

In Table 6.1, the qualities of the UEQ for each condition are shown. The values are taken from the UEQ data analysis tool [49]. Thereby, *Pragmatic Quality* includes the dimensions *Perspicuity*, *Efficiency*, and *Dependability* and refers to task related quality aspects. *Hedonic Quality* includes the dimensions *Stimulation* and *Novelty* and refers to the non-task related quality aspects. *Attractiveness* contains just the dimension *Attractiveness.* For all qualities the means are reported.

| | Map | Halo | Map and Halo |
|---|---|---|---|
| **Attractiveness** | 1.791 | 1.306 | 1.398 |
| **Pragmatic Quality** | 1.819 | 1.083 | 1.171 |
| **Hedonic Quality** | 1.438 | 1.750 | 1.657 |

**Table 6.1:** The means for *Attractiveness*, *Pragmatic Quality*, and *Hedonic Quality* for the conditions *Map*, *Halo*, and *Combination of Map and Halo* are shown.

The data analysis tool for the UEQ, provided by the authors, allows comparing the techniques to a benchmark data set consisting of 468 studies. In Figure 6.10 the benchmarks of the three visualization techniques are shown.

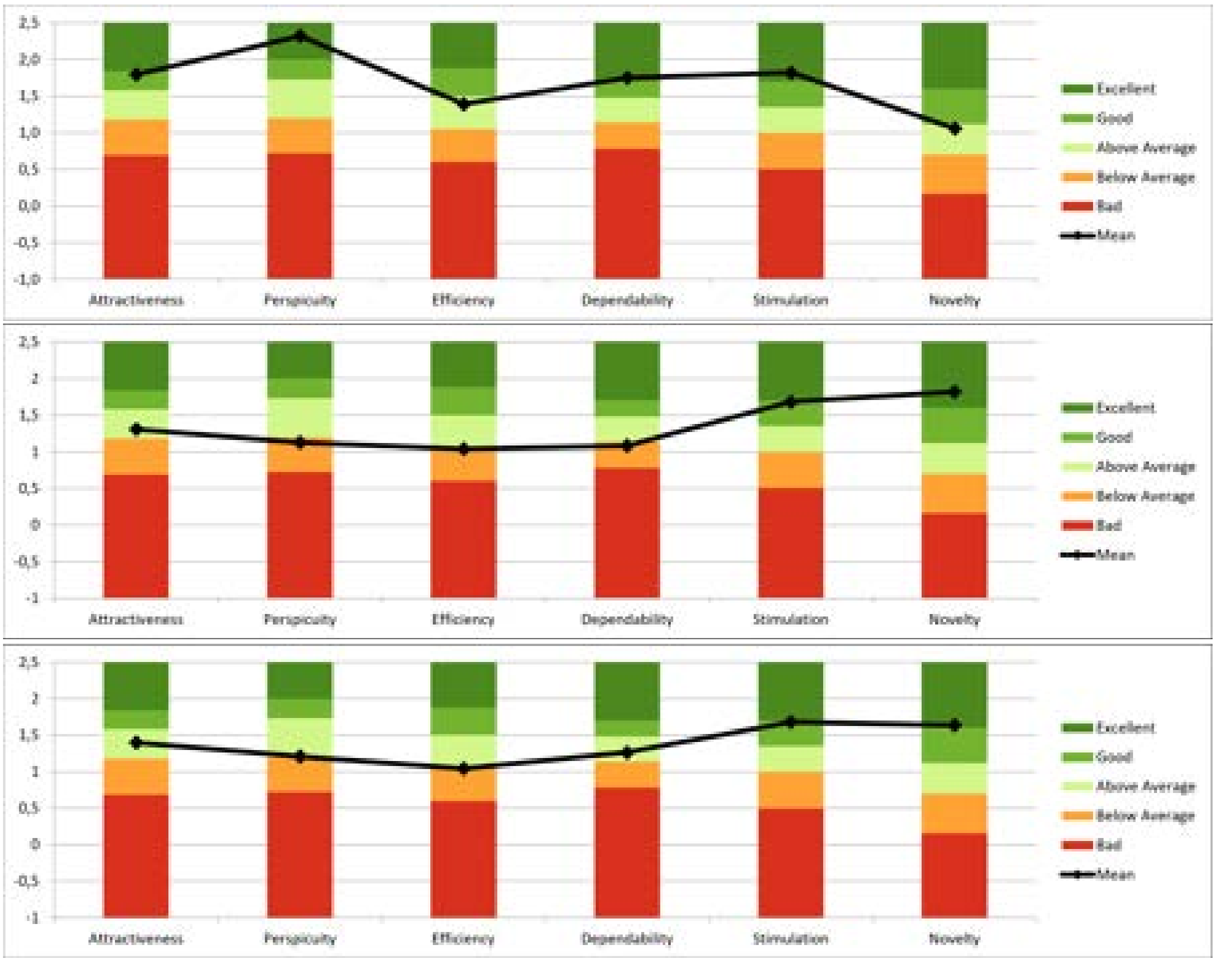


**Figure 6.10:** The means of the UEQ dimensions are shown in relation to benchmark data set. The visualization is taken from the official UEQ data analysis tool [49]. *Map* is shown on top, *Halo* in the middle, and *Combination of Map and Halo* on the bottom.

### 6.4.2 Map usage

As another indicator of *User Experience*, the amount of time spent using the map was measured. Since *Halo* contained no map, the evaluation was done for *Map* and *Combination of Map and Halo*. The map becomes visible if the participants' non-dominant hand is tracked by the MRTK [29] and invisible if the tracking is lost. Each time the map visibility changes, the value true or false was logged. To calculate the map usage in percent, the times in which the map was visible are added up and are then divided by the whole task completion time. The map usage was calculated in percent since each participant had individual task completion times in each condition. By calculating the percentage, the values become comparable. In this case, the task completion time, is defined as the time between pressing the button to highlight the first object until the first object is moved after highlighting the last target. These events were also used as start and end time in which the map visibility was tracked.

The map usage with *Map* was significantly higher compared to *Combination of Map and Halo* with $p < .001$. In the Map condition the median for using the map was $M_m = 38.749\%$ of the time, while with the Combination the median was $M_c = 16.815\%$. The values can also be seen in Figure 6.11.


**Figure 6.11:** The map usage is shown for the conditions *Map* (left) and *Combination of Map and Halo* (right). The value 1 represents a map usage during the whole task and a value of 0 indicates the map not being used at all. Medians are shown as horizontal lines inside each box and means are represented by crosses. Significant differences are indicated by brackets with an asterisk next to it.

### 6.4.3 Additional Questionnaire

The additional questionnaire, consisted of five questions. Each question contained a likert-scale with 5 possible answers from "very easy" to "very hard", or "easily recognizable" to "difficult to recognize", depending on the question. For statistical evaluation, the answers were translated to numbers from one to five (e.g., 1 for "very easy"). The scores for each dimension can be seen in Figure 6.12.

The Friedman test was significant for Question 1: "*How helpful was the visualization technique in finding the objects?*", but no statistically significant differences were found between the conditions ($\chi^2(2) = 6.118$, $p = .047$). The medians were $Mdn_m = 1$, $Mdn_h = 2$, and $Mdn_c = 1.5$.

There were significant differences for Question 2: "*How easy was it for you to understand how the visualization technique works?*" ($\chi^2(2) = 12.824, p = .002$). The score was significantly lower for *Map* ($Mdn_m = 1$) than for *Combination of Map and Halo* ($Mdn_3 = 2, z = -1, p = 0.008$). The median for Halo was $Mdn_h = 1.5$.

For the other questions no significant differences were found.

For Question 3: *"How easy was it for you to recognize which object is currently being searched for, with the help of the visualization technique?"* ($\chi^2(2) = 3.962$, $p = .138$) the medians were $Mdn_m = 1$, $Mdn_h = 2$, and $Mdn_c = 2$.

For Question 4: *"How easy was it for you to see where the object is placed in the room, with the help of the visualization technique?"* ($\chi^2(2) = 5.32$, $p = .070$) the medians were $Mdn_m = 1$, $Mdn_h = 2$, and $Mdn_c = 1$.

For Question 5: *"How easy was it for you to remember the objects' position?"* ($\chi^2(2) = 1.182$, $p = .554$) the medians were $Mdn_m = 2$, $Mdn_h = 2$, and $Mdn_c = 2$.

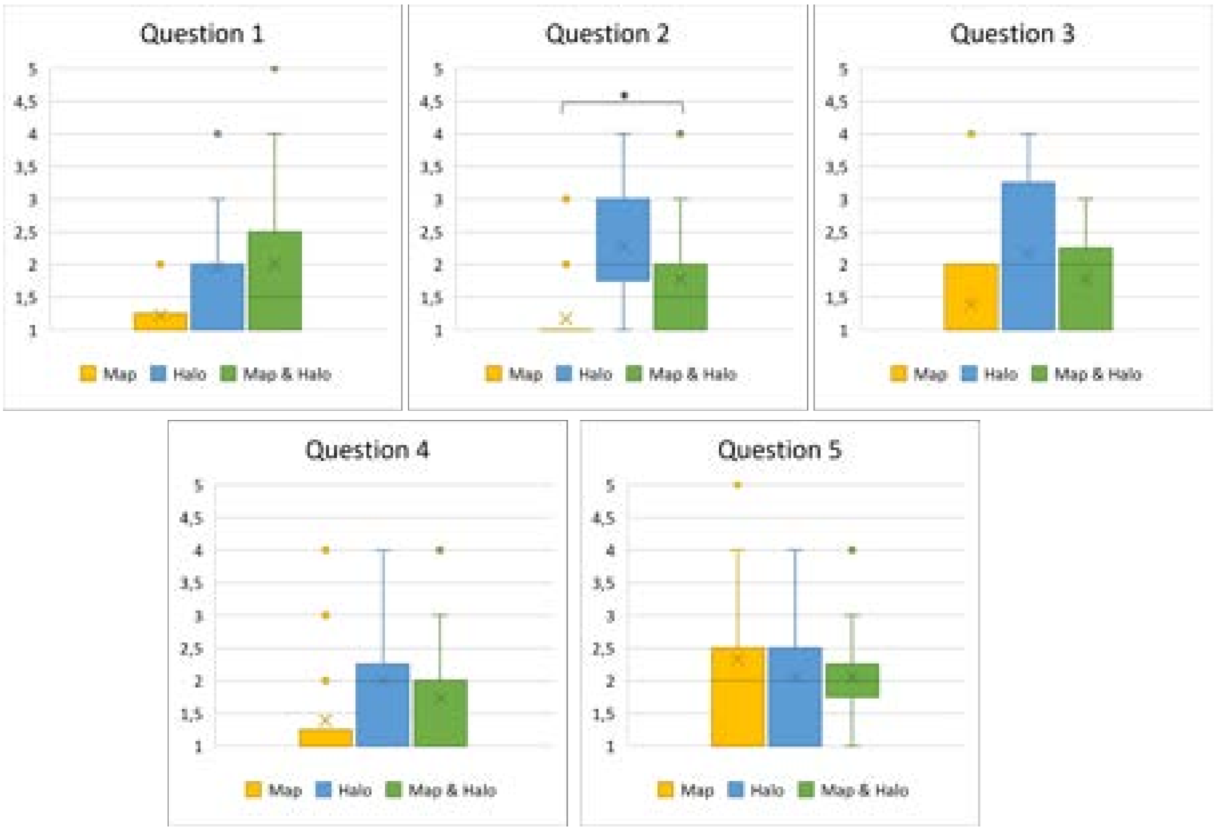


**Figure 6.12:** The scores for each question of the additional questionnaire are shown. Medians are shown as horizontal lines inside each box and means are represented by crosses.

Furthermore, the participants had the possibility to name objects that were easy or difficult to detect as being searched (Question 3), name objects that were easy or difficult to find (Question 4), and name objects that were easy or difficult to remember their position (Question 5). In Figure 6.2, Figure 6.3, and Figure 6.4 the amount of objects named for each category can be seen. In Figure 6.6, Figure 6.5, and Figure 6.7 the objects for each category grouped by object set are shown.

| Map | | | | | |
|---|---|---|---|---|---|
| Detect which object is searched | | Detect where the object is located | | Remember the objects' position | |
| Easy | Difficult | Easy | Difficult | Easy | Difficult |
| 6 | 3 | 3 | 2 | 9 | 8 |

**Table 6.2:** The amount of objects named for *Map* are shown.

| Halo | | | | | |
|---|---|---|---|---|---|
| Detect which object is searched | | Detect where the object is located | | Remember the objects' position | |
| Easy | Difficult | Easy | Difficult | Easy | Difficult |
| 4 | 6 | 2 | 5 | 17 | 6 |

**Table 6.3:** The amount of objects named for *Halo* are shown.

| Map und Halo | | | | | |
|---|---|---|---|---|---|
| Detect which object is searched | | Detect where the object is located | | Remember the objects' position | |
| Easy | Difficult | Easy | Difficult | Easy | Difficult |
| 10 | 7 | 8 | 4 | 16 | 14 |

**Table 6.4:** The amount of objects named for *Combination of Map and Halo* are shown.

| | Object Set 1 | | | | | |
|---|---|---|---|---|---|---|
| | Detect which object is searched | | Detect where the object is located | | Remember the objects' position | |
| | Easy | Difficult | Easy | Difficult | Easy | Difficult |
| **Cat** | 2 | 0 | 1 | 0 | 2 | 3 |
| **Football** | 6 | 1 | 3 | 0 | 2 | 1 |
| **Saxophone** | 0 | 2 | 2 | 0 | 3 | 3 |
| **Yellow Flowers** | 1 | 4 | 0 | 3 | 4 | 2 |
| **Camera** | 3 | 1 | 0 | 0 | 6 | 0 |
| **Sum:** | 12 | 8 | 6 | 3 | 17 | 9 |

**Table 6.5:** The amount of objects named for *Object Set 1* is shown.

| | Object Set 2 | | | | | |
|---|---|---|---|---|---|---|
| | Detect which object is searched | | Detect where the object is located | | Remember the objects' position | |
| | Easy | Difficult | Easy | Difficult | Easy | Difficult |
| **Basketball** | 2 | 0 | 1 | 0 | 3 | 4 |
| **Laptop** | 2 | 1 | 2 | 1 | 5 | 1 |
| **Cow** | 0 | 1 | 1 | 1 | 2 | 2 |
| **Rose** | 0 | 2 | 0 | 1 | 3 | 2 |
| **Guitar** | 1 | 0 | 1 | 1 | 1 | 2 |
| **Sum:** | 5 | 4 | 5 | 4 | 14 | 11 |

**Table 6.6:** The amount of objects named for *Object Set 2* is shown.

| | Object Set 3 | | | | | |
|---|---|---|---|---|---|---|
| | Detect which object is searched | | Detect where the object is located | | Remember the objects' position | |
| | **Easy** | **Difficult** | **Easy** | **Difficult** | **Easy** | **Difficult** |
| **Smartphone** | 1 | 0 | 0 | 0 | 4 | 0 |
| **Trumpet** | 1 | 1 | 0 | 2 | 4 | 1 |
| **Purple Flower** | 0 | 2 | 0 | 1 | 1 | 4 |
| **Dog** | 1 | 0 | 0 | 0 | 0 | 2 |
| **Tennis Racket** | 0 | 1 | 2 | 1 | 2 | 1 |
| **Sum:** | 3 | 4 | 2 | 4 | 11 | 8 |

**Table 6.7:** The amount of objects named for *Object Set 3* is shown.

### 6.4.4 Interview

After finishing the three conditions, the participants were asked some questions in a semi-structured interview. In the beginning, the participants were asked questions concerning the off-screen visualization technique *Map*. Afterwards, the same questions were asked for *Halo*. Furthermore, some questions concerning *Combination of Map and Halo* were asked. Finally, two general questions about the techniques followed. For *Map* and *Halo*, the participants were asked to name the advantages and disadvantages of the techniques and give suggestions for improvement. Additionally, they were asked whether the representation of the icons at the halos, the objects on the map, the avatar, and the map itself were understandable. They were also asked to describe the search process for each technique. Furthermore, the participants were asked whether they already knew the technique or a similar one. For *Combination of Map and Halo*, only the questions about the advantages, disadvantages, suggestions for improvements, and search process were asked, since the other questions were already covered with the individual techniques. As general questions, the participants should rank the different techniques. Additionally, they were asked if they have ideas for possible applications of the different techniques. In the following the given answers are summarised. Thereby, $n$ is used to state how many participants shared a specific opinion, and # is used with an appended number to indicate a statement from a specific participant.

**Advantages**

As advantages for *Map*, the participants liked that they directly had an overview ($n = 10$). For example, they mentioned having an overview of everything (#01), or that they could recognize where all objects are in one view (#06, #16). They also liked seeing their position in relation to the objects ($n = 6$). Additionally, it was mentioned that it was helpful that the table was displayed ($n = 2$). Furthermore, two participants stated that they liked the on-demand aspect and having no crowded field of view (#13)). Finally, participants mentioned some general positive sensations: two participants found *Map* to be intuitive(#01, #05). While other participants claimed that the map was clearly arranged ("übersichtlich", #05, #12, #15, #16), efficient (#13), and that it was easier to remember the positions, and to find the objects faster (#13).

As advantages for *Halo*, the participants liked that they could see the direction in which the object is placed ($n = 6$). Moreover, they also liked having no extra step, like lifting the hand ($n = 4$). Additionally, some also found it easier to identify which object is represented by the icons ($n = 2$). It was also mentioned that *Halo* directs the view ($n = 4$) as advantage. Furthermore, two participants mentioned that you can find objects faster (#08, #16). As general positive sensations participants mentioned that *Halo* is more interesting, innovative, and exciting (#01), very intuitive (#02), plausible (#02), and that the hints are always visible (#03).

As advantages for *Combination of Map and Halo*, using the map in the beginning as overview was mentioned ($n = 2$). However, another participant mentioned, they were using *Halo* in the beginning and *Map* if they could not find the object with *Halo* (#01). Additionally, some stated advantages were individual advantages for *Map* combined with individual advantages for *Halo* ($n = 6$). For example, it was mentioned that one can see directly what is searched with Halo but also have the better orientation of *Map* (#19). Furthermore, it was mentioned that *Map* provides a clear overview and *Halo* is fast (#08). Finally, three participants mentioned advantages of one technique, to help compensate for disadvantages of the other one, e.g., *Map* makes *Halo* clearer (#12), or with *Map* it is bypassed that objects are not detected when they are already in the field of view, which is the case for *Halo* (#11).

### Disadvantages

As main disadvantage when using *Map*, the need to raise the hand ($n = 9$) was mentioned. Additionally, three participants had trouble with the objects on the map, e.g., by finding them too small (#15, #06) or having trouble to identify the object when it is highlighted (#19). Some participants also struggled to identify the orientation of the avatar ($n = 2$), and two paticipants mentioned that they relied a lot on the map (#10, #17). Additionally, general negative sensations were mentioned: *Map* was found to be slower (#16), that the transformation is difficult (#10), that *Map* is not visible the whole time (#13), and that *Map* took too much space in the small field of view (#03).

For *Halo*, one disadvantage was that it is overloaded and too much is going on in the field of view ($n = 7$). Participant also mentioned overlapping icons as downside ($n = 4$) and that they did not understand how the technique works in beginning ($n = 5$). Additionally, they mentioned problems when the halo for the currently searched target was not visible, which was the case if the object is already in the field of view ($n = 4$). Some participants also found it hard to understand which object is currently highlighted ($n = 2$). Furthermore, it was mentioned that the depth and distance information is missing (#10). Some comments also regarded the spatial knowledge, e.g., participants stated that they could find the objects but had no imagination about the position in the room (#16), or that it was not possible to concentrate on the surrounding (#16), and that the distribution of all objects was not clear (#04). Finally, as general disadvantages, it was mentioned that *Halo* is jumbled (#06), unintuitive (#05), not intuitive at all (#01), confusing (#03), and that it was rather confusing (#05).

As disadvantages for *Combination of Map and Halo*, several participants mentioned the technique being overloaded, or there being too much information ($n = 7$). Four participants found that one technique would be enough, with two participant saying that only *Map* would be enough (#01, #05) and one participant saying that *Map* is not needed for the search task (#16). Additionally, two participant mentioned that the only disadvantages are the ones from *Halo* (#07, #12), while one participant mentioned only the individual drawbacks if *Map* as disadvantage (#11). Further comments were that with *Combination of Map and Halo* it was confusing to combine the two individual concepts (#19), and that *Halo* was used due to the overload (#13), or that *Halo* was used due to being overwhelmed (#04). Finally, it was mentioned that *Map* was only used to check the objects' positions for the memory task (#13, #16).

### Suggestions for Improvement

For *Map*, some participants suggested to make the orientation of the avatar clearer ($n = 4$), e.g., with an arrow or a triangle to indicate the viewing direction (#10). It was also suggested not to place the map on the hand ($n = 4$) and instead in the field of view with a button to lock it (#03), or in a corner in the field of view (#11). Additionally, it was suggested to show more details of the room ($n = 3$), e.g., the windows (#04). Furthermore, increasing the map size was suggested ($n = 2$), either by making the map bigger in general (#06), or by making it adjustable (#03).

As Suggestions for improvement for *Halo*, participants suggested changing the icons on the halos ($n = 6$), either by avoiding overlay (#07, #18), by distributing the items (#03, #06, #07, #12), or by omitting the items completely (#13). Other suggestions concerned the amount of information that is shown ($n = 7$), e.g., it was suggested to show only one halo at a time (#01, #13), or to show the other halos more transparent (#03). Additionally, only showing the halos that are placed on the same side of the display as the currently searched object was mentioned (#06). Furthermore, participants also suggested to improve the highlights ($n = 3$), e.g., by making the red lines stronger (#08), or by highlighting the object in the room, if it is visible in the field of view (#05, #11).

For *Combination of Map and Halo* it was suggested not to use both techniques at the same time. For example, three participants suggested to only use one technique. Furthermore, it was suggested to allow the user to turn on and off the individual techniques (#03), to show the map in the beginning and then the Halos (#04), or to let the user select objects on the map, an thereby toggle the individual halos (#13). Additionally, two participants suggested integrating the map into the display, e.g., in the corner of the display (#18). There were also suggestions to change the halo technique, e.g., by omitting the icons on the halos (#08), moving the halos further to the side (#15), or displaying only the halos on the right or left, depending on the side on which the red halo is positioned (#15). Moreover, it was mentioned that the technique is currently not meaningful (#13).

**Understandability**

Participants were asked whether the representation of the objects on the halos with icons was understandable. This was done because this property differentiated from the HaloAR technique [2]. Thereby, insights could be gathered whether this functionality is useful and was implemented reasonable. Five participants said that the icons are understandable, while seven participants mention the overlapping of the icons negatively. Furthermore, it was mentioned that the icons are not needed (#13), that the icons are less understandable compared to *Map* (#16), and that they could not be easily recognized, which was similar with *Map* (#17). Additionally, two participants also found the red coloring of the icons to not always be clear. On the other hand, it was also mentioned that the objects' shapes where easier to identify (#03).

For *Map* it was asked how easy it was to understand the representation of the avatar. Thereby, 14 Participants found this to be the case. However, three participants claimed that they did not pay attention to the avatar. Some participants were also unsure where the front and back of the avatar is ($n = 3$), and one participant found it complicated to understand the avatar in the beginning (#06).

Additionally, participants where asked whether the representation of the objects on the map was understandable. This was the case for most participants ($n = 16$). Furthermore, participant found it good that you can see the relation to one another (#04) and recognize the height of the objects (#03). Additionally, the cylinder was found to be good (#01). However, it was also mentioned that some objects where not easy to recognize ($n = 4$), that the objects were small (#15), and that the cylinder makes it harder to recognize the objects (#10).

When asked about the representation of the room itself, 17 participant found the representation to be understandable. It was mentioned, by seven participants, that the table was a helpful orientation. Additionally, it was found to be good that the walls are emphasized (#06), but representing more items would be helpful (#04).

**Search Process**

When describing the search process with *Map*, eight participants mentioned to use the map only shortly to look for the object and mentioned that they would go to object without using the map. Some also mentioned that the map was needed longer in beginning ($n = 3$). Additionally, some participants mentioned looking for additional information, like the avatars position, or whether the object is on the left or on the right. However, the additional information was rather diverse.

When using *Halo* many participants mentioned rotating there head first ($n = 7$), or looking whether the object is left or right ($n = 6$). Other statements were very diverse and no uniform pattern were seen.

With *Combination of Map and Halo* more than half of the participants described using the map first and that they would then follow the halos ($n = 10$). Other participants claimed to mostly have used *Halo* and that they only used *Map* when they could not immediately find the object with *Halo* (#1, #14), or that they would use *Map* only as overview (#16). Furthermore, three participants said that they only used the halos.

**Prior Experience**

When asked about prior experiences with map-like or halo-like techniques, no participant was familiar with map- or halo-like techniques in augmented reality. Maps in general where familiar to 13 participants. Furthermore, eight of them knew them from computer games. Additionally, it was claimed that participants know maps in the context of wayfinding, e.g., from bike tours (#16), hiking (#15), or amusement parks (#15). On the other hand, halo-like techniques were familiar to three participants (#10,#11,#13). Two of them knew the technique only in theory.

**Possible Application Areas:**

As possible application areas most proposals made use of *Map* and were applied in a room or building. For example, it was suggested to use maps in architecture to show objects in a room (#08), or for assessing a building and thereby seeing the layout of the building on the map (#10). Other participants suggested it might be helpful to furnish an apartment. Thereby the map could include furniture and the user could then select the object on the map to place them in the room (#12). Another participant also suggested using a map in an application similar to the app provided by Ikea to furnish a room (#03). Other proposals included using the map in a Hotel tour for easier orientation (#15), for shopping to find the desired departments (#18), or to find rooms in the university (#18). Additionally, it was mentioned that a map could help find beakers in a drawer (#05), or to show fire hydrants for firefighters (#13). Finally, it was suggested to use the application similar to google maps (#17).

There were also some proposals for *Halo*. One proposal was to use in in school, e.g., in chemistry. Thereby, in a game students could have to merge molecules. To do so, they have to find the correct molecules in the room, with the positions being indicated by halos (#02). Another proposal was to use the technique inside one room, or when few things need to be searched, e.g., find animals in a zoo (#10). Furthermore, using it to find something in an apothecary cabinet, which only requires 2D visualization was suggested (#13).

No explicit suggestions were made for *Combination of Map and Halo*.

### Ranking

In the interview the participants were asked to rank the visualization techniques *Map*, *Halo*, and *Combination of Map and Halo*. For statistical evaluation, the rankings were translated to values between one and three (e.g., 1 one for best and 3 for worst). The different rankings can be seen in Figure 6.13.

The Friedman test was significant ($\chi^2 = 6.778, p = .034$), but there were no significant difference in the pairwise comparisons. Between *Map* and *Combination of Map and Halo* the adjusted significance was $p = .091$, and between *Map* and *Halo* $p = .059$. The significance for *Halo* and *Combination of Map and Halo* was $p = 1$. The medians were $Mdn_m = 1$, $Mdn_h = 2$, and $Mdn_c = 2$.

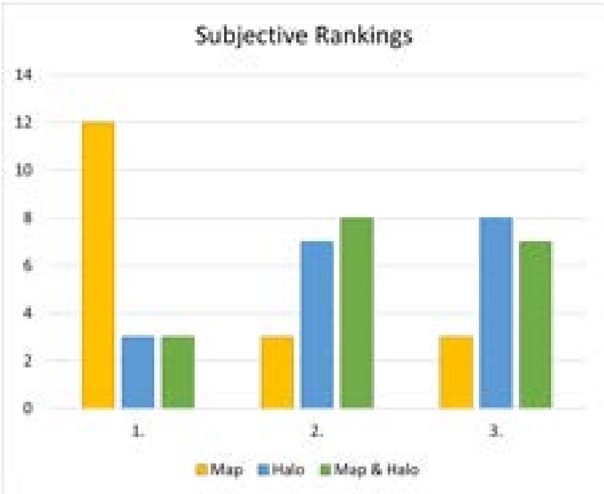


**Figure 6.13:** The rankings from the most preferred technique (1.) to the least preferred technique (3.) are shown for the conditions *Map*, *Halo*, and *Combination of Map and Halo*. The y-axis represents how many participants chose the rank for the visualization technique.

# 7 Discussion

In the following the study results and their meaning are discussed. The structure follows the order of the research questions.

## 7.1 Performance (RQ1)

In the search task no significant differences were found regarding task completion times between the conditions. Additionally, for each pass, no significant differences could be found between the conditions. And there were also no significant differences in error rates. The lack of differences indicates a fair comparison between the techniques.

Interestingly, longer task completion times for *Map* were expected due to the extra step to lift the hand and due to the mental translation needed to switch between the perspectives. However, this was not the case. There were no significant differences in task completion times between the conditions. Only one participant mentioned the transition between the views as a disadvantage (#10). Therefore it cannot be confirmed whether the mental translation influences the task completion time. Additionally, nine participants mentioned lifting their hands as a disadvantage. The lack of significant differences regarding task completion times between the conditions indicates that the mental translation and lifting the hand might either have a small influence on the task completion time, or it might influence the task completion time negatively, but other factors might compensate for it, e.g., the overview that *Map* provides, which was mentioned by ten participants, or seeing the objects position in relation to yourself, which was mentioned by six participants. Those advantages could influence the task completion time positively and therefore, compensate for negative influence of having to lift the hand first.

The lack of differences in task completion time between the conditions might also be influenced by drawbacks and benefits of the other techniques. For example, the overlapping of icons or the overloaded display with *Halo* and *Combination of Map and Halo* might negatively influence the task completion time, which was mentioned by four participants. Additionally, the longer time needed to understand *Halo* could negatively influence task completion time. Five participants mentioned this aspect. While *Halo* was a new concept to most participants, maps are a concept that 13 participants already knew. Therefore, familiarity could have positively influenced the task completion times with *Map*. However, *Halo* also shows the direction in which the object is placed (n=6) and no extra step to make the visualization technique visible is needed (n=4). All those individual benefits and drawbacks that might influence the task completion time positively or negatively and might have led to the overall lack of differences regarding task completion time in the search task.

Even though there are no differences in task completion time and error rate between the conditions, when comparing the individual passes within a condition, the second and third pass was always significantly shorter compared to the first pass. This implies an intended learning effect for all conditions. Furthermore, with *Halo*, there is additionally a significant improvement between the second and third pass, which was not the case for *Map* and *Combination of Map and Halo*. This indicates that the learning effect with *Halo* extends over a longer period of time. The different learning effect might be explained due to the longer time needed to understand how *Halo* works, which five participants mentioned. Therefore, it is possible that with more passes, the task completion time for *Halo* would decrease even more, which could result in significantly shorter task completion times.

Although there were no significant differences between the conditions, the overall low error rate of $1.36\%$ indicates good applicability of all techniques when low error rates are desired but some wrong picks are still tolerated. The lack of significant difference regarding the error rate between the conditions is also in line with the answers given in the additional questionnaire. For question 3 ("*How easy it is to identify which object is currently being searched?*") and question 4 ("*How easy it is to identify where the object is placed in the room?*") no significant difference occurred. This indicates a fair comparison of the techniques.

Furthermore, the participants had the possibility to name examples for objects that were easy or difficult to identify as being searched, or examples for objects that were easy or difficult to identify where they are placed in the room. It could be shown that the objects and object sets are overall comparable. For example, the *football* was often found to be easy to find and to identify that it is searched. On the other hand, the *yellow flower* was often found to be difficult to find and to identify that it is currently searched. This might be the case because the volume of the *football* is bigger compared to the volume of the *yellow flower*. However, other objects were also slightly bigger or smaller in volume. For example, the other *flowers* and the *saxophone* also had a smaller volume and the *basketball* had a bigger volume. But for those objects no accumulations could be found that indicate a negative or positive influence. The missing accumulations for other objects regarding positive or negative findings also indicates that the objects were comparable regarding finding their positions and understanding that they are currently searched.

When comparing the objects, named with each visualization technique, it was found that overall most objects were named with *Combination of Map and Halo* . Additionally, in most cases more objects were named in a positive context for all techniques. Only with *Halo*, for more objects it was found to be difficult to understand where they are positioned and to understand which object is highlighted. This is in line with disadvantages for *Halo*. For example that it was difficult to understand the technique in the beginning, which was mentioned by five participants, or that it was difficult to understand which object is highlighted, which was mentioned by two participants. Furthermore four participants found it difficult to identify the target if the halo disappeared because the object was already in the field of view.

With *Map*, the objects were always found correctly. This indicates that the map provides a high accuracy in identifying the correct objects and makes the visualization technique suitable for use cases requiring precise target detection.

With *Halo* and *Combination of Map and Halo* some objects were not identified correctly. This might be the case due to disadvantages of *Halo*. For example two participants mentioned, having trouble to identify which object is highlighted with *Halo*. Furthermore, other disadvantages like the overloaded field of view, which was mentioned by seven participants for *Halo* and by eleven participants for *Combination of Map and Halo* might also contribute to it.

## 7.2 Spatial Memory (RQ2)

In the memory task, no significant differences regarding distance and task completion time could be found between the conditions. This is in line with the subjective evaluation in the additional questionnaire for question 5 ("*How easy was it for you to remember the objects' position?*"), were no significant differences where found between the conditions. The missing difference between the conditions also indicates good comparability of the techniques.

Furthermore, when asked if objects were easy or difficult to remember, it could be shown that the objects were comparable. The position of the *camera* and *laptop* were often found to be easy to remember. It is assumed that this was the case because the objects were positioned next to the table. The additional context information provided by the surrounding might provide an advantage for remembering the position. However, the *purple flower* was also positioned next to the table and was found to be difficult to remember. Additionally, for other objects next to the table, no accumulations for remembering the positions were found. Therefore it is assumed, that the objects were comparable.

It was expected that there were statistically significant differences regarding spatial memory between the techniques. More precisely, it was expected that the overview of the room provided by *Map*, would result in better spatial cognition and therefore, in smaller distances or shorter task completion times. However, this was not the case. There were no significant differences in task completion time or distance between the conditions. A possible explanation for the lack of differences, is the small number of objects that are additionally searched three times. This makes it possibly easy to remember the objects' positions independent of the visualization technique. The overall small distances, with medians below 28 cm for all conditions supports the assumption that placing the objects near the original position in the search tasks was generally rather easy. However, when having to place a bigger amount of objects, there might still be a threshold above which a significant difference is observed. If this is the case, it is required to search for more than five objects.

Additionally, individual factors for each technique might influence the distance and task completion time in the memory task. For example, it was mentioned that participants relied on the map too much, and therefore did not have to deal with the room itself (#10, #17). Additionally, participants also said that when they were using *Halo*, it was more like searching, whereas when using *Map* they could see directly where the objects were. This could indicate that the participants had to think more about the objects placement in the search task with *Halo*, and might also indicate an advantage for *Map*, e.g., due to the overview provided by *Map*, which was mentioned by ten participants.

## 7.3 Cognitive Load (RQ3)

The statistical evaluation of the *Cognitive Load* with the NASA-TLX [48] showed no significant differences in all dimensions of the questionnaire. The overall score also showed no significant differences. Interestingly, it was expected that the map would result in a higher *Cognitive Load* due to switching between the ego- and exocentric viewpoint. However, this aspect was only mentioned by one participant (#10). Combined with the missing significant difference regarding the *Cognitive Load*, it can be assumed that *Map* does not affect the cognitive load negatively.

For *Physical Demand* also no significant difference was found. The medians for all conditions were between 10 and 12.5, which is rather low. However, nine participants mentioned, the need to lift the hand with *Map* as disadvantage. This is in line with the map having the highest median. But interestingly, the value is still rather small, and no significant difference was found, even though lifting the hand was mentioned as disadvantage. This indicates, that the influence on the physical demand due to the need of lifting the hand with *Map* is rather low.

Furthermore, the missing significance in *Temporal Demand* and *Performance* is in line with the missing significance in task completion time and error rate in the search task.

Even though disadvantages for each technique were mentioned in the interview, like the overload with *Halo* and with *Combination of Map and Halo*, or the longer time that is needed to understand *Halo*, no differences were found for *Mental Demand*, *Effort*, and *Frustration*. Combined with the missing differences in the other dimensions, this shows that *Map*, *Halo*, *Combination of Map and Halo* produce a similar cognitive load.

## 7.4 User Experience (RQ4)

The quantitative evaluation of the *User Experience* showed an overall positive evaluation for each technique. In the additional questionnaire the first question ("*How helpful was the visualization technique in finding the objects?*") implies that all techniques were helpful, with an average answer in all conditions between "very easy" and "rather easy". This is in line with the overall positive evaluation in the UEQ [49], where all means were above 1.0 and values above 0.8 are considered to be a positive evaluation. Furthermore, this is in line with the low error rates, small distances between the objects' placement in the memory and search task, and similar task completion times in the search and memory task. In the following more insights about the *User Experience* for the individual techniques will be given.

The most prominent indicator for *User Experience* is the ranking of the techniques. It also gives an overall impression about the user preference. Interestingly, there were no significant differences in the ranking between the conditions. However, 11 out of 18 participants preferred *Map* over the other techniques, this shows a clear preference for *Map*. Furthermore, this is in line with the scores in the UEQ [49]. While for most dimensions no significant differences were found, the dimension *Dependability* and *Perspicuity* scored significantly better with *Map*. A possible explanation is that the mental model of an overview map is already known, and therefore familiar to the participants, this could positively influence *Perspicuity*. Moreover, the on-demand aspect gives the user more freedom to decide when they want to use the map. This could have a positive impact on *Dependability*. Additionally, *Map* scored significantly better in the additional questionnaire for question 2 ("*How easy was it for you to understand how the visualization technique works?*"). This might also be related to the familiarity of the mental model of maps, which makes it easier to understand the technique.

Additionally, the benchmarks for the UEQ dimensions in the data analysis tool [49], shows that *Map* scored at least above average in all dimensions. Furthermore, *Map* has excellent *Perspicuity*, *Dependability*, and *Stimulation*, which means that the scores are in the best 10% compared to the benchmark data set. Combined with with a mean value of 1.8 in *Pragmatic Quality*, this implies a great user experience for *Map*. Furthermore, this is in line with the generally good performance with no error rate, and low distances in the memory task.

The interview showed that all techniques have strengths and weaknesses, some were clearly perceived by many participants, while there were also individual opinions that were very distinctive. With *Map* three key strengths could be identified. First, the map provides an overview. Second, one can not only see the objects on one view, but also the relations to each other, including your own position in the room. Finally, participants liked the table being shown on the map. It is assumed that Showing details in the room is useful to provide additional orientation. These strengths mentioned with *Map* refer to aspects that can not be provided by *Halo*. Namely, *Halo* does not provide an overview of the surrounding, and shows no details in the room, besides the hints about the virtual objects. Furthermore, it indicates the relation between oneself in the room and the objects, but does not indicate the relation on one view, and does not show the relations between the virtual content, the room itself, and the physical objects. The broad strengths of *Map* also go in line with the higher amount of application ideas named for *Map*. The diverse proposals indicate that *Map* is suitable in many use cases. This is in line with the versatile application areas identified by Danyluk et al. [23].

However, half of the participants also mentioned lifting their hand as disadvantage. The drawback of lifting the hand goes in line with the suggested improvement by participants to place the map somewhere else. While nine participants mentioned the placement of the map as disadvantage, only four participants suggested changing the placement. The need to lift the hand seems to have an impact on the participants due to how often it was mentioned negatively, but the missing significant difference regarding *Performance*, the overall preference in the ranking, and also the low values for *Physical Demand* in the NASA-TLX [48] indicate that the usability is still good. This might either be the case because the physical impact is negligible, or because other factors, like the identified strengths mentioned above, make up for the negative influence of lifting the hand. Other disadvantages seem to be the unclear avatar orientation, which was mentioned by three participants as disadvantage and by four participants as suggestion for improvement. Making the avatar rotation clearer could be achieved by making the avatar more detailed, or by indicating the view frustum. Indicating the view frustum was also suggested by Danyluk et al. as possible link between the map and the environment [23]. Thereby, indicating the view frustum would belong to their proposed dimension *links*.

Finally, the map usage gives insights about the usability of the on-demand aspect of *Map*. With *Map*, the median for using the map was lower than 40%. This implies that the visualization technique is not needed the whole time. The limited usage leads to less space being continuously occupied in the field of view and indicates that the on-demand aspect might be helpful. Nevertheless, the amount of time spent with the map visible in the field of view, could also be influenced by the need to lift the hand which was mentioned negatively. This could lead to using the map less. However, as mentioned above, the *Physical Demand*, which is also an indicator whether lifting the hand negatively affects the map usage, was not statistically higher compared to the other techniques. This indicates that the negative influence of lifting the hand to make it visible might not influence the amount of time spent with the map. Furthermore, the amount of time spent with the map being visible, is also in line with descriptions of the search process which indicate that the map is not needed the whole time. According to statements of eight participants, the map was mostly used to identify the object and its position, but walking to the object was mainly done without using the map.

While most participants preferred *Map*, *Halo* was preferred by three participants. For *Halo* main advantages seem to be that *Halo* directly indicates the direction, which was mentioned by six participants. Furthermore, this also includes seeing whether you have to turn left or right. This is in line with descriptions of the search process, where participants stated that they would first move their head until the object is in view. This was mentioned by seven participants. The description of rotating the head first was also described by Gruenefeld et al. [24]. They described the process of locating physical objects in two steps. The first step is understanding the head movement to bring the object in view and the second step is perceiving the location. Their description also fits the process described by the participants. Besides the mentioned advantages by the participants, the UEQ [49] shows an excellent score for *Novelty* and the *Hedonic Quality* of *Halo* is is also rather high with a mean score of 1.75. Possible explanations are that only three participants were familiar with a halo-like technique and two of them knew the technique only in theory. Therefore, *Halo* was a new concept to most participants, which makes it more interesting to use. This is also supported by general comments of the participants.

Besides the overall positive quantitative evaluation for all techniques, the dimensions *Perspicuity*, *Efficiency*, and *Dependability* scored below average for *Halo* in comparison to the benchmark data. *Perspicuity* was also statistically significant lower compared to *Map*. A possible explanation is that the time needed to understand *Halo* which was mentioned by five participants might influence *Perspicuity* negatively. Furthermore, the overload mentioned by seven participants, and the overlapping icons mentioned by four participants might influence *Perspicuity*, *Efficiency* and *Dependability* negatively. Interestingly, there was no significant difference in the additional questionnaire for question 2 ("*How easy was it for you to understand how the visualization technique works?*") between *Halo* and the other conditions. Furthermore, the median for question 2 in the additional questionnaire is "rather easy". This is interesting because five participants mentioned trouble to understand the technique in the beginning and the lower score for *Perspicuity* is in line with those arguments. However, the missing significance in the additional questionnaire for question 2, indicates that *Halo* might have been overall still relatively easy to understand. Another disadvantage, which was mentioned by four participants was that it was difficult to understand which object is highlighted when the halo is not visible, because the object is already inside the current field of view. As solution, two participants suggested highlighting the object in the room when it is visible in the field of view. This suggestion is similar to the in-view visualization technique proposed by Gruenefeld et al. [5]. Their developed technique showed that the in-view visualization reduced error rates. Furthermore, the suggestions of the participant in the study for this thesis, also indicate that using an in-view visualization might help selecting the correct object.

The mentioned weaknesses and proposals for application areas of *Halo* indicate that the use cases in which *Halo* is beneficial, are more limited than for *Map*. The possible application ideas mentioned by the participants concentrated on a more narrow space compared to the application suggestions for *Map*. Additionally, it was even suggested to use *Halo* only when information in two dimensions is needed. Furthermore, the perceived clutter with *Halo* also implies showing less information or fewer halos in general. This narrows down the possible use cases further. Moreover, the clutter with the *Halo* technique developed in this thesis is also in line with findings of previous halo approaches [1, 2]. They also found halo-techniques to easily get clutter and suggested to use as few halos as possible simultaneously.

Similar to *Halo*, also three participants preferred *Combination of Map and Halo*. The strengths that were mentioned for *Combination of Map and Halo* were either advantages of the individual techniques, which was mentioned by six participants, or strengths of one technique to compensate for the drawbacks of another technique, which was mentioned by three participants. Additionally, three participants mentioned that they can use one technique and then switch to another one, which was found to be beneficial.

In the Benchmark comparison *Combination of Map and Halo* scored below average in the dimension *Efficiency*, the other dimensions scored at least above average. Statistically significant differences occurred in the UEQ for *Dependability*, and *Perspicuity*. Thereby, *Map* scored significantly better than *Combination of Map and Halo*. Possible explanations can be found in the interview. For example, seven participants mentioned that *Combination of Map and Halo* is overloaded, which might influence the *Dependability* and *Perspicuity*. The overload might come from having two techniques visible at the same time. However, also the individual *Halo* technique suffered from being overloaded, this was mentioned by seven participants. Therefore, it is not clear whether the combination itself would be overloaded if the individual techniques were not already overloaded. This is in line with the combination of an in-view and an out-of view visualization technique developed by Gruenefeld et al. [5]. They also found that their combination suffered from being cluttered, which was also the case for the individual out-of-view technique. Besides the overload as disadvantage, four participants suggested to only use one technique at a time. The proposals on how to do this were very divers. For example, it was suggested to use only one technique in general, or to show the map only in the beginning. Furthermore, it was suggested to give the user the possibility to toggle which *Halos* should be shown, or reduce the information of the halos by omitting the icons. The proposed suggestion imply reducing the amount of information shown simultaneously, and are in line with the disadvantage of the technique being overloaded. Furthermore, the suggestions are in line with the findings in the related work. For example, the suggestion to show the map only in the beginning has parallels to the approach of differentiating between coarse and fine navigation and show only one technique at a time [6]. However, the suggestions for *Combination of Map and Halo* did not differentiate between an angular distance. The suggested differentiation would be between providing an overview and guiding the user to the object. This is also in line with the findings by Gruenefeld et al. [5]. They claim that when it is known in which of two techniques the participant is currently interested, only this visualization technique is required to stay active. Additionally, the suggestions to reduce the amount of information presented by the halos, e.g., by omitting the icons on the halos, is also supported by Gruenefeld et al. [5]. For their proposed combination they suggested to reduce the amount of information shown by the out-of-view technique.

The overload and the suggestions for improvement, which suggest far-reaching changes indicate that the current implementation of *Combination of Map and Halo* cannot outperform the individual techniques, and that adjustments must be made to provide an advantage in combining two techniques compared to the single techniques.

An additional aspect of *User Experience* is the amount of time in which the participants used the map. The map was used significantly shorter with *Combination of Map and Halo* than with *Map*. Since two techniques were used simultaneously, it was expected that the map would not be used more with *Combination of Map and Halo* compared to the single *Map* condition. This is in line with the measured data. Additionally, the significantly less usage with *Combination of Map and Halo* is in line with the described search process. It was mentioned that the map was often only used in the beginning to get an overview and then halo was used afterwards. This description is in line with the mentioned strengths of *Map* to provide an overview, and the strength of *Halo* to directly guide the view towards the target. A possible explanation for the low amount of map usage is also the overload of information with *Combination of Map and Halo*. When using the map, the halos are still visible in the field of view, which leads to more space being occupied in the field of view. Therefore, it might also be the case that participants would like to use the map more, but the overload made it not helpful because the field of view was too crowded. Other possible explanations for the lower usage is the effort to perform the extra step to lift the hand. The effort to lift the hand to make the map visible might be too big, when the visualization technique *Halo*is already shown. However, it cannot not be fully clarified whether the need to lift the hand effects the amount of time spent with the map being visible.

## 7.5 Limitations and Future Work

Different factors limit the generalizability of the user study. One limitation is the design of the techniques itself, e.g, the chosen design dimensions for *Map*. The chosen design limits the generalizability. Furthermore, choosing the design of the techniques differently might lead to different findings. This can be seen in the strengths and weaknesses that were shown in the interview for each technique. For example choosing a different avatar design that also indicates the viewing direction could help eliminate the disadvantage of not understanding the users rotation.

Additionally, the choice of the visualization techniques itself could influence how the techniques are evaluated. For example it was seen that advantages and disadvantages for one technique were mentioned in relation to the other techniques. Therefore, comparing different techniques could reveal other strengths and weaknesses in relation to the other technique. Furthermore, combining different techniques could results in different advantages and disadvantages. Nevertheless, it could be interesting to investigate different individual techniques and also combine those techniques. Since few research in combining several techniques was preformed but the existing research seems promising. Additionally, it was shown that a combination can help to compensate for disadvantages of the other technique and complement the advantages of the additional technique. Therefore, further research about combining off-screen visualization techniques would give more insights about their usability.

A different study procedure could also influence the outcome. For example, if the order of memory task and answering questionnaires was different, or if different questions and questionnaires were used. Furthermore, the limited study procedure also includes the choice of objects, their placement in the room, their height, and the amount of objects used in total. For Example, using more objects, with different distributions could increase error rates, or the distance between the objects placement in the memory and search task could increase with more objects. The amount of objects in the study was limited due to the *Halo* technique. If this constraint can be bypassed, further research in spatial memory using maps is interesting, to investigate whether there is an advantage in spacial memory for *Map* when more objects are present.

Another factor is the limited amount of participants, with 18 participants in total. Additionally the age range is limited, with all participants being between 19 and 27 years old, and all participants having an academic background. Thereby, the study outcome could differ for participants with different backgrounds or different ages. Additionally, two participants had dyschromatopsia. However, no one of these participants mentioned having trouble to identify anything but it cannot be excluded that this might effect the study. Another factor that could limit the study, are gender effects. However, the study was conducted with 10 female and 8 male participants, this is almost balanced, which reduces the risk of influences due to the participants gender. Another factor that might influence the study is the prior experience, while many where familiar with maps, only few knew the concept of halo-like approaches. Further research seems especially interesting concerning the experience of the participants, since it was also mentioned in the related work that the study outcome could differ for experienced and inexperienced users [14]. In the context of this study, most participants were familiar with the mental model of maps, but only three knew the halo-like approaches. Investigating the techniques with the same level of experience for the techniques might show another study outcome.

Finally, the study is limited due to the choice of the device. As hardware the HoloLens 2 was used, therefore, all study results are only valid for this device. For example, the HoloLens 2 has a small field of view, which also limits the size of the map and the distribution of the halos. Using a different device with a different field of view could influence the study outcome. This is also indicated by Gruenefeld et al. [2]. They found HaloVR to perform better than HaloAR due to the bigger field of view. It is assumed that *Halo* could result in less clutter with a bigger field of view. Furthermore, lifting the hand to view *Map* could be perceived less negatively if the devices' display would be bigger and the user would not have to lift the hand as much as with the current implementation.

# 8 Conclusion and Outlook

This thesis showed that off-screen visualization techniques are helpful tools to improve spatial awareness on mixed reality head-mounted displays. The help is especially relevant due to the small field of view on those devices. When analyzing related work, it was shown that 3D overview maps and halo-based approaches are promising techniques with relevance for XR research [23, 2]. Furthermore, advantages in combining several techniques could be shown. Therefore, in this thesis, three off-screen visualization techniques were compared to get insights into their usability for augmented reality head-mounted displays. Namely, the techniques were 1) *Map*, 2) *Halo*, and 3) *Combination of Map and Halo*.

A study was conducted with 18 participants to compare the three techniques regarding *Performance* (RQ1), *Spatial Memory* (RQ2), *Cognitive Load* (RQ3), and *User Experience* (RQ4). The study revealed no significant differences between the techniques in *Performance* (RQ1), *Spatial Memory* (RQ2), and *Cognitive Load* (RQ3). However, *Map* scored better for *User Experience* (RQ4).

Overall, *Map* was subjectively found to be best, with 11 out of 18 participants preferring *Map*. The study showed that *Map* has advantages by providing an overview of the environment. Furthermore, the preference for *Map* and the diverse information provided by the technique suggests using *Map* for most use cases.

On the other hand, *Halo* performed objectively as good as *Map*. Furthermore, it was found to have an advantage by indicating the direction towards the objects and immediately directing the gaze to the desired object. However, it should also be considered that *Halo* is harder to understand for inexperienced users and a longer time to get used to the technique might be needed. Additionally, clutter was also found to be a problem. Therefore, *Halo* was found to be suitable when immediately indicating the direction towards an object is needed, but only a few objects need to be visualized simultaneously.

*Combination of Map and Halo* was found to objectively perform as good as *Halo* and *Map*. Viewed subjectively, participants liked the advantages of both individual techniques, but they also found the technique to be overloaded. Therefore, the current implementation of *Combination of Map and Halo* could not outperform the individual techniques *Map* and *Halo*.

The study aimed to compare the three off-screen visualization techniques and find individual strengths and weaknesses. Furthermore, the study showed limitations, and unused potential of each technique, which makes further research interesting. For example, to investigate using a higher number of objects and a different distribution of the objects. This could also include occluded objects to further investigate the capabilities of the spatial memory with *Map*. Additionally, studying different designs of the individual techniques could improve the techniques further. For example, investigating different placements of *Map*, or exploring solutions to indicate the object's appearance with *Halo* while preventing clutter and occluded objects. And finally, further research for combining several techniques seems promising since it was shown that a combination can help to compensate for disadvantages of the other technique and complement the advantages of the additional technique. Since most participants preferred *Map*, while *Halo* and *Combination of Map and Halo* were found to be overloaded, it could be interesting to investigate a technique that combines a map with another technique that occupies less space in the field of view, and additionally, investigate mechanisms to switch between the techniques when only one technique is needed.

# References


[1] Patrick Baudisch and Ruth Rosenholtz. “Halo: A Technique for Visualizing off-Screen Objects”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’03. New York, NY, USA: Association for Computing Machinery, 2003, 481–488. DOI: 10.1145/642611.642695 (cited on pages i, 1, 5, 7, 8, 9, 15, 20, 22, 52).

[2] Uwe Gruenefeld et al. “Beyond Halo and Wedge: Visualizing out-of-View Objects on Head-Mounted Virtual and Augmented Reality Devices”. In: MobileHCI ’18. Barcelona, Spain: Association for Computing Machinery, 2018. DOI: 10.1145/3229434.3229438 (cited on pages 1, 3, 8, 9, 10, 13, 15, 20, 21, 22, 44, 52, 54, 55).

[3] *Microsoft HoloLens 2*. https://www.microsoft.com/de-de/hololens. (accessed August 29, 2022) (cited on pages 1, 4, 16).

[4] Sean Gustafson et al. “Wedge: Clutter-Free Visualization of off-Screen Locations”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’08. Florence, Italy: Association for Computing Machinery, 2008, 787–796. DOI: 10.1145/1357054.1357179 (cited on pages 1, 5, 8, 9, 10, 15, 22).

[5] Uwe Gruenefeld, Lars Prädel, and Wilko Heuten. “Locating nearby physical objects in augmented reality”. In: *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia*. 2019, pp. 1–10 (cited on pages 1, 13, 14, 15, 22, 51, 52).

[6] Philipp Hein, Max Bernhagen, and Angelika C Bullinger. “Two is Better Than One. Improved Attention Guiding in AR by Combining Techniques”. In: *IEEE Computer Graphics and Applications* 40.5 (2020), pp. 57–66 (cited on pages 1, 14, 15, 52).

[7] Paul Milgram and Fumio Kishino. “A Taxonomy of Mixed Reality Visual Displays”. In: *IEICE Trans. Information Systems* vol. E77-D, no. 12 (Dec. 1994), pp. 1321–1329 (cited on pages 3, 13).

[8] Hans Strasburger, Ingo Rentschler, and Martin Jüttner. “Peripheral vision and pattern recognition: A review”. In: *Journal of Vision* 11.5 (Dec. 2011), pp. 13–13. DOI: 10.1167/11.5.13 (cited on page 3).

[9] *HoloLens 2’s Field of View Revealed*. https://uploadvr.com/hololens-2-field-of-view/. (accessed August 29, 2022) (cited on pages 3, 4).

[10] *Varjo XR-3*. https://varjo.com/products/xr-3/. (accessed August 29, 2022) (cited on pages 3, 16).

[11] *Oculus Quest 2 FOV and Comparison With Other Headsets*. https://smartglasseshub.com/oculus-quest-2-fov/. (accessed August 29, 2022) (cited on page 4).

[12] *What makes Pimax so immersive?* https://pimax.com/de/8kx-tech-specs/. (accessed August 29, 2022) (cited on page 4).

[13] Franziska Trueb. *Seminar to the Bachelor Project "3D Overview Map as Off-screen Visualization for Mixed Reality Head-mounted Displays"*. 2021 (cited on page 5).

[14] Stefano Burigat and Luca Chittaro. “Navigation in 3D virtual environments: Effects of user experience and location-pointing navigation aids”. In: *International Journal of Human-Computer Studies* 65.11 (2007), pp. 945–958. DOI: https://doi.org/10.1016/j.ijhcs.2007.07.003 (cited on pages 5, 6, 7, 15, 53).

[15] Teresa Siu and Valeria Herskovic. “SidebARs: Improving Awareness of off-Screen Elements in Mobile Augmented Reality”. In: *Proceedings of the 2013 Chilean Conference on Human - Computer Interaction*. ChileCHI ’13. Temuco, Chile: Association for Computing Machinery, 2013, 36–41. DOI: 10.1145/2535597.2535608 (cited on pages 5, 6, 7).

[16] Inger Ekman and Petri Lankoski. “What Should It Do? Key Isssues in Navigation Interface Design for Small Screen Devices”. In: *CHI ’02 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’02. Minneapolis, Minnesota, USA: Association for Computing Machinery, 2002, 622–623. DOI: 10.1145/506443.506514 (cited on pages 7, 15).

[17] Uwe Gruenefeld et al. “Visualizing Out-of-View Objects in Head-Mounted Augmented Reality”. In: MobileHCI ’17. Vienna, Austria: Association for Computing Machinery, 2017. DOI: 10.1145/3098279.3122124 (cited on pages 9, 15, 20).

[18] Hyungeun Jo et al. “Aroundplot: Focus+context interface for off-screen objects in 3D environments”. In: *Computers & Graphics* 35.4 (2011). Semantic 3D Media and Content, pp. 841–853. DOI: https://doi.org/10.1016/j.cag.2011.04.005 (cited on pages 10, 11, 15).

[19] Randy Pausch et al. “Navigation and Locomotion in Virtual Worlds via Flight into Hand-Held Miniatures”. In: *Proceedings of the 22nd Annual Conference on Computer Graphics and Interactive Techniques*. SIGGRAPH ’95. New York, NY, USA: Association for Computing Machinery, 1995, 399–400. ISBN: 0897917014. DOI: 10.1145/218380.218495. URL: https://doi.org/10.1145/218380.218495 (cited on page 12).

[20] Alessandro Mulloni, Hartmut Seichter, and Dieter Schmalstieg. “Indoor Navigation with Mixed Reality World-in-Miniature Views and Sparse Localization on Mobile Devices”. In: *Proceedings of the International Working Conference on Advanced Visual Interfaces*. AVI ’12. Capri Island, Italy: Association for Computing Machinery, 2012, 212–215. ISBN: 9781450312875. DOI: 10.1145/2254556.2254595. URL: https://doi.org/10.1145/2254556.2254595 (cited on page 12).

[21] Tobias Höllerer et al. “User interface management techniques for collaborative mobile augmented reality”. In: *Computers Graphics* 25.5 (2001). Mixed realities - beyond conventions, pp. 799–810. ISSN: 0097-8493. DOI: https://doi.org/10.1016/S0097-8493(01)00122-4. URL: https://www.sciencedirect.com/science/article/pii/S0097849301001224 (cited on page 12).

[22] Richard Stoakley, Matthew J. Conway, and Randy Pausch. “Virtual Reality on a WIM: Interactive Worlds in Miniature”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’95. Denver, Colorado, USA: ACM Press/Addison-Wesley Publishing Co., 1995, 265–272. DOI: 10.1145/223904.223938 (cited on page 11).

[23] Kurtis Danyluk et al. “A Design Space Exploration of Worlds in Miniature”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI ’21. Yokohama, Japan: Association for Computing Machinery, 2021. DOI: 10.1145/3411764.3445098 (cited on pages 11, 12, 13, 15, 16, 17, 50, 51, 55).

[24] Uwe Gruenefeld et al. “Eyesee360: Designing a visualization technique for out-of-view objects in head-mounted augmented reality”. In: *Proceedings of the 5th symposium on spatial user interaction*. 2017, pp. 109–118 (cited on pages 13, 51).

[25] Frank Biocca et al. “Attention funnel: omnidirectional 3D cursor for mobile augmented reality platforms”. In: *Proceedings of the SIGCHI conference on Human Factors in computing systems*. 2006, pp. 1115–1122 (cited on page 14).

[26] Patrick Renner and Thies Pfeiffer. “Attention guiding techniques using peripheral vision and eye tracking for feedback in augmented-reality-based assistance systems”. In: *2017 IEEE symposium on 3D user interfaces (3DUI)*. IEEE. 2017, pp. 186–194 (cited on page 14).

[27] Patrick Perea, Denis Morand, and Laurence Nigay. “[POSTER] Halo3D: A Technique for Visualizing Off-Screen Points of Interest in Mobile Augmented Reality”. In: *2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)*. 2017, pp. 170–175. DOI: 10.1109/ISMAR-Adjunct.2017.58 (cited on page 15).

[28] *Webiste of Unity3D*. https://unity3d.com/de/get-unity/download. (accessed August 29, 2022) (cited on page 16).

[29] *GitHub link to the Mixed Reality Toolkit for Unity3D*. https://github.com/Microsoft/MixedRealityToolkit-Unity. (accessed August 29, 2022) (cited on pages 16, 39).

[30] *Webiste of Vuforia Engine.* https://developer.vuforia.com/. (accessed August 29, 2022) (cited on page 16).

[31] *GitLab link to the Room-Marker Plugin, provided by the HCI group.* https://gitlab.inf.uni-konstanz.de/ag-hci/research/room-marker. (accessed January 15, 2022) (cited on page 16).

[32] *Unity model of media room.* https://gitlab.inf.uni-konstanz.de/ag-hci/research/mediaroom. (accessed August 23, 2022) (cited on page 16).

[33] *Football.* https://sketchfab.com/3d-models/football-072a7e8d610f4143aa510256112d97cf. (accessed August 23, 2022) (cited on page 16).

[34] *Basketball.* https://sketchfab.com/3d-models/basketball-e3c719662981472f8479031a074bc727. (accessed August 23, 2022) (cited on page 16).

[35] *Tennis racket.* https://sketchfab.com/3d-models/tennis-racket-c314dcce06ba488ca624957f579b8196. (accessed August 23, 2022) (cited on page 16).

[36] *Camera.* https://sketchfab.com/3d-models/instax-mini-8-instant-camera-606912cf09074dcbb35f6c4a3842d528. (accessed August 23, 2022) (cited on page 16).

[37] *Laptop.* https://assetstore.unity.com/packages/3d/props/electronics/hq-laptop-computer-42030. (accessed August 23, 2022) (cited on page 16).

[38] *Smartphone.* https://assetstore.unity.com/packages/3d/props/electronics/free-smartphone-90324. (accessed August 23, 2022) (cited on page 16).

[39] *Flowers.* https://sketchfab.com/3d-models/colored-flower-6b3020fed29c4976bc44ed1b7cb7e960. (accessed August 23, 2022) (cited on page 16).

[40] *Rose.* https://sketchfab.com/3d-models/red-rose-74520e87c3ed46898668c83356dd9cfa. (accessed August 23, 2022) (cited on page 16).

[41] *Cat.* https://sketchfab.com/3d-models/cat-3d-f21a51cb652f478bb4621c7e94a065cf. (accessed August 23, 2022) (cited on page 16).

[42] *Cow.* https://sketchfab.com/3d-models/cow-99d333e3b4e4470a8d7d38436489c001. (accessed August 23, 2022) (cited on page 16).

[43] *Dog.* https://sketchfab.com/3d-models/dog-a89b49b3d9c647a8805d8d5287f47f48. (accessed August 23, 2022) (cited on page 16).

[44] *Guitar.* https://sketchfab.com/3d-models/guitar-a44930f9c14544a6ae6967d5544417e8. (accessed August 23, 2022) (cited on page 16).

[45] *Saxophone.* https://sketchfab.com/3d-models/saxophone-f72747715883480b9555a75558b3e9cd. (accessed August 23, 2022) (cited on page 16).

[46] *Trumpet.* https://sketchfab.com/3d-models/trumpet-3f2d4f5b962340b2933012e1bc634d88. (accessed August 23, 2022) (cited on page 16).

[47] *GitHub link to the HaloAR code provided by Uwe Gruenefeld.* https://github.com/UweGruenefeld/OutOfView. (accessed August 29, 2022) (cited on pages 16, 20).

[48] Sandra G Hart and Lowell E Staveland. "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research". In: *Advances in psychology.* Vol. 52. Elsevier, 1988, pp. 139–183 (cited on pages 28, 35, 36, 49, 50).

[49] *User-Experience Questionnaire.* https://www.ueq-online.org/. (accessed August 23, 2022) (cited on pages 28, 30, 36, 37, 38, 50, 51).

# Appendix

### Content of Attached USB Stick

The attached USB stick contains the following data:

- Seminar to the Bachelor Project
- Bachelor Project Report
- A Digital version of this thesis
- Documents used in the study
- Data gathered during the study

Furthermore, the source code of the developed techniques that were subject of the study can be found under: `https://gitlab.inf.uni-konstanz.de/ag-hci/student-projects/bsc-trueb/laptop/-/tree/studySecondTry`

## Welcome Letter

# Herzlich willkommen!

Vielen Dank, dass Sie sich dazu bereit erklärt haben, an unserer Studie teilzunehmen und uns damit in unserer Arbeit wertvoll unterstützen. Bevor es losgeht, möchten wir Ihnen kurz vermitteln, um was es bei der Untersuchung geht und welche Rolle Sie dabei spielen.

**Ziele und Ablauf der Studie**

In der Studie geht es darum Visualisierungstechniken zu untersuchen, die verschiedene Hinweise über die Position von virtuellen Objekten in einem Raum geben.

Der Ablauf der Studie gestaltet sich wie folgt: Nach dem Unterschreiben der Einwilligungserklärung werden Sie gebeten einen Fragebogen auszufüllen, in dem Fragen zu Ihrer Person gestellt werden.

Im Anschluss gibt es eine Übungsaufgabe um die Interaktion mit virtuellen Objekten kennen zu lernen. Danach wird es drei Durchläufe geben, die immer ähnlich aufgebaut sind: jeder Durchgang beginnt mit einer weiteren kurzen Übungsaufgabe, um mit der jeweiligen Visualisierungstechnik vertraut zu werden. Rückfragen können in diesem Zeitraum gerne gestellt werden. Im Anschluss an diese Übungsaufgabe wird die eigentliche Aufgabe gestellt. Dabei müssen zuerst Objekte mit dem System gesucht werden. Danach müssen diese Objekte möglichst genau an den Positionen platziert werden, an denen sie sich zuvor befanden. Wir bitten Sie, die Aufgabe gewissenhaft und in möglichst kurzer Zeit auszuführen. Wir möchten hier noch einmal darauf hinweisen, dass wir nicht Sie oder Ihre Leistung bewerten möchten, sondern an der Tauglichkeit des Systems zur Aufgabendurchführung interessiert sind. Wir möchten Sie bitten, Fragen zur Nutzung des Systems entweder vor oder nach der eigentlichen Aufgabendurchführung zu stellen. Am Ende jedes Durchgangs bitten wir Sie, einen kurzen Fragebogen auszufüllen.

Am Ende der drei Durchgänge werden Sie noch einmal gebeten, uns in einem abschließenden **Interview** Ihre Einschätzungen mitzuteilen.

Um möglichst umfassende Erkenntnisse zu erhalten, wird die Studie zusätzlich in Bild und Ton aufgezeichnet. Für diese Aufzeichnungen ist Ihr Einverständnis erforderlich. Im Gegenzug verpflichten wir uns dazu, das Material pseudonymisiert und lediglich zu Auswertungszwecken zu verwenden. In diesem Zusammenhang haben wir eine Einverständniserklärung vorbereitet, die diesem Schreiben beiliegt.

**Zeitrahmen und Entlohnung**

Die Dauer der Studie beträgt insgesamt ca. 1 Stunde. Falls Sie sich zu irgendeinem Zeitpunkt unwohl fühlen und Ihre Teilnahme beenden möchten, ist das selbstverständlich auch ohne Angabe von Gründen möglich. Bitte wenden Sie sich dann an den Versuchsleiter.

Nach der Durchführung der Studie werden Sie für Ihre Hilfe mit 10 Euro entlohnt. Wir wünschen Ihnen jetzt gutes Gelingen und bedanken uns noch einmal recht herzlich für Ihre Unterstützung!

## Consent Form

# Einverständniserklärung

ID: ______

**Informationen zur Studienleitung**

Studienleiter: Franziska Trüb
Institution: Arbeitsgruppe Mensch-Computer Interaktion, Fachbereich Informatik und Informationswissenschaft, Universität Konstanz

**Erklärung**

Über das Ziel, den Inhalt und die Dauer der Studie wurde ich informiert. Im Rahmen dieser Studie werden in Fragebögen personenbezogene Daten erhoben. Zusätzlich wird die Studie auf Video aufgezeichnet, es werden Audioaufnahmen gemacht und Bewegungsdaten erfasst.

Hiermit bin ich darüber aufgeklärt, dass die personenbezogenen Daten vertraulich behandelt werden. Die Ergebnisse der Analyse der Video-, Audio- und Bewegungsdaten werden eventuell in späteren Publikationen pseudonymisiert veröffentlicht. Wir garantieren dabei absolute Diskretion. Es wird zu keinem Zeitpunkt Rückschluss auf Sie als Person möglich sein.

**Optional** *(Bei Zustimmung bitte ankreuzen)*

☐ Ich bin damit einverstanden, dass meine Videodaten zusätzlich zu internen Präsentationszwecken genutzt werden können.

Hiermit erkläre ich mich mit den unter „Erklärung“ genannten Punkten und den angekreuzten optionalen Punkten einverstanden:

| | Konstanz, | |
|---|---|---|
| (Name) | (Ort, Datum) | (Unterschrift) |

Hiermit verpflichtet sich die Studienleitung, die Video- und Audioaufzeichnung sowie sämtliche sonstigen gewonnenen Daten lediglich zu Auswertungszwecken im Rahmen dieser Untersuchung zu verwenden:

| Franziska Trüb | Konstanz, | |
|---|---|---|
| (Name) | (Ort, Datum) | (Unterschrift) |

## Demographic Questionnaire

# Demographischer Fragebogen                ID: ______

## 1.Personenbezogene Daten

Alter: ______ Jahre

Geschlecht: [ ] männlich [ ] weiblich [ ] divers

Bist du Student*in? [ ] ja [ ] nein

Falls ja, was studierst du und in welchem Semester?

______________________________________________________________________

Falls nein, was ist deine momentane Tätigkeit/ Beruf?

______________________________________________________________________

Benutzt du eine Sehhilfe? [ ] ja [ ] nein

Falls ja, trägst du überwiegend… [ ] eine Brille [ ] Kontaktlinsen [ ] beides

Falls ja, welche Art von Sehschwäche hast du?

[ ] Kurzsichtigkeit – wie stark? _____________

[ ] Weitsichtigkeit – wie stark? _____________

[ ] Sonstiges: ___________________________

Hast du eine Farbfehlsichtigkeit? (z.B. Rot-Grün-Schwäche)

Falls, ja welche? _______________________________________

Bist du…?

[ ] Linkshänder [ ] Rechtshänder [ ] Beides [ ] Weiß nicht

## 2. Vorerfahrungen – Augmented Reality **ID: ______**

Hast du schon mal eine Augmented Reality Brille verwendet? [ ] ja [ ] nein

Hast du bereits Erfahrung mit Augmented Reality Anwendungen? [ ] ja [ ] nein

Wie vertraut bist du mit der Verwendung von Aumented Reality?

[ ] sehr vertraut

[ ] vertraut

[ ] etwas vertraut

[ ] eher nicht vertraut

[ ] überhaupt nicht vertraut

Mit welchen Augmented Reality Anwendungen konntest du bisher Erfahrungen sammeln?

[ ] Smartphone AR

[ ] Tablet AR

[ ] Head-Mounted-Displays (AR Brillen)

[ ] andere: ____________________________________________________________

## Additional Questionnaire

### Fragen zu Map

1. Wie hilfreich war die Map bei der Suche nach den Objekten?

   [ ] sehr hilfreich [ ] eher hilfreich [ ] weder noch [ ] eher nicht hilfreich [ ] gar nicht hilfreich

2. Wie leicht fiel es dir die Funktionsweise der Map zu verstehen?

   [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

3. Wie leicht fiel es dir mit der Map zu erkennen, welches Objekt gerade gesucht ist?

   [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

   Gab es Objekte die leichter zu erkennen waren? ____________________

   Gab es Objekte die schwerer zu erkennen waren? ____________________

4. Wie leicht fiel es dir mit der Map zu erkennen, wo sich die Objekte im Raum befinden?

   [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

   Gab es Objekte die leichter zu erkennen waren? ____________________

   Gab es Objekte die schwerer zu erkennen waren? ____________________

5. Wie leicht fiel es dir dich an die Positionen der Objekte zu erinnern?

   [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

   Gab es Objekte, an die du dich leichter erinnern konntest? ____________________

   Gab es Objekte, an die du dich schlechter erinnern konntest? ____________________

## Fragen zu Halo

6. Wie hilfreich waren die Halos bei der Suche nach den Objekten?

   [ ] sehr hilfreich [ ] eher hilfreich [ ] weder noch [ ] eher nicht hilfreich [ ] gar nicht hilfreich

7. Wie leicht fiel es dir die Funktionsweise der Halos zu verstehen?

   [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

8. Wie leicht fiel es dir mit den Halos zu erkennen, welches Objekt gerade gesucht ist?

   [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

   Gab es Objekte die leichter zu erkennen waren? ________________________________

   Gab es Objekte die schwerer zu erkennen waren? ________________________________

9. Wie leicht fiel es dir mit den Halos zu erkennen, wo sich die Objekte im Raum befinden?

   [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

   Gab es Objekte die leichter zu erkennen waren? ________________________________

   Gab es Objekte die schwerer zu erkennen waren? ________________________________

10. Wie leicht fiel es dir dich an die Positionen der Objekte zu erinnern?

    [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

    Gab es Objekte, an die du dich leichter erinnern konntest? ___________________________

    Gab es Objekte, an die du dich schlechter erinnern konntest? __________________________

### Fragen zu <u>Kombination aus Map & Halo</u>

11. Wie hilfreich war die Kombination aus Map und Halo bei der Suche nach den Objekten?

    [ ] sehr hilfreich [ ] eher hilfreich [ ] weder noch [ ] eher nicht hilfreich [ ] gar nicht hilfreich

12. Wie leicht fiel es dir die Funktionsweise der Kombination aus Map und Halo zu verstehen?

    [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

13. Wie leicht fiel es dir mit der Kombination aus Map und Halo zu erkennen, welches Objekt gerade gesucht ist?

    [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

    Gab es Objekte die leichter zu erkennen waren? ______________________________

    Gab es Objekte die schwerer zu erkennen waren? ______________________________

14. Wie leicht fiel es dir mit der Kombination aus Map und Halo zu erkennen, wo sich die Objekte im Raum befinden?

    [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

    Gab es Objekte die leichter zu erkennen waren? ______________________________

    Gab es Objekte die schwerer zu erkennen waren? ______________________________

15. Wie leicht fiel es dir dich an die Positionen der Objekte zu erinnern?

    [ ] sehr leicht [ ] eher leicht [ ] weder noch [ ] eher schwer [ ] sehr schwer

    Gab es Objekte, an die du dich leichter erinnern konntest? _________________________

    Gab es Objekte, an die du dich schlechter erinnern konntest? _______________________

## Questions for Interview

### Fragen für Interview

Fragen zu Verschiedenen Techniken & Runden, also Map und Halo Technik und der Kombination.
Beginnen mit Fragen zur Map.

#### Interviewfragen zu Map

1. Welche **Vorteile** hat die Map deiner Meinung nach?

2. Welche **Nachteile** hat die Map deiner Meinung nach?

3. War die **Darstellung** des Avatars, der Objekte auf der Map, und die Darstellung des Raum selbst **verständlich**?

4. Wie bist du bei der Suche mit Hilfe der Map vorgegangen? Beschreibe den **Suchprozess**.

5. Hast du **Vorschläge** wie die Map **verbessert** werden könnte, um die Suche zu erleichtern?

6. Hast du bereits **Erfahrungen** mit Techniken, die der eben getesteten Map ähneln?

## Interviewfragen zu Halo

1. Welche **Vorteile** haben die Halos deiner Meinung nach?
2. Welche **Nachteile** haben die Halos deiner Meinung nach?
3. War die **Darstellung** der Objekte an den Halos **verständlich**?
4. Wie bist du bei der Suche mit Hilfe der Halos vorgegangen? Beschreibe den **Suchprozess**.
5. Hast du **Vorschläge** wie die Halos **verbessert** werden könnte, um die Suche zu erleichtern?
6. Hast du bereits **Erfahrungen** mit Halos oder ähnlichen Techniken?

## Interviewfragen zu <u>Kombination aus Map & Halo</u>

1. Welche **Vorteile** hat die Kombination aus Map & Halo deiner Meinung nach?

2. Welche **Nachteile** hat die Kombination aus Map & Halo deiner Meinung nach?

3. Wie bist du bei der Suche mit Hilfe der Kombination aus Map & Halo vorgegangen? Beschreibe den **Suchprozess**.

4. Hast du **Vorschläge** wie die Kombination aus Map & Halo **verbessert** werden könnte, um die Suche zu erleichtern?

## Fragen <u>Allgemein</u>

1. Ordne die Techniken „Map", „Halo" und „Kombination aus Halo & Map" ein. Welche Technik fandest du am besten, welche am schlechtesten und begründe.

2. Hast du Ideen für **Einsatzmöglichkeiten** der Techniken, also Map, Halo und Kombination aus Map und Halo?

3. Weitere Bemerkungen?