Bachelor Thesis

3D User Interaction in Mobile Augmented Reality Games

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Declaration

I declare that this bachelor thesis was composed by myself, that the work contained herein is my own, except where explicitly stated otherwise in the text.

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Abstract

Interest in Augmented and Virtual Reality has been growing strongly in recent years. With the development of new devices, improved tracking techniques and displays the technology is about to reach a mature state. Leading software companies are investing in new Augmented and Virtual Reality products, which are about to reach public markets within the next months and years. Modern smartphones and tablets do already contain the necessary software and hardware to realize mobile Augmented Reality applications, such as Augmented Reality games. Augmented Reality technology opens up new spaces for innovative and immersive games that lead to new exciting ways of playing. As a relatively new technology Augmented Reality still faces challenges that require new solutions. One area that requires more exploration is the field of 3D interaction in augmented environments. This thesis presents and evaluates interaction metaphors, designed for mobile handheld Augmented Reality games. Two different concepts of a directly controlled 3D cursor are used to select, rotate and position objects in 3D space – a small magnetic sphere and an UFO with a tractor beam. The developed metaphors are applicable to games of different genres and even though the evaluation results revealed some ergonomic issues, both techniques were reported by the testers as being fun to play with.

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List of Abbreviations

AR	Augmented Reality
DoF	Degree of Freedom
GEQ	Game Experience Questionnaire
HARUS	Handheld Augmented Reality Usability Scale
HCI	Human-Computer Interaction
HMD	Head-Mounted Display
MMORPG	Massive Multiplayer Online Role-Playing Game
MR	Mixed Reality
NASA TLX	NASA Task Load Index
SUS	System Usability Scale
UX	User Experience
VR	Virtual Reality

1 Introduction

The idea of Augmented Reality (AR) and Virtual Reality (VR) dates back to the pioneering work of Ivan Sutherland in 1968 [42]. Both AR and VR applications enable the interactive and spatial experience of virtual content, such as images and sounds. In AR the virtual elements are presented in addition to the real environment, whereas VR seeks to replace the real world with virtual stimuli. In 1968 the technology was not yet ready to support a convincing mixed reality experience. But during the recent years the technical advances, accompanied by large investments from Google[1,2], Microsoft[3], Facebook[4], Qualcomm[5] and others, have led to a growing public interest in AR and VR. Following this development of new devices and software tools various early commercial applications are starting to emerge.

AR and VR could be a great step in the field of Human-Computer Interaction (HCI). The technology creates the illusion of virtual content being located in 3D space, instead of existing only within the limits of a screen area. Together with properly adapted 3D User Interfaces, this spatial visualization might open new ways to more direct and natural interactions and play a role in reaching the vision of ubiquitous computing. Many applications are likely to benefit from such a development, but the immersive character of AR and VR environments particularly draws attention from the game industry. In fact, games belong to the main applications that drive innovation for AR, VR and 3D UIs. VR games eliminate the player's perception of the real world, offering a very immersive experience. AR, in contrast, does not separate users from their environment and will, therefore, probably have a wider scope of application, including mobile games. AR and VR are still facing many challenges, but also profit from rapid technical improvements, such as the development of smartphones and tablet computers or new tracking and display technologies. Research on 3D UIs has been rather slow in comparison, but the development of new suitable interaction techniques is essential for the success of AR and VR applications.

[1] http://www.theverge.com/2014/10/21/7026889/magic-leap-google-leads-542-million-investment-in-augmented-reality-startup
[2] https://www.google.com/glass/start/
[3] https://www.microsoft.com/microsoft-hololens/en-us
[4] http://www.businessinsider.com/facebook-to-buy-oculus-rift-for-2-billion-2014-3?IR=T
[5] https://www.qualcomm.com/products/vuforia
Accessed on September 1, 2015.

To enable the development of immersive mobile AR games, this thesis explores the design space of 3D user interaction for handheld devices. It presents the relevant background information about AR technology, 3D UIs and game experience. An overview on related research and games illustrates the current state of handheld AR games. From there, the thesis introduces own concepts of 3D interaction techniques, developed for mobile handheld AR games. The concepts focus on basic object manipulation tasks, such as selection, positioning and rotation. The designed interaction metaphors are implemented, using the cross-platform mobile development tool Unity[6]. Qualcomm's AR library Vuforia[7] is used to perform the marker-based tracking and registration. Mobile devices are chosen as technical platform for two main reasons – first, their broad user base and second, their unique combination of sensors, computing power and display technology, which enables AR applications without the need for additional hardware. The developed prototypes are evaluated through informal tests and a formal user study.

[6] http://unity3d.com/
[7] https://developer.vuforia.com/
Accessed on September 9, 2015.

2 Background

The topic of this thesis intersects with the research areas of AR technology, 3D interaction and game experience. The following sections contain basic concepts, definitions, and references to more detailed examinations and related works from the fields of handheld AR and AR games.

2.1 Augmented Reality

Explaining AR without mentioning VR would offer only a constricted view on the topic. AR and VR are closely related. They motivate similar research directions, such as 3D interaction, tracking and display technologies. Milgram's Mixed Reality continuum [31] describes AR and VR as two regions on the same scale with AR lying closer to the Real Environment and VR closer to the Virtual Environment endpoint of the scale (**Figure 1**).

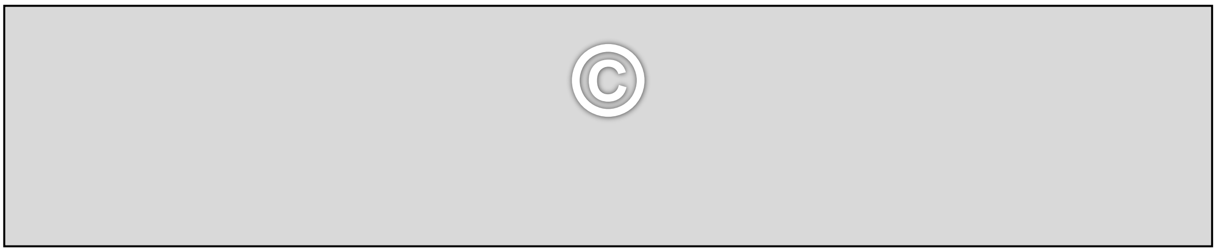


Figure 1: *Milgram's Mixed Reality continuum*.

VR is about leaving reality behind and stepping into a virtual world. In AR users stay in their real environment and virtual elements are brought into their world. Azuma's [3] widely accepted definition characterizes AR as follows:

1) Combines real and virtual

2) Interactive in real time

3) Registered in 3D

Azuma's definition is not restricted to a certain hardware setup, but is designed general enough to consider different existing AR solutions, such as video see-through, optical see-through or projected AR. Projection-based systems are used in *Spatial AR* [9] and video or optical see-through techniques can be realized with different kinds of head-mounted or handheld displays. Dörner et al. give a good overview on these visualization techniques in their recent book [17]. Handheld devices, such as smartphones and tablets, work with the video see-through technique and act as a *Magic Lens* [13], showing an augmented view of the world. This *Magic Lens* effect is often weakened, because the user's field of vision is not taken into account and therefore, does not match the camera's field of vision [17]. This is illustrated in **Figure 2**.

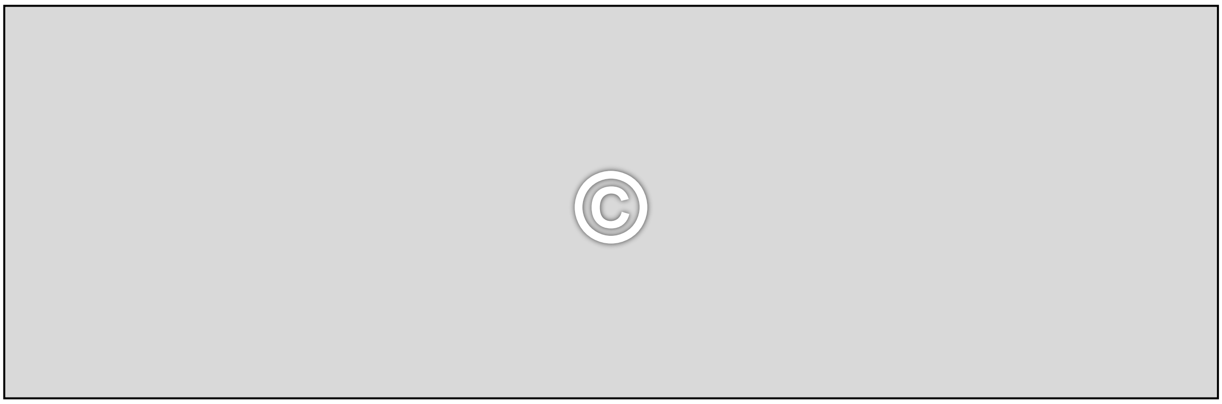


Figure 2: *Examples of a handheld AR visualization with different user and camera perspectives (left) and a photometrically registered virtual object (right) [17].*

To fulfill the *3D registration* part of Azuma's definition, the user's environment is tracked by the AR system to correctly place or register virtual objects within the physical environment. Different tracking techniques exist, such as magnetic, inertial, GPS, vision based or hybrid tracking [7]. Vision based techniques determine the camera's 3D position with six degrees of freedom (DoF), three for the translation and three for the rotation of the camera. The vision based tracking uses either optical markers (e.g. Poupyrev et al. [35]), placed in the tracked environment, or relies on natural feature tracking algorithms (e.g. Taehee and Hollerer [43]). The speed and accuracy of the tracking and registration process greatly influences the AR experience. Even small delays or mistakes can destroy the illusion. Additional to the *geometric registration* (correct position in space), *photometric registration* (**Figure 2**) improves the AR illusion by simulating realistic lighting conditions, such as shadows, cast and received by virtual objects, and reflected lights [17]. Shadows are very important for a correct depth perception [36] and therefore, essential for 3D interaction in AR. Another challenge in integrating virtual objects into the real world is the problem of object occlusion between virtual and real items for which additional depth cameras can provide the necessary data.

The *real time interaction* requirement excludes films and other non-interactive media from Azuma's AR definition, even though they might integrate virtual images very convincingly into the real world. But also for most interactive AR applications user interaction has until recently [8, 17] only been a minor matter next to the dominant visualization part. Even though many different interaction techniques have been applied in an AR context, they are mostly adaptions from existing 2D desktop applications or 3D and VR interfaces. These techniques range from simple information browsing, over 3D object manipulation, tangible UIs and natural interaction with free hand gestures, to multimodal interfaces that combine different input methods, such as gestures and speech [7]. Billinghurst et al. note in their current AR survey [7] that the new interface medium of AR has not yet reached the state of new specific interaction metaphor development, not to mention the development of formal theoretical models.

2.2 3D Interaction

The basic five interaction tasks are selection, manipulation, navigation, system control and symbolic input [10]. The navigation task, requires special attention in VR applications, but can be handled very naturally in AR, because in AR scenarios the user is moving and interacting within his physical environment. On smartphones and tablets, established solutions already exist for the system control and symbolic input tasks. The 2D touch screen interactions suit them well and for most applications no 3D alternatives will be required. New approaches for the tasks of 3D object selection and manipulation could, in contrast, benefit handheld AR applications, such as mobile AR games. Interacting with virtual 3D objects, located in the real world, through 2D inputs on the touch screen could be perceived as inconsistent and damage the AR illusion.

A variety of 3D interaction solutions, such as different pointing techniques and virtual hand metaphors, have been designed. But still no standardized metaphors and techniques exist and may never be established, because compared to the thoroughly examined desktop applications, 3D UIs involve a vast amount of different hardware setups with differing requirements [11]. Interaction metaphors support users in understanding the affordances and constraints of a new interaction tool [10, 47]. Although, there is still a discussion about the two directions of natural and “magic” metaphors. Natural metaphors might be easier to understand and use, but they also translate unnecessary restrictions from the real world to the virtual interaction [11].

The development of 3D User Interfaces is closely connected with AR and VR applications, but most techniques have been developed for free hand interactions in combination with head-mounted displays (HMDs). Therefore, they are not directly applicable to handheld AR with its inseparable connection between camera and manipulation tool. Furthermore, handheld AR has its own special ergonomic issues (see Veas and Kruijff [45]), in addition to those common to most 3D interactions. An example is limited precision, because of hand jitter [11]. Users are not accustomed to "full" 3D interactions, and thus, required DoF for the interaction task, should be limited wherever possible. New 3D UIs should be evaluated in user studies, because user or player reactions and expectations cannot be reliably predicted (see Hornecker and Dünser [24]). Bowman et al. [10] mention a variety of evaluation issues that should be considered for 3D UIs, such as keeping a good view on an actively moving tester without interfering with his interaction experience.

2.3 Games and User Experience

Many definitions for games exist. One of the shorter ones by Scott Rogers [39] states that a game is an activity that requires at least one player, has rules and a victory condition. Besides the rules and the goal, McGonigal [30] also mentions feedback and voluntary participation as defining traits of a game. They can be found in all (video) games, from simple arcade games, such as Tetris, to massive multiplayer online role-playing games (MMORPGs).

User experience (UX) is an important topic of discussion in HCI research and still misses a clear definition [6]. Hassenzahl [20] sees experience as "*memorized* stories of use and consumption". User experience is about the user and his emotions and therefore depends on many factors that cannot all be controlled by the application alone. Two players can have a very different experience with the same game, depending on their skill and engagement level, previous experience or further factors. Different aspects of a game, such as story, mechanics, competition or graphics style, influence the experience as well as usability issues that can impair an otherwise positive experience. But usability requirements in games differ from usability requirements in other applications. Playing is not about performing a task in a fast, effective and satisfying way. The experience of a game often involves exploring, making mistakes and learning from them. In many games information is hidden from the player and traps await him on his way. Something like this would be unthinkable for an office application.

Designing and evaluating user experience in games is a complex topic for which a number of heuristics and guidelines have been designed [16, 29, 34]. Important concepts in this context include playability, fun, challenge, engagement, flow [15] and immersion. These should not be seen as completely independent dimensions of the experience, but rather as interrelated. The state of flow in a game can only be reached with a well-adjusted level of challenge and a better flow experience can intensify the feeling of immersion. Challenge can be established through time limits, competition or puzzles and for certain skill games mastering the controls is the greatest challenge. The concept of immersion or involvement in a game and the concept of presence [5] in an AR environment are related in their focus on a sense of "being there". In an AR context this refers to the spatial relationship between the user and virtual and real objects. Immersion is less concerned with the actual physical presence in the game world, but more about a rich experience through the game's content and the player's imagination.

2.4 Related Work

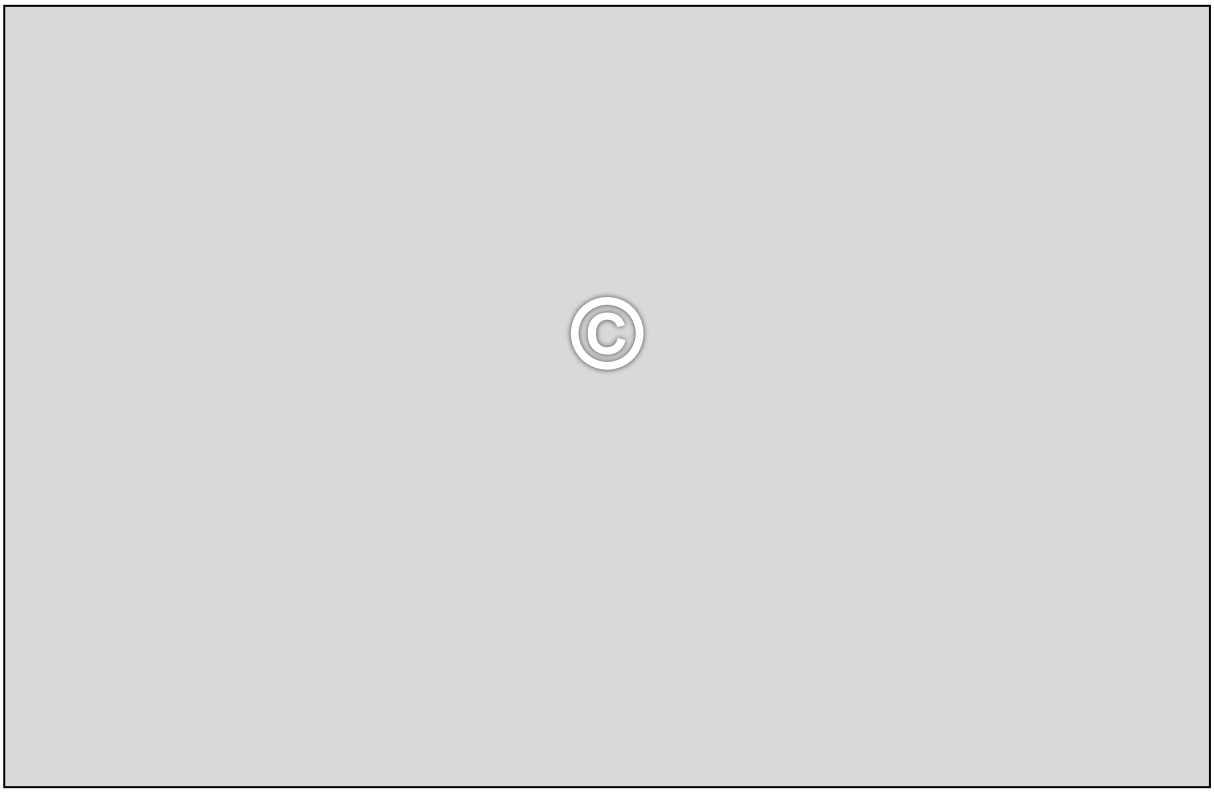


Figure 3: *Examples of other AR games. In a row from left to right: AR-Tennis [22], levelHead[11], ARhrrrr[12], Nintendo 3DS AR[13], Nerdherder[14] and Pokémon GO[8].*

Arth et al.'s work from 2015 has summed up the nearly 50 years of mobile AR history [2] with a view on hardware and tool development, research work and business deals. The overview shows important steps in handheld AR, such as the upcoming of laptops and smartphones, huge investments and innovative projects and games. In the field of 3D UIs the

[8] http://www.lostateminor.com/2015/09/14/pokemon-go-lets-you-live-out-your-childhood-dreams-in-real-life/. Accessed on September 14, 2015.

Microsoft Kinect[9] and Nintendo Wii[10] have brought new forms of interaction to commercial entertainment and sparked various research projects on natural interaction. Many research prototypes and AR games have already been developed, demonstrating different approaches of playing with the new technology. Only some of the more recent games, most designed for mobile handheld devices and therefore closest to the research question of this thesis, are listed here and illustrated in **Figure 3**:

AR-Tennis [21] (2005): A small collaborative AR tennis game in which two players are seated at a table, facing each other. They pass a virtual ball over a virtual net with the mobile device acting as a tennis racket.

levelHead[11] (2008): AR game with a tangible UI. A small tracked cube is tilted and rotated to guide the character's way through a labyrinth of rooms.

ARhrrrr![12] (2009): A handheld AR shooter, played on the table with an augmented map of a city. It employs small colored sweets as tangible game elements.

Nintendo 3DS AR[13] (2011): Game collection, containing archery, fishing and golfing games. The tracked objects are playing cards, laid out on a table.

Nerdherder[14] (2012): A puzzle game, shooing and baiting small virtual workers into their office cubicles. The mobile device acts as a fishing rod to pick up objects and move them around the scene.

Pokémon GO[15] (announced 2015): A GPS-based mobile AR game that lets players find and catch virtual Pokémon in the real world.

[9] http://www.xbox.com/en-US/xbox-one/accessories/kinect-for-xbox-one
[10] http://wii.com/
[11] http://julianoliver.com/levelhead/
[12] http://ael.gatech.edu/lab/research/games/arhrrrr/
[13] http://nintendo3ds.wikia.com/wiki/AR_Games
[14] http://ael.gatech.edu/nerdherder/
[15] http://www.pokemon.com/us/pokemon-video-games/pokemon-go/
Accessed on September 14, 2015.

3 Concept

This chapter describes the concept of the designed interaction techniques. The introduced design goals guide all concept decisions and later serve as evaluation criteria. Three metaphors are illustrated, discussed and classified – a magnetic cursor, an UFO and a shovel.

3.1 Design Goals

Handheld AR applications rely mostly on common touch screen and gesture input from other mobile phone interactions [7] and are not specifically designed for AR requirements. The developed interaction techniques use touch screen input only as a supportive discrete event for the interaction. They should further:

a) Preserve the illusion of an augmented reality

b) Be fun to play with

c) Avoid frustration, discomfort or fatigue

d) Support rather general tasks, applicable to many types of games

The first point is about *presence*, more precisely the subjectively perceived spatial relationship between player, real and virtual objects. The interaction should be located in the perceived mixed reality and not on the display. Ideally, the applied interaction techniques should not remind the player of the device in his hands, because this could interrupt the game and destroy the player's immersion.

Fulfillment of the *fun to play with* requirement depends on many factors, but the interaction itself should add to a pleasant experience and encourage users to play around. Another target is that of invoking a feeling of competence in the player or at least giving him the promise to become competent after enough practice. Not all common usability requirements need to be fulfilled, such as accuracy, effectiveness or error prevention. The player may well be challenged by the interaction task and prone to fail. This can be an important part of the game experience, instead of being considered poorly designed from a usability point of view.

Criterion c), i.e., the *avoidance of frustration, discomfort and fatigue,* on the other hand, is about the usability requirements that should be met. For example, high mental or physical effort can quickly lead to frustration and fatigue and should therefore be avoided. The ergonomics of the interaction will strongly depend on the specific characteristics of the employed device, but the interaction technique should nonetheless be designed with the player's comfort in mind.

The last point on generalizability requests only a tendency, because the variety of games is much too large to define a general interaction technique, which could cope with all of them. The interaction should not be planned to fit a very specific task, a certain genre or user group. Its core elements should be usable in many different game scenarios.

3.2 Game Concept

The game itself does not stand in the center of the prototype concept. It serves primarily as a test environment for the interaction techniques. Therefore, the game structure, graphical appearance and rule set follow a simplistic design. The concept is inspired by a game that small children play with toy blocks, where each block can be put into a container by pushing it through the fitting hole (**Figure 4**). This game appeals to children who are still learning the basic laws of the physical world around them and how they can use their motor skills to interact with it. Besides the problem of matching a block with its corresponding hole, grabbing it and modifying its orientation until it aligns correctly with the goal is a challenging task for a young child. Using a similar design for the prototype makes the game easy to understand and puts a clear emphasis on the interaction tasks – selection, positioning and rotation.

The prototype setup is a table top game, whose playing field is defined by the dimensions of the employed image marker. The virtual scene, built on top of the marker, can be seen in **Figure 5**. It contains five interactive objects (virtual toy blocks) and five small platforms, marking their assigned goal positions. To complete the game the player has to put each block correctly aligned on its corresponding platform.

One of the goal platforms is hidden inside a large transparent pillar and only becomes accessible after all other blocks have found their destination. This divides the single positioning tasks into four sub-goals and a final goal to give the player a clearer motivation. The last goal platform also offers some additional visual feedback on the player's progress by moving it a step further up towards the pillars surface with each block being correctly placed. It is also a slightly greater challenge to place the last object, because no shadows are cast on the transparent pillar's upper surface. Together with its elevated position, this makes the navigation and positioning task harder.

To add some challenge, the goal platforms are each positioned under a partly closed roof, so they are not all visible at the same time from one perspective and cannot be reached from a top view. This way the player has to navigate to another perspective to move a formerly occluded goal into his view. The blocks are arranged on a circular platform that is slowly turning like a carousel. Most video games contain dynamic elements. Thus, making the objects move around results in a better representation of a typical game.

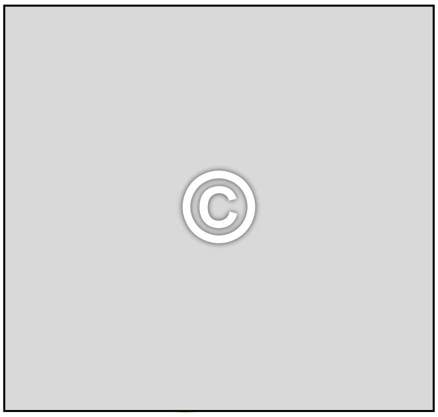


Figure 4: *A children's toy block game*[16].

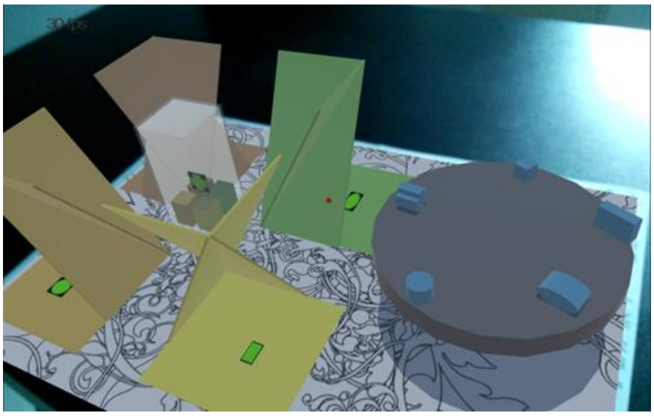


Figure 5: *The game scene at start.*

The game scene is supposed to appear as existing in the real world, right on the table. To support this illusion, lighting conditions and physics behavior are simulated as realistic as possible. This is also a common approach in many video games to achieve deeper player immersion and make the playing experience more enjoyable.

Employing a physics simulation, the virtual objects are affected by gravity and collisions with other objects. They can only be placed on a solid ground, which reduces the potential positions for object placement to a small number of horizontal planes, avoiding the cognitively demanding task of a "full 3D" interaction. Falling objects are returned to their initial position after exceeding a certain speed, so they cannot get lost from the game.

A top-down directional light, following the vector of gravity, results in vertically projected shadows. These give important depth cues, which are essential for an effective navigation. The shadows also act as a kind of preview for the positioning task, because they continuously

[16] http://www.aliexpress.com/item-img/Free-delivery-wooden-toys-multi-function-module-assembly-kit-geometric-shape-block-matching-child-puzzle/32216003081.html. Accessed on August 24, 2015.

show the position on the ground below, where the selected object would be placed, when released.

As mentioned earlier occlusion and shadow casting between real and virtual objects is a complex problem. Therefore, the prototype only settles for a simple approach concerning this issue. A virtual plane with the marker image is rendered over the marker's camera picture. Consequently the virtual image visually resembles the real marker object, while at the same time receiving virtual shadows and occluding virtual objects, acting as an important connection between the real and the virtual world.

3.3 Magnetic Cursor Metaphor

This interaction technique uses the metaphor of a small magnetic sphere. Such as an electromagnet, its magnetic force can be switched on and off. The 3D cursor is a sphere, positioned at a fixed distance from the camera in the center of the screen. Hence, it follows the movement of the camera and is not blocked by collisions with other objects. Instead, it passes directly through, staying at its position relative to the camera. To support a correct depth perception the cursor casts shadows on the ground and gets occluded by other virtual objects.

3.3.1 Object Selection and Positioning

While the device's screen is touched, the magnetic force of the cursor is activated and can be used to pick up a selectable object. The active state is visualized by a change in the cursor's color, also affecting the color of the point light connected with the cursor. This light assists in precisely positioning the cursor next to other objects by illuminating them within a small radius. If the active cursor touches a selectable object, a physical joint is created between the cursor and the collision point on the object's surface. This connection forces the object to follow the cursor's position, while its angular movement is not constrained. At the same time it behaves like a physical object, being pulled down by gravity and slowed by its own inertia. This way the object appears to be hanging from the cursor and getting pulled behind, when the cursor is moved. The selection process, object movement and positioning are illustrated in **Figure 6**.

While connected to the cursor, the object's physical collision with other objects is deactivated, so the dragged object can follow unrestrictedly. The object can be dropped by releasing the touch on the screen. The joint is then destroyed, all current physical forces acting on the object are removed and the object falls to the ground. Removing the forces prevents the object from getting thrown around, when released during fast camera movements. Allowing this kind of interaction would encourage the player to perform fast movements with the device, but those should be avoided to keep the tracking stable. It also makes the interaction harder to control and results hard to predict, when physical objects can fly around the scene.

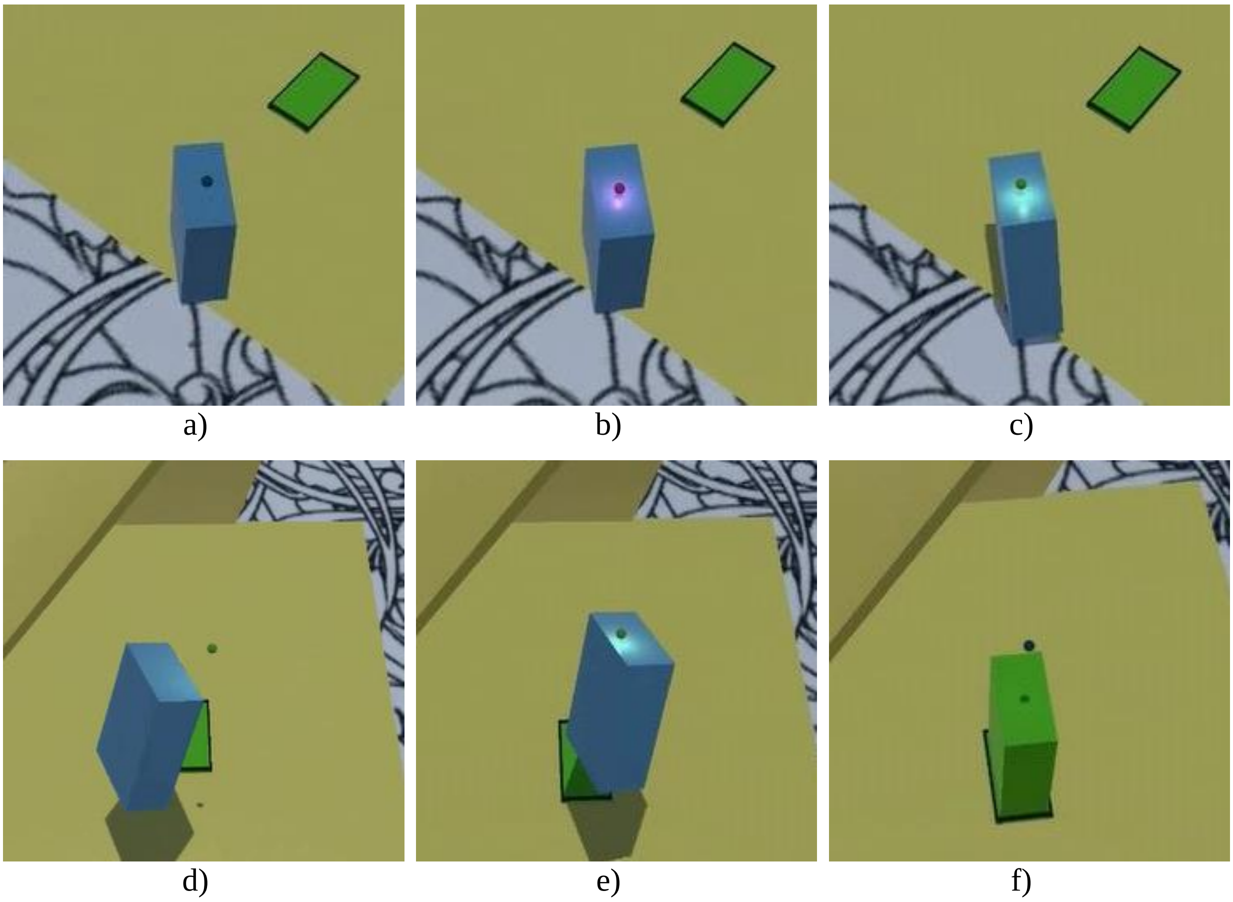


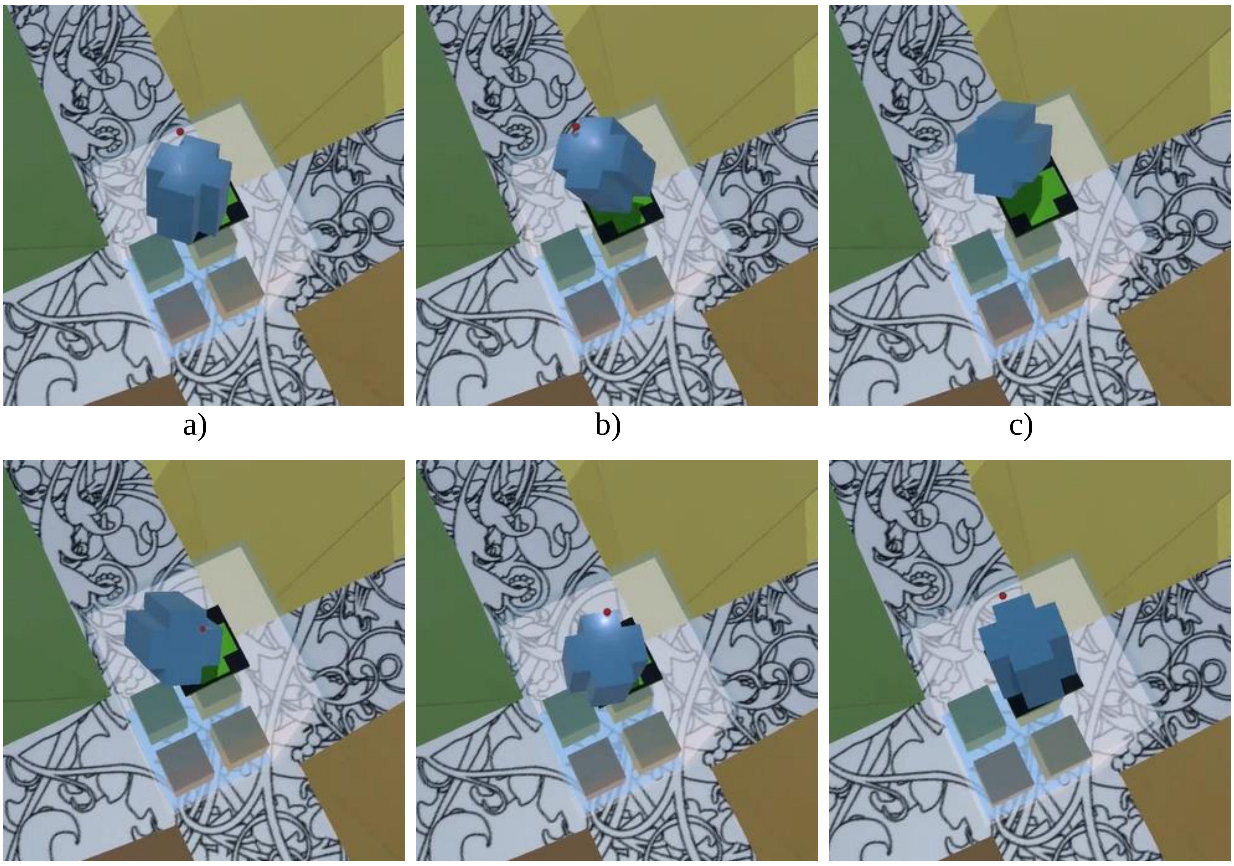
Figure 6: *Target selection and placement with the magnet metaphor. a) shows the inactive magnet approaching the target. In b) the magnet has been activated and positioned just above the cuboid. At the moment of collision c) the magnet and the object become connected and the cuboid follows the magnet toward the goal d) and e). The magnet is then deactivated, dropping the object on the goal f).*

3.3.2 **Object Rotation**

When objects are picked up, the point on which they have been touched becomes the object's new highest point (**Figure 7**). Thus, the player can target the cursor's touch at the side he wants to turn up. This strategy works well for two rotation directions, but not for the vertical axis of rotation. However, the object's orientation can also be manipulated by swinging it around in the air. Moving the camera in a circular motion parallel to the ground gives the object a momentum that makes it turn around the axis perpendicular to the ground (**Figure 8**). While the two other rotations will be corrected, when the object settles in a stable position on the ground, this last rotation is controlled completely free.

a) b) c) d) e)

Figure 7: *Rotating an object with the magnet cursor by picking it up from a lateral face. The object follows the cursor and the picked face turns upwards. a) shows the frame in which the activated magnet touches the object and the joint is created. In d) the object has been completely turned. The point connected to the cursor is now the highest point of the object. The selected object can now pass through the floor like the cursor. At the end of the sequence e) the target gets lifted from the ground and pulled to the left.*



a) b) c)

d) e) f)

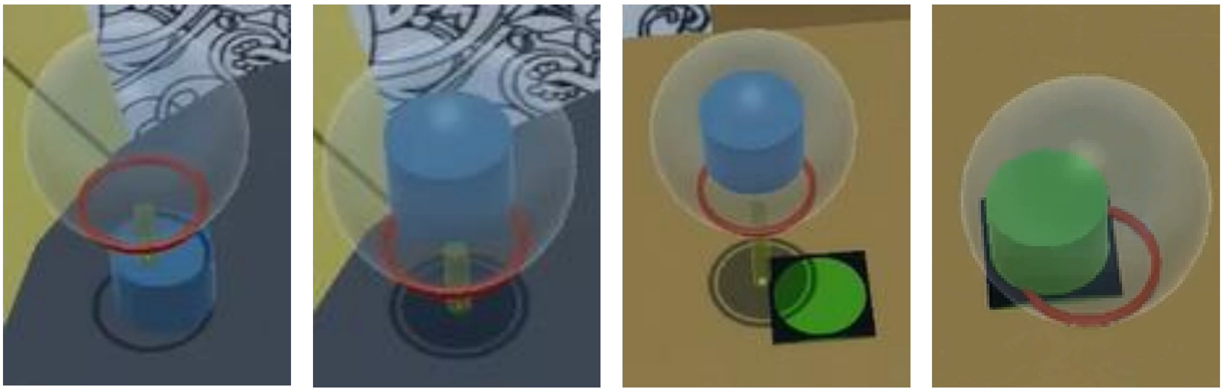
Figure 8: *Rotating the object around its vertical axis by swinging the magnet along a circular path. The object in the sequence is turned by approximately 45 degrees counterclockwise. In frame c) the cursor has moved inside the object, getting obstructed until the object follows the movement.*

3.4 UFO Metaphor

The second metaphor is a small UFO with a green tractor beam, containing a spot light, pointing to the ground. It follows the camera at a fixed distance, always at the center of the screen, like the magnetic sphere does. The UFO consists of a small ring with a transparent sphere on top. Only the solid ring casts a shadow to the ground. Moving the device around the scene rotates the UFO around its vertical axis, but it does not get turned upside down, when the device is tilted along the other axes. It flies parallel to the ground with the ring on the bottom and the beam pointing straight down. The ring's shadow and the light beam together show the UFO's position relative to the objects below.

3.4.1 Object Selection and Positioning

This interaction technique does not require touch input for the selection and positioning tasks, illustrated in **Figure 9**. To select an object it needs to be approached from the top. When an object is touched by the UFO, while being hit by its beam from above, the object gets teleported inside the UFO. In this state the object can be carried around within the UFO to another position. The selected object can be released by making the UFO land on a horizontal surface. When the UFO touches the ground from above, the object will be left at the point of collision. A small time slot directly after selecting an object was implemented, in which the object will not be deselected, when touching the ground. This avoids an unintended deselection during the picking movement.

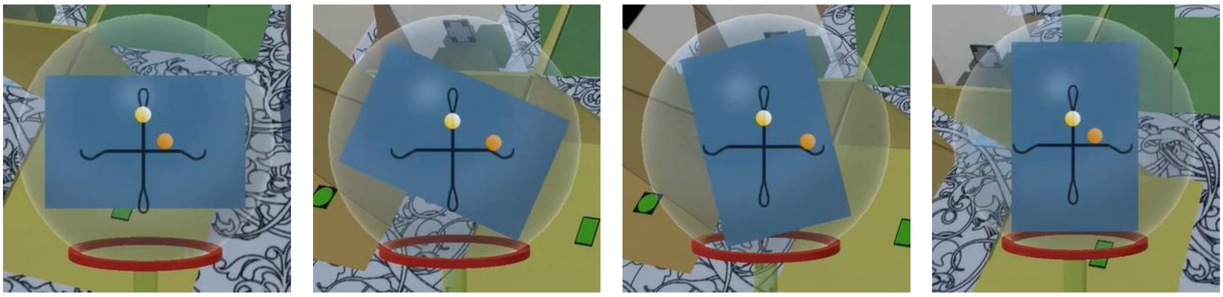


a) b) c) d)

Figure 9: *Target selection and placement with the UFO metaphor. In a) the empty UFO approaches the cylinder with its beam from above. After touching the object, it is selected and moved inside the UFO b). c) and d) show the UFO hitting the goal from above and placing the cylinder.*

3.4.2 Object Rotation

While inside the UFO, objects follow its position and orientation and can therefore be turned around the vertical axis directly by changing the camera perspective. To rotate a selected object around the two remaining axes, a separate rotation mode can be enabled by holding a touch on the screen. This brings the UFO close up to the screen from a frontal perspective (**Figure 10**). In this mode the rotation is controlled using the gyroscopic sensors of the device. Nothing changes while the device's orientation is inside the rest-zone. Tilting the device out of this zone makes the selected object rotate in the direction of the tilt. The rotation is stopped, when returning to the rest-zone. The rest-zone orientation is designed to be as close as possible to the natural viewing angle of the handheld device. Rotations around the x and z axes are controlled separately to reduce the complexity. While one rotation is active, the other one gets locked. Two small balls visualize the state of the gyroscope by rolling along two bars, symbolizing the rotation axes. Rotations are restricted to axis-aligned orientations by snapping the object to the closest allowed orientation state, when the rotation is stopped. The object's orientation is also aligned during selection, but not when placing it on the ground. Rotating objects by tilting has already been explored in other studies (see [23]).



a) b) c) d)

Figure 10: *UFO rotation mode. The cuboid is rotated clockwise by 90 degrees. The small orange ball indicates how far the device has been tilted to the left or right.*

3.5 Shovel Metaphor

The tool in this interaction is inspired after a shovel that can be used to scoop up objects. Since this metaphor has several problems, which are discussed later, it is only described conceptually and was not implemented. The shovel is positioned in front of the camera and moves with it, like the two preceding tools did. Tilting the shovel to either the left or the right side, moving it under an object and tilting it back will select the target. The selected object can further be dropped at another location by tilting the shovel again, dropping the object. To rotate objects, they can be rolled around inside the shovel. The shovel is handled like a real physical shovel, thus, requiring a good physics simulation of surface friction, collisions and forces. A draft of the concept and a model are shown in **Figure 11** and in **Figure 12**.

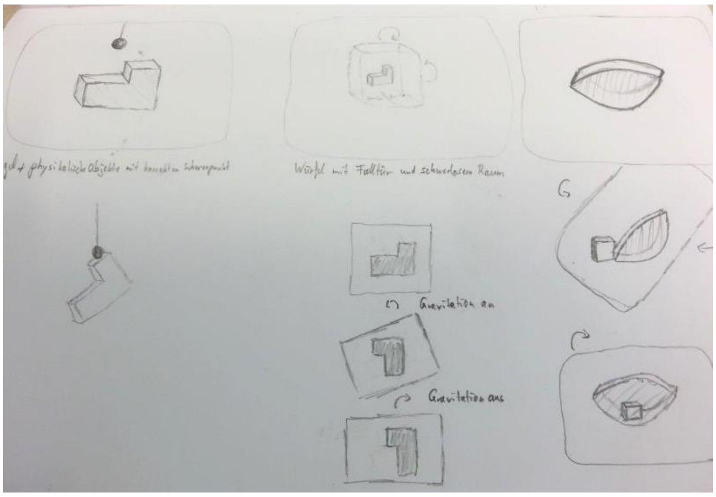


Figure 11: *Draft of the three metaphors. From left to right: magnet, UFO, shovel.*

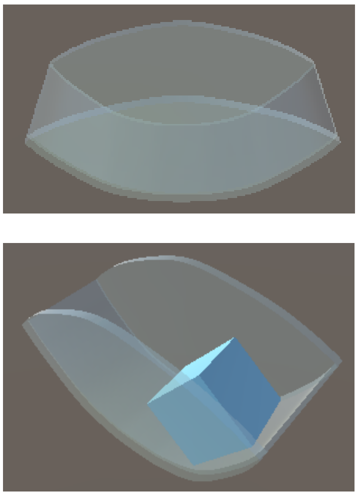


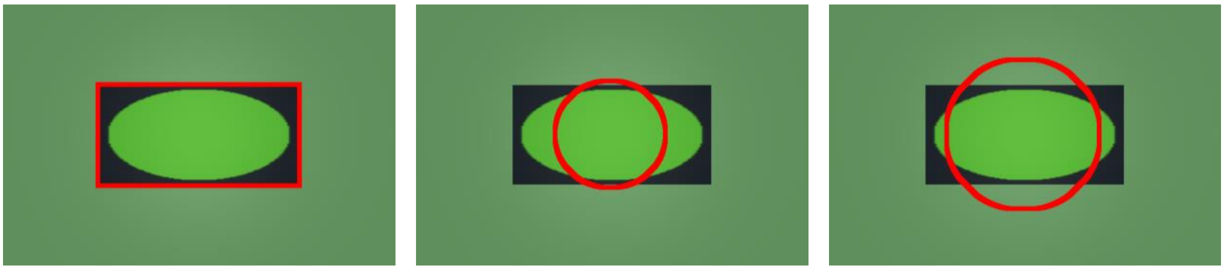
Figure 12: *Model of the shovel. Empty and holding a cube from the scene.*

Another draft for this metaphor considers only the selection and positioning tasks. It does not involve a realistic physics simulation. The shovel tilting acts as a symbolic gesture to confirm the selection or deselection of an object. For this draft the shovel is not always visible. It appears automatically, when a selectable object is within camera sight and at a close distance. The precise tool positioning is also carried out automatically, so the player only has to perform the rough navigation and confirm the selection. The object can be deselected by again tilting the shovel. Nevertheless, it can only be placed on predefined spots. An interactive spot is targeted automatically, when at close sight, such as objects during a selection process. Tilting confirms the placement.

Both drafts have not been implemented due to the following reasons. The latter was abandoned, because it is too simple. It lacks the power to manipulate object orientation, impeding a meaningful comparison with the other metaphors. The physical shovel simulation, on the other hand, would serve such a comparison very well, but its implementation would be very time-consuming and has disadvantages with respect to user interaction. The physical simulation would have to be controlled very carefully to make the shovel a useful tool for interaction, instead of creating a tool of destruction by translating all device movements directly into forces within the simulation. But then, too much control might defeat the initial intention to design an interaction – close to reality and intuitive to use. As the least promising approach, this concept was dropped to free more time for the improvement and completion of the other two metaphors.

3.6 Concept Changes concerning Tolerance Limits

To complete the game each virtual toy block needs to be placed on its assigned goal area and correctly aligned with the goals orientation. Objects are considered correctly placed and oriented, when their position and orientation is inside the defined tolerance limits.



a) b) c)

Figure 13: *Tolerance limits for the target position (elliptic cylinder goal). An object is considered correctly placed, if its center is located within the area, marked by the red line. For the UFO placement this area is the entire goal field, including the black edges a). b) shows the limits for the preliminary study and c) the increased tolerance limits for the final study.*

These limits have originally been designed differently for the magnet and the UFO technique. With the UFO, placing a target on its goal requires the same accuracy as the selection of the target does. If the goal is touched by the UFO while the beam is hitting the goal area, the target gets snapped to the goal's center. Thus, the target position is accepted, if its center is placed above the goal area (**Figure 13** a). For the magnet the target is considered correctly positioned, when its center is placed within a defined radius around the ideal placement position (**Figure 13** b). In the prototype version used for the preliminary study this radius was set to a rather low value, resulting in stricter tolerance limits than those set for the UFO positioning. The limits for the rotation were set to equally low values (a tolerance of 15°) for both metaphors. But two rotation dimensions are already restrained for the UFO metaphor and the vertical rotation can be directly controlled together with the camera perspective.

The results from the preliminary study (see Chapter 5) showed that most players had problems to achieve the required accuracy with the magnet interaction technique, leading to a lot of frustration. To better balance the difficulty level of both techniques, the tolerance radius for the magnet positioning task and the tolerance limits for the target rotation have been increased. The new limits are illustrated in **Figure 13** c) and **Figure 14** b). In the new prototype version the rotation only needs to be closer to the correct angle than it is to the adjacent angles. Thus, the same accuracy is required for the rotation with the magnet as it already was with the UFO for the gyroscope-controlled rotations, where the orientation will always correct itself to the nearest angle.

a) b)

Figure 14: *Tolerance limits for the target orientation (elliptic cylinder goal). An object is considered correctly placed, if it is not further rotated from the goal's orientation than the defined limit in both directions. The tolerated area for a clockwise rotation is marked in red. Limits for the preliminary study are 15° a) and for the final study 44° b).*

Another problem, observed in the preliminary study, was the point of time in which the target positioning was evaluated. For both techniques this test was performed at the moment of collision between the goal field and the selected object. Using the magnet, objects could be dropped onto the goal in every possible tilted position. When hitting the goal with an edge, the object was often too far away from the ideal position and orientation, and therefore evaluated as not correctly placed, even if it shortly after settled into an acceptable position on the ground (**Figure 15**). Introducing a second test in the new prototype version resolved this issue. The second test was performed at the moment, when the physical object stopped moving.

a) b)

Figure 15: *Placement test. Image a) shows the cylinder falling on its goal field. It collides with the ground while in a tilted orientation. The performed acceptance test at collision evaluates the target as not being correctly placed. In b) the target has settled on the ground in an acceptable position, but because no further test is performed, the placement is not accepted.*

3.7 Interaction Technique Classification

The magnet, the UFO and the shovel are all designed as 3D interaction tools to be operated through a handheld mobile device. They support the basic interaction tasks, selection, positioning and rotation. Following a description by Dörner et al. [17] the handheld device can be categorized as a direct pointing tool and the three metaphors as local interaction techniques. Local techniques make use of a person's daily experiences, facilitating orientation. The handheld device is used to directly position a 3D cursor at a point in space - in the shape of a sphere, UFO or shovel. This enables normal use of hand-eye coordination, making the tool easy to employ, but may also make its use tiring and inaccurate over a long time [17].

Positioning the 3D cursor requires the control of five degrees of freedom (DoFs). The device could be positioned using only three DoFs, but the cursor is placed at a constant offset, such as the tip of a wand is located at a distance from the hand holding it. The device therefore needs to be positioned at offset distance from the cursor's desired point (three DoFs) and at the same time be oriented towards this position (two DoFs) to place the cursor in the spot aimed at. There are several ways these five DoFs can be combined to reach the same cursor position. In fact, if a sphere was to be drawn around the cursor position with a radius equal to the cursor offset size, the device could be placed on any point of this sphere's surface with the camera pointed towards the sphere's center (**Figure 16**).

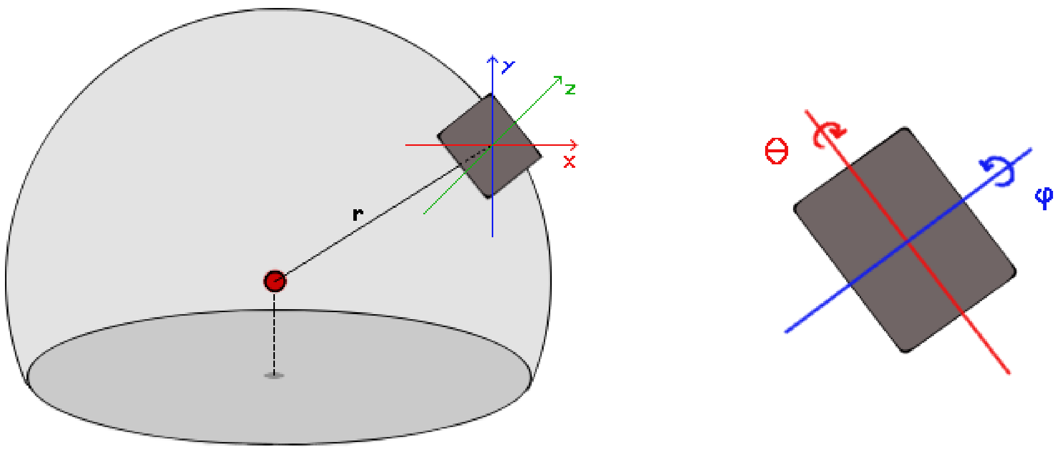


Figure 16: *Illustration of the interaction's DoF. To place the cursor (red sphere) in the shown position over the table, the mobile device (dark grey rectangle) can be moved to any position (x,y,z) on the sphere's surface with radius r = cursor offset and oriented to face (θ,φ) the sphere's center.*

For their 3D selection technique classification Argelaguet and Andujar [1] do not only examine DoFs and the selection tool shape, but also focus on aspects, such as disambiguation mechanisms, motor and visual space relationship and control-display ratio. The developed techniques do not include any mechanism for disambiguation. For the magnet and UFO the issue of disambiguation does not apply, because they are not volumetric selection tools and only allow single target selection. The shovel tool might collect more than one target at a time, but the concept provides no mechanism to prevent this. The motor and visual spaces are separated by an offset, because moving the camera into the current visual space, of course moves the visual space away, so it is always staying in front of the camera. The control-display ratio is isomorphic for all three techniques, because the cursor and camera are directly connected. An anisomorphic ratio could only be used in a restricted interaction space, because otherwise the cursor would at some point leave the camera viewport, because it is either moved too fast or too slow.

This problem of a cursor outside the camera's field of view can emerge, when the cursor's fixed connection with the camera is loosened. The camera movement is only restricted by constraints of the user's body and the real environment. No virtual constraints can be applied to it. With a rigid connection between cursor and camera this also applies for the cursor movement. A cursor movement, unrestricted by virtual objects, cannot be combined with the simulation of a physical cursor object. Thus, the advantages of direct control come at the cost of a believable bodily tool, and vice versa. For the UFO and the magnet the decision was made for the directly controlled ghostly cursor, whereas the shovel intends to simulate a real tool, accepting a loss of control.

In the development of the interaction concepts some of the pre-patterns, proposed by Yan et al. [47], have been applied. Most obviously, the pre-pattern *Device Metaphors*, recommending metaphors to make the new tool and its functions more accessible, inspired the use of metaphors for the 3D cursors. Two of the three *Control Mapping* mechanisms – projection from screen to space and device manipulation – can also be found in the tools design. The first one is used in all three techniques. The UFO additionally uses the device manipulation mechanic, in conjunction with the *Seamfull Design* pre-pattern, switching between tracking-controlled and gyroscope-controlled interactions.

In the following, different properties of the three metaphors are described. They employ different visualizations, and therefore obstruct more or less screen space depending on their size, shape and distance to the camera. All three tools cast shadows. The magnet provides an additional depth cue with the point light to clarify its 3D position relative to close objects. The UFO's beam illustrates its flying height above the ground. The interaction ranges from the realistic shovel, over the somewhat realistic magnet, to the rather magical interaction of the UFO tool.

Table 1: *Classification of the three interaction techniques*

	Magnet	**UFO**	**Shovel**
Tool Visualization	Small Sphere	Transparent Sphere on a Ring with Tractor Beam	Shovel
Depth Cues	Cursor is a Point Light Shadow Casting	Light Beam, pointing from Cursor to Ground Shadow Casting	Shadow Casting
Realistic or Magical	Mixed	Magical	Realistic
Supported Tasks	Selection Positioning Rotating	Selection Positioning Rotating	Selection Positioning Rotating
Target Count	Single Target	Single Target	Multi Target (Constrained by Object and Shovel Size)
Accuracy Required for Selection	3D Object Collision, but Exact Point influences Target Rotation	Ray Cast on Target from Above	3D Object Collision
Selection Trigger	Hold and Touch	Touch from Above / No Explicit Command	No Explicit Command
Target Manipulation Constraints	None	Rotation along X and Z Axes constrained to 0°, 90°, 180° and 270°	None
Position and Rotation Relationship	Combined	Combined Position and Y Axis Rotation Separate X and Z Axes Rotation within a *Quasimode*	Combined
Requirements User	Body A&S Naïve Physics Environmental A&S	Body A&S Naïve Physics Environmental A&S	Body A&S Naïve Physics Environmental A&S
Requirements System	Touchscreen Physics Simulation	Touchscreen Gyroscope	Physics Simulation

*A&S is short for Awareness and Skills

The tools differ in their control accuracy, required for the target selection. The UFO needs to be positioned with its center above the target and then moved down to touch it. The required accuracy depends on the size of the target's upper surface. The magnet can select a target by touching it anywhere on its surface. Larger targets will be easier to select, but the exact point of collision will still influence the target's rotation state. The shovel requires the least accuracy. UFO and shovel use no explicit command to confirm the target selecting, making them sensitive to the *Midas Touch effect* [27], resulting in objects being selected or deselected inadvertently, for example during navigation. The magnet avoids this issue by using an additional input signal from the touch screen. This confirmative touch can result in a small undesired change of the device's position, called the *Heisenberg effect* [12]. But because the touch needs to be held on the screen to select a target, it can be activated before precisely positioning the cursor, thus, the effect is not very problematic.

Shovel and magnet are not designed to explicitly separate the manipulation tasks positioning and rotating. This might make the handling of these tools more complex, because the intended manipulation of a target's position can at the same time result in an unintended change of the target's orientation. The UFO unlinks the three separate dimensions of the rotation task. One dimension is controlled combined with the position manipulation. The other two get controlled within a Quasimode [37], activated by holding a touch on the screen and left when the touch is released. The necessary confirmation of the held touch and the clear visual change between the two interaction modes ensures that the player is always aware of the rotation mode's active or inactive state. Together with the constraints applied to two of the target's rotation dimensions (helpful, if no free rotation is required) target rotation can be very consciously controlled.

To employ the discussed tools the user needs to be aware of his environment and his own body, have common sense knowledge about the physical world and know how to coordinate his movements and manipulate his environment [26]. To enable the realistic interaction the system needs to provide a good physical simulation. The magical UFO interaction does not depend on a correct simulation, but requires the device's gyroscopic sensors to control object rotation. Both, magnet and UFO can only be used, if the touch screen of the device is accessible during the interaction.

Table 1 summarizes the described properties.

4 Implementation

The introduced concepts are implemented as testable prototypes, using the game engine Unity and the AR library Vuforia. Unity permits the quick development of small 2D or 3D games and the Vuforia plugin performs the tracking and registration tasks, required for AR applications. The following section introduces both tools and describes the prototypes' implementation in more detail.

4.1 AR Library – Vuforia

Qualcomm Vuforia is an AR library that handles the tasks of tracking and geometric registration (see Chapter 2.1). Vuforia offers different tracking techniques, such as frame and image markers, object recognition, smart terrain and extended tracking. The prototype implementation uses an image marker, together with the extended tracking feature. Both techniques are shortly described in the following section.

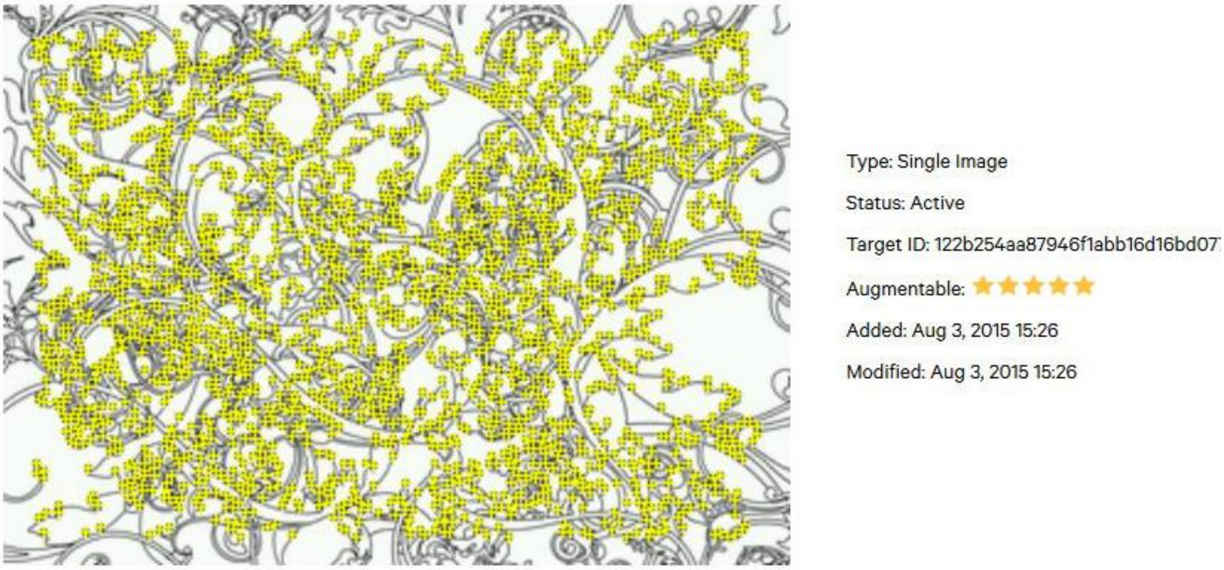


Figure 17: *Image target with trackable features and a five star rating. The features are marked by small yellow crosses. The algorythmically determined rating predicts the tracking robustness.*

An image marker or image target is an image with natural features that can be recognized by the tracking algorithms. On the Vuforia homepage it says: „A feature is a sharp, spiked, chiseled detail in the image“[17]. **Figure 17** shows the employed marker and its metainformation with a rating on its tracking suitability. Tracked features are marked with a small yellow cross. The tracking works best, if the image contains many evenly distributed features and no repetitive patterns or symmetries. The rating is calculated based on these properties. The tracking algorithm analyzes the video stream that is recorded by the device camera. It detects corners in the image and compares them to the stored marker image in the database. Only a small distinct region of the image, and with it some of the trackable features, need to be visible to the camera to receive a successful recognition. The marker’s position and orientation is thereby tracked by the system and can be used for the registration process. Vuforia allows different settings for the scene’s coordinate system. The scene’s origin is either anchored to the camera or a defined target. This implementation uses one image marker and the game scene is always aligned with this marker, because its center is the determined origin of the coordinate system. The extended tracking feature ensures a continous tracking result, even if the image target is lost from the camera’s view. This is achieved through an extension of the tracked area from the image to the complete environment. Features in the environment are dynamically recognised and can improve tracking, if the surroundings are relatively static.

4.2 Unity Prototyping

The cross-platform game engine Unity, developed by Unity Technologies, was initially released in 2005 and has by now reached its fifth version and supports 21 platforms. Most of the development can be done directly (and graphically) within the integrated editor or programmed via scripts. Objects are set up in the scene preview as they should appear in the finished game. The prototype’s scene hierarchy (**Figure 18**) contains the image target object and an AR camera from the Vuforia plugin. The image target is the base for the game scene, which is viewed from the AR camera perspective during gameplay. As mentioned in Chapter 3.2, the actual marker is covered by a plane and textured with the marker image. The transparent pillar in the center (recall **Figure 5**) consists of two nested cuboids with the inner cuboid using a custom front-face culling shader. Most objects in the scene possess a rigid

[17] https://developer.vuforia.com/library//articles/Solution/Natural-Features-and-Ratings. Accessed on September 11, 2015

body component to either be moved by the physics engine, or to receive trigger events at collision with other physics objects. Every Unity game object contains at least one component, a module with a number of properties and functions, and more components can be added for more functionality. The circular platform rotates with constant speed and the blocks on it follow the movement, because of the simulated friction between them.

The 3D cursor objects (magnetic sphere and UFO) are child objects of the AR camera and thereby, their transform components, defining position, rotation and scale, are moved simultaneously. Thus, they appear in a fixed position in front of the camera. Unity uses different update cycles to render a frame and calculate physical behavior. While the frame rendering rate is dynamic, the physics engine uses a separate fixed frame rate. This is a problem for the magnet metaphor, because selected objects are attached to the cursor via a physical joint and are moved during the physics update. Movements of the cursor and the selected object are not exactly synchronized and the object appears to jitter while following the cursor, because the physics update receives only previous cursor coordinates. To solve this issue and remove the jitter, another invisible sphere acts as an anchor between the cursor and the target. The physical joint is created between the target and this anchor, which then follows the actual cursor with a small delay.

Figure 18: *Unity scene hierachy.*

Three different scripts are attached to the movable blocks to handle:

1. Joint creation and destruction for the magnet metaphor
2. Gyroscopic rotation with the UFO
3. The blocks' respawn behavior

The physical joint is configured as unbreakable, locking all target movement directions and leaving all target rotation directions free. For the gyroscopic rotation the assumed device orientation is “landscape” and the position of the rest-zone is defined accordingly. The goal objects handle the tests for correct object placement. Each goal has two properties, defining the corresponding object and the vector of the target’s ideal placement position. Accepted target orientation states are defined individually for each object, depending on its symmetry properties. For example, the cylinder object is placed correctly, if one of the two accepted orientations for each, the x and z axes, are met. The y axis orientation is always considered correct, because of the cylinder’s rotational symmetry.

Because shadows are important for the depth perception, the default shadow quality settings for mobile games are increased to allow high quality shadows and shadow rendering from a greater distance.

5 Evaluation

The prototype evaluation has been composed of several steps. Informal tests accompanied the implementation process to early uncover problems and collect first opinions, leading to iterative improvements of the concepts. A preliminary study was performed, which led to small adjustments, mainly concerning the difficulty level of the prototype game (see Chapter 3.6). Apart from these changes, the setup of both, main and preliminary study, was identical.
Results of the assessed playing times, subjective ratings on game experience and usability, and recorded thoughts from players during the tests are summarized and interpreted. The discussion focuses on the comparison between the magnet and UFO metaphors, and the effects of the difficulty adjustment in the final study. The results are further discussed using the design goals from Chapter 3.1 as evaluation criteria.

5.1 Design and Procedure

5.1.1 Informal Tests

The informal tests provided positive and constructive feedback. One of the improvements resulting from these tests was the change of the directional light to a top down orientation, resulting in a vertical shadow projection as an important visual depth cue. Because some users accidentally deselected objects right after they selected them in the same downward motion of the UFO, the described small time frame, in which deselection is deactivated (see Chapter 3.4.1), was added to avoid this problem.
The prototype has been tested in both, sitting and standing positions. The seated players could not walk around the scene to navigate. Instead they simply used one hand to turn the printed marker on the table. One tester even used the marker to correctly align the target not by rotating it directly with the cursor tool, but instead rotating the complete scene. Another test demonstrated clear signs of the game’s immersion and a well working illusion. While testing, one player tried to turn the marker very carefully, because he did not want the movement to tip over the already correctly positioned objects, until he realized that this would not influence the virtual objects.
The testers reported that moving the marker by hand felt very natural, supporting the notion that tangible interfaces are very promising for AR applications. Nevertheless, this interaction did not suit the concept of controlling the device with both hands, so a different setup was chosen for the later tests.

5.1.2 Survey Questions

To decide, if the evaluation criteria (specified in Chapter 3.1) are fulfilled by the developed prototypes, an extensive search for different questionnaires was performed to measure the different aspects of game experience, presence and usability.

Nordin et al. [32] list some of the more frequently used questionnaires in measuring game experience, but most of them focus only on a certain dimension of the experience, such as flow or immersion. The Game Experience Questionnaire (GEQ), developed by IJsselstein et al. [25], has for the most part been designed general enough to be applicable for games independent of their specific genre. This makes it suitable to test even the very simple prototype game. It does not focus only on a single aspect of the game experience, but considers the seven dimensions:

1. Competence
2. Sensory and imaginative immersion
3. Flow
4. Tension/annoyance
5. Challenge
6. Negative affect
7. Positive affect

As Norman [33] in reviewing the GEQ anticipated, the questionnaire had to be adjusted by removing the item “I was interested in the game's story”, because it obviously was not applicable to the tested game. This left 32 items with each of the seven dimensions being represented by three to five questions.

Van Baren et al. [44] authored a compendium of presence measurement approaches in 2004, but did not mention a single AR questionnaire and since then no AR scale has been established. To study presence in AR applications, other researchers adapted VR or cross-media presence measuring tools to fit their specific purposes. One example is the research of von der Pütten et al. [46] on spatial and temporal presence in their collaborative AR game TimeWarp. A work in progress by Regenbrecht et al. [38] on measuring presence in mixed reality applications has been considered for the prototype evaluation, but the 33 items additional to the 32 GEQ items have been decided as being too much for the survey.

Measuring the game experience was prioritized over evaluating presence. Hence, no separate presence questionnaire was employed in the survey.

Common usability scales, such as the NASA Task Load Index (NASA TLX) [19] and the System Usability Scale (SUS) [4], evaluate the ease of use of a system, but are not tailored to take into account the ergonomic issues of a handheld AR application. The handheld AR Usability Scale (HARUS) [40] was inspired by the NASA TLX and SUS and developed specifically for the ergonomic and perceptual issues common to handheld AR. Of the 16 HARUS items, the eight items concerning handheld AR ergonomics have been used in the survey to gather subjective measures on comfort, fatigue and ease of use.

5.1.3 Experimental Setup of Preliminary and Final Study

The survey was conducted with nine participants. Five of them were female and four were male. The average age was 26 (min: 22, max: 32) and all participants were computer scientists, either students or university employees. **Table 2** shows the testers' own estimation of their previous experiences with related technologies. Most participants reported to have had only few previous experiences with VR or AR applications. But all testers possessed many or at least several experiences with games and were proficient in the use of mobile smartphones and tablet devices.

Table 2: *Overview on the nine testers‘ previous experiences with VR, AR, games and mobile devices*

	VR Exp.	AR Exp.	Game Exp.	Mobile Exp.
0 None	1	-	-	-
1	6	7	-	-
2	1	1	2	-
3	1	1	-	3
4 Many	-	-	7	6

The experiments took place around the game area, set up on a high, narrow table. The employed image marker was a DIN A3 printout (see Appendix 8.4), nearly filling the complete table area. With this setup, illustrated in **Figure 19**, the marker was arranged to be at a comfortable height for the standing players and accessible from all sides. A Google Nexus 7 with an Android 4.4.1 system was used as test device.

To avoid the influence of interpersonal differences, the experiment was conducted with a within-subjects design, i.e., each test subject played the prototype game twice with both metaphors. The sequence of the UFO and magnet metaphor was randomized with biased coin randomization [41], which prevents sequence effects. The sequence in the first test gets decided by a flipped coin. The following test will then use the opposite metaphor sequence. The third test sequence is again chosen randomly. And the forth will be opposite to the third and so on. Each participant got a short introduction to the game prior to their first test. After a demonstration of the according interaction technique testers were allowed some time to practice until they thought, they understood its usage. Employing the think-aloud protocol [18] subjective data was collected on the testers' thoughts and impressions during gameplay. The testers, but not the device screen, have been observed from a distance to not further disturb their game experience. For later evaluation purposes the screen has been directly recorded by the device during the tasks. After completing the game with one metaphor the players were asked to rate their experience with the GEQ. The same was done with the second metaphor. After finishing the game twice the HARUS questionnaire was filled out, rating the experience for both tasks together.

Figure 19: *Experimental setup with marker, test device and tester.*

The described procedure was used in the preliminary and the final study. The distribution of age, gender and experience levels of the five subjects taking part in the preliminary study and the four participants of the final study have been similar in both studies.

5.2 Results

5.2.1 Objective/Quantitative Data

The time taken by the players to complete each game was measured and the four average times for both studies and both interaction techniques are displayed in **Table 3**. One participant of the preliminary study could not complete the game within 30 minutes when using the magnet metaphor and thus, did not have enough time to finish the UFO experiment. For the eight remaining participants average completion time for both metaphors in the final study and the UFO in the preliminary study was just about six minutes. The result for the magnet from the preliminary study (Ø 12 min) is nearly twice as high. The standard deviation shows the differences in completion times between testers. These differences are greater for the magnet metaphor than for the UFO. Times ranged between three and 20 minutes.

Table 3: *Average playing times (min) for each interaction technique during preliminary and final study*

	Preliminary Study		**Final Study**	
	Magnet	UFO	Magnet	UFO
Average Time	12.0	6.3	6.5	6.0
SD	4.69	0.83	3.91	1.73

The displayed frame rate was also measured during the experiments. It never dropped below 20 frames per second, thus always being above the required limit for an interactive system.

5.2.2 Usability

Because testers were asked to rate their overall experience, the HARUS results do not distinguish between interaction techniques. The subjective ratings have only been collected from the eight participants completing both tasks. **Figure 20** summarizes the results from both studies. Users rated their agreement for the eight HARUS items on a Likert scale of 1 to 7, with 1 (*strongly disagree*) and 7 (*strongly agree*). The chart lists all statements in short form. The HARUS score between 0 and 100 is determined as described by Santos et al. [40]: The scale is translated from the 1-7 into a 0-6 scale and ratings from the four negatively stated questions are inversed to align with the four positive ratings. After that, the values are normalized. The average of these values is displayed in **Figure 20**. Therefore, it is important to note that a high rating on the chart for a negatively stated question means an originally low rating on the presented scale. A value of six for the statement “I felt that I was losing grip and dropping the device at some point.”, for example, means that testers strongly disagreed with that statement and did not at all feel like they might drop the device.

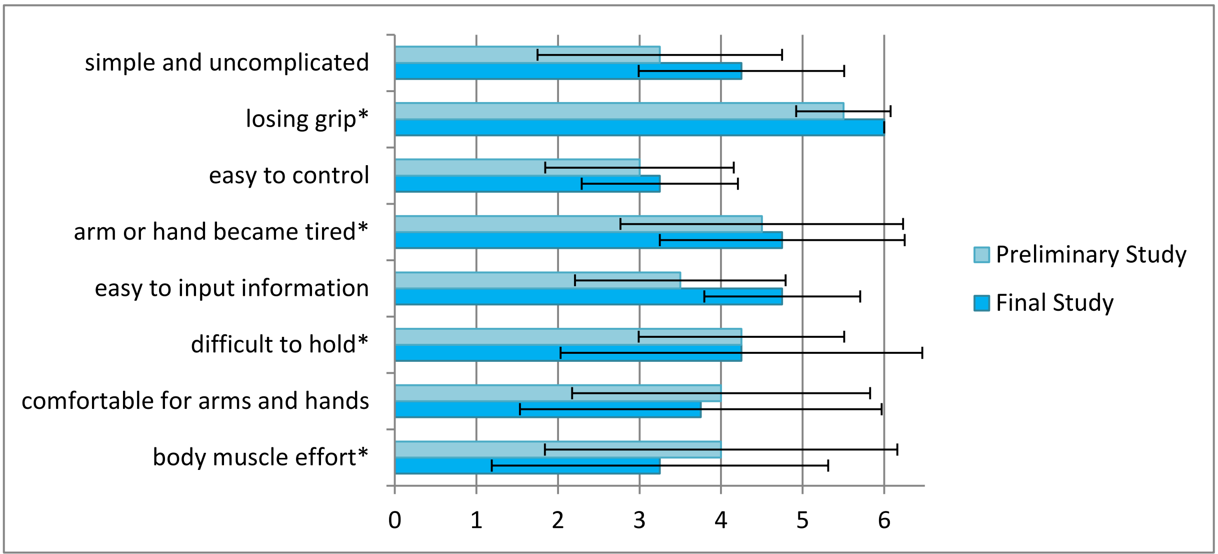


Figure 20: *Summery of HARUS questionnaire items and their average (normalized) user ratings. Negatively stated questions are marked with an *.*

The statements “I think the operation of this application is simple and uncomplicated.” and “I found it easy to input information through the application.” have been rated about one scale point lower in the preliminary study than in the final study. But measures for all statements, except the “losing grip” one, are widely scattered and their areas within standard deviation are clearly overlapping. The calculated HARUS score from the final study was 71 with an SD of 19. It is slightly higher than the preliminary score of 67 (SD = 15). Only the final score is just above the acceptable SUS score of 70 or above [4].

5.2.3 Game Experience

The GEQ has been answered separately for each metaphor on a Likert scale of 0 to 4, with 0 (*not at all*), 1 (*slightly*), 2 (*moderately*), 3 (*fairly*) and 4 (*extremely*). The 32 questions belong to seven different categories – competence, sensory and imaginative immersion, flow, tension/annoyance, challenge, negative affect and positive affect. The score for each category is calculated as the average of all ratings from the belonging items. These scores for both metaphors are shown in **Figure 21** for the preliminary study and in **Figure 22** for the final study. **Figure 23** and **Figure 24** display the same values, but instead of directly comparing the magnet and the UFO, they show the differences between the two studies for each metaphor.

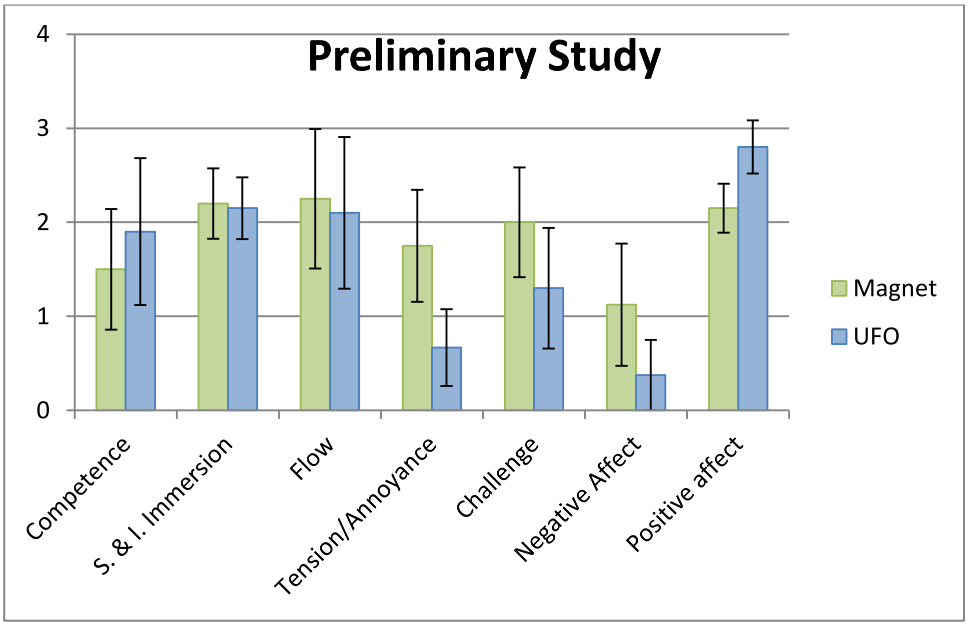


Figure 21: *Average GEQ user ratings from preliminary study: Comparison of the two interaction techniques.*

The preliminary study (**Figure 21**) shows the UFO and magnet metaphors to be relatively similar. But the testers felt a bit more competent, less challenged and experienced less negative and more positive affect using the UFO than they did, when playing with the magnet. The largest difference can be seen in the tension/annoyance category. The game experience with the UFO was rated less than slightly annoying, while playing with the magnet was close to being moderately annoying. In summary, the results of the preliminary study show the UFO to be the clearly preferred metaphor.

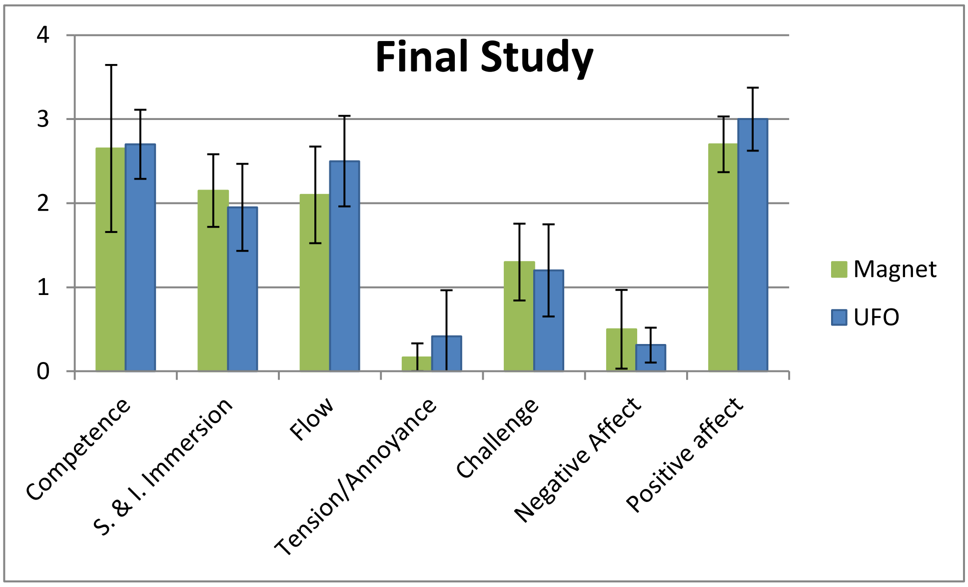


Figure 22: *Average GEQ user ratings from final study: Comparison of the two interaction techniques.*

The same cannot be said for the final study (**Figure 22**). There might be a small tendency for the flow category in preference of the UFO or an even smaller one for the positive affect. But all in all the ratings are very equal for both metaphors.

The GEQ results from the final study can be roughly summarized, as describing the experience of playing the prototype as not annoying or negative, slightly challenging and moderately immersive. The experience of flow has been moderate and testers felt fairly competent and positive while playing.

Looking at the details, a few questionnaire items stood out from the others in two categories. Within the challenge category two of the five statements have been rated very low compared to the other three items. Both, “I felt time pressure” and “I felt pressured”, directly or indirectly address the time-related component of challenge. Testers had not been instructed to perform the task in a certain time and the game also did not set any time-based incentives. Taking these two items out of the calculation changes the average challenge rating for both, magnet and UFO, from slightly challenging to moderately challenging.

The statement “I lost connection with the outside world” was also rated remarkably low compared to other items of the belonging flow category.

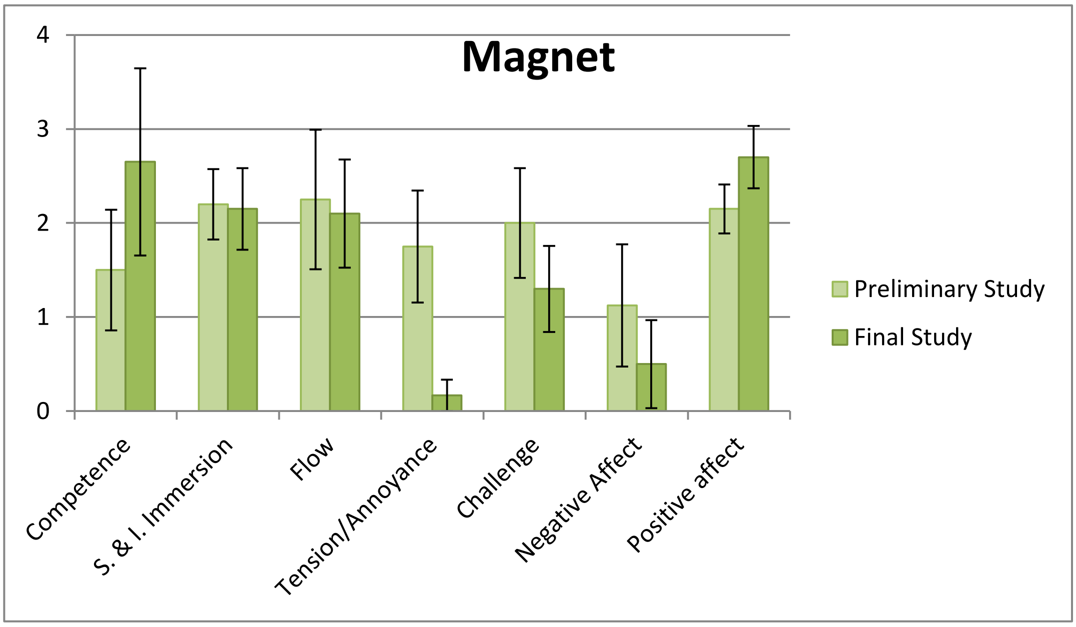


Figure 23: *Average GEQ user ratings for the magnet metaphor: Comparison of preliminary and final study.*

Comparing the preliminary and final user ratings of the magnet metaphor (**Figure 23**) reveals some interesting changes. Only immersion and flow were rated similar in both studies. Competence and positive affect were rated higher and challenge and negative affect lower in the final study. Again the tension/annoyance category displays the largest difference, dropping from nearly moderately annoying in the preliminary study to not at all annoying in the final study. The magnet interaction technique was obviously experienced as less frustrating and more positive during the final study, than it had been in the preliminary study.

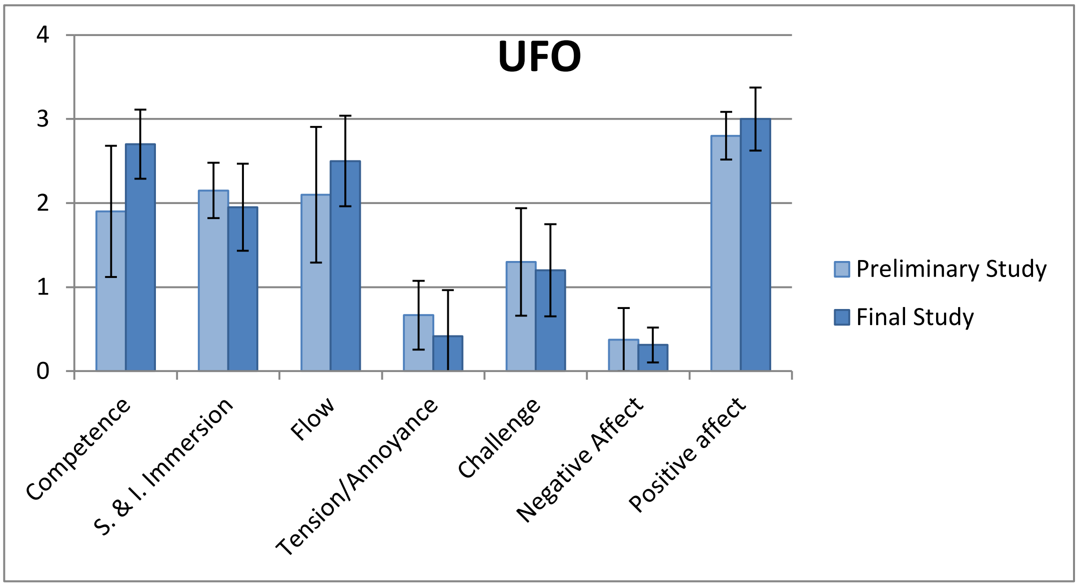


Figure 24: *Average GEQ user ratings for the UFO metaphor: Comparison of preliminary and final study.*

The UFO metaphor on the other hand has been perceived quite similar in both preliminary and final study (**Figure 24**). Only the competence rating changed from moderately in preliminary study to being closer to fairly in the final study.

5.2.4 Think-Aloud Protocol, Observations and Screen Recording

A vast amount of comments and opinions could be collected from the nine testers via think-aloud protocol, observing the players and sighting the screen recordings. They have been sorted and summarized into the more general categories:

1. Frequent problems and mistakes
2. Players' strategies
3. Opinions and evaluations
4. Wishes and suggestions

Items within these categories are further sorted as applying to the prototype in general, being specific for the magnet or specific for the UFO metaphor.

<u>Frequent problems and mistakes:</u>

General

- Jitter, because of shaky hands
- Loosing marker tracking or noticeable lag (seldom)
- Last target needed to be placed at an uncomfortable height (located on the pillar)
- Confusing targets or placing targets with wrong orientations (rules)
- “Ah, it goes through the floor” (expected the selected object to collide with the floor, when carried by magnet)

Magnet

- Objects dropped below floor with the magnet
- Hard to hit a precise point of an object with the magnet
- Vertical object rotation not easy to control with the magnet
- The UFO is much easier to use (only preliminary study)
- “It would be easier, if it didn’t have to be placed so precisely.” (only preliminary study)

UFO

- Hard to pick up objects from the rotating platform with the UFO, because either too difficult to aim (need to stay above target and then move straight down without losing aim) or not clear that it has to be touched from above (trying to simply move the target inside the UFO)
- Accidentally placing objects on ground with the UFO (e.g. when switching back from rotation mode)
- Other rotation direction expected, problems with frontal view or hard to estimate how far to rotate the target to make it snap into the correct position (UFO rotation mode)

<u>Players’ strategies:</u>

General

- Leaning on table to reduce jitter

Magnet

- Shortly picking and dropping targets with the magnet to fine-tune position
- Circular camera movements to rotate targets with magnet

- Letting the rotating platform turn the target to the desired rotation before picking it up with the magnet
- Flinging the target around with the magnet and dropping it, hoping it will land correctly (similar to rolling a dice)
- Waiting with magnet in a position on the rotating platform, where the target will move automatically

UFO

- Stopping the target rotation in the UFO rotation mode by ending the mode, instead of tilting the device back into the resting position

<u>Opinions and evaluations:</u>

General

- Hard to place the last target without a shadow on the transparent pillar
- Cursor height not easy to estimate
- “A lag is noticeable, but it isn’t troublesome”
- “Unfamiliar movement, but not difficult, a bit cumbersome. Probably uncomfortable in the long run.”
- “Nice that it snaps in a bit.” (object snapping on to goal platform)

Magnet

- “I actually have no clue how the rotating is controlled, but somehow it always worked”
- “Stupid that it doesn’t interact with the environment anymore” (moving selected target with the magnet)
- Selecting objects is more fun with the magnet, because it does not matter where they are touched
- “It’s actually more fun, only the fine-tuning is frustrating”

UFO

- Shadows and UFO beam are a great help in navigation
- “The rotation is done really cool”
- “Placing and rotating objects is quite easy to understand, feels intuitive”
- “Not enough feedback for selecting. I have the feeling I’m right on top of it, but nothing happens.”

- Objects are easier to place, because shadows remain the same (UFO, objects stay oriented parallel to the ground)
- Rotation is easier, more accurate and faster with UFO

Wishes and suggestions:

Magnet

- Better visualize that the cursor is not on the display like a crosshair, but in the space in front of it

UFO

- More Feedback to show when the UFO beam is on the target
- Use top view on target for the UFO rotation mode

5.3 Discussion

5.3.1 Preliminary and Final Study

Because the preliminary study revealed such a clear inequality concerning the difficulty level and some testers became frustrated with the magnet technique, some changes have been applied to the prototype, adjusting the tolerance limits to better balance the two metaphors. These changes are described in detail in Chapter 3.6. The effect of these changes on the evaluation results are discussed in this section.

For the UFO metaphor no changes could be observed between the preliminary and final studies, besides an increased rating for the GEQ competence dimension. This might be due to the greater tolerance values for the accepted object orientation, which have been applied to both techniques in the course of the prototype revision. The competence ratings in the preliminary study have a wide range from slightly competent to fairly competent and do not always correlate with the testers’ actual performance. It is a subjective measure of items, like “I was good at it” and “I was fast at reaching the game's targets”, and players might evaluate their own performance very differently. The difference between the two average ratings could be associated with a relatively great data variance and might vanish in tests with a greater sample size. With AR being a new technology, testers also did not have other familiar applications to relate to, making it harder to assess their competence level without knowing the expectations.

The change on tolerance limits had a clear effect for the magnet metaphor on the subjective GEQ ratings, player comments and also nearly halved the objectively measured playing time. With the better adjusted difficulty level players' efforts and failed attempts in precisely positioning the objects have been greatly reduced. Without the frustrating experience of failing again and again, nearly no tension and annoyance was measured in the improved prototype. Players were faster at reaching the next small achievement, which made them feel less challenged and more competent. In the preliminary study the low tolerance limits were perceived as unfair. Because most testers could not control their movements precisely enough, success was greatly dependent on luck and was therefore often preceded by many futile attempts, spoiling the game experience.

The results are yet another case that shows the importance of a well-adjusted difficulty level. If one of the game's incentives is very hard to reach, the reward needs to be large enough to make up for all the effort. A good game gives players enough motivational experiences right from the start with many easy to reach small awards and presents the greater challenges after the player has had enough time to practice and prepare himself. The prototype was only played for a few minutes and it was a new experience for the testers. Therefore, the easier version used in the final study was better adjusted for these circumstances.

5.3.2 **UFO and Magnet**

After adjusting the magnet's difficulty level the GEQ measures from the final study do not show any clear differences between the metaphors. But the think-aloud protocol and observations indicate that they were indeed perceived rather unequal. Both metaphors lead to a similar game experience according to the questionnaire's dimensions, but they also show different strengths and weaknesses.

The magnet performs better for selecting moving objects, is easy to understand, but hard to precisely control. Selection alone is an easy task, if the accompanied change in the target's rotation can be neglected. But if the selection is used to intentionally rotate the target, players are having difficulties to precisely hit a point on the target's surface. Rotating a selected object around the vertical axis is an even harder task, because this rotation cannot be precisely controlled. Depending on the required accuracy, this can become a source of frustration (see Chapter 5.3.1). On the positive side the magnet offers more freedom to play around and experiment with the interaction. But players also expected more realism from the magnet metaphor and were surprised to discover that it was a partly magical technique, when the selected objects freely moved through other solid objects, instead of colliding with them. The behavior was perceived as inconsistent with no obvious justification, because users are not aware of the trade-off between directly and indirectly controlled tools for 3D interaction, mentioned in Chapter 3.7.

The greatest challenge in playing with the UFO metaphor was the selection task, especially for the moving objects on the platform. Target position and rotation can be better controlled, compared to the magnet. For one reason, rotating and positioning are perceived as two separate tasks. Therefore, users also expect to be able to perform them separately and not influence the rotation, when they are focused on changing the position. The UFO, in contrast to the magnet, fulfills these expectations, making both tasks easier to control. And only four discrete rotations have to be controlled for each of the two dimensions in the rotation mode.

Most observed differences and some of the challenges have already been predicted in the classification section (see Chapter 3.7), such as the easier to control UFO rotation and the *Midas Touch effect* [27], occurring in the UFO's object selection and deselection. Players' difficulties in touching targets from above with the UFO emerged, because of missing feedback and could be solved by improving the visualization. In the final study none of the metaphors has been clearly preferred by the testers. Some favored the separately controlled and constraint rotation with the UFO technique, making the interaction easier to control. Others liked the freedom of the magnet's unrestraint movement and the space it offers to explore and experiment.

5.3.3 Interpretation of Results in respect of the Design Goals

Players' subjective sense of presence has not been directly measured in the performed studies, but observations indicate that players quickly recognized the marker as the playing field and had no problems to navigate by walking around it. The testers were confident with the robustness of the marker tracking. It was rarely lost and usually quickly regained, and therefore not disturbing the gameplay. Losing the tracking, of course, shortly reveals which objects are real and which are virtual. The time delay between the real scene and the camera video did not bother the testers, even though most have been aware of the lag. Some saw it as an issue, when making small adjusting movements, because the delayed visual feedback led to the players underestimating the movement's magnitude. One subject criticized that the camera view was too small and did not overlap correctly with the real scene, visible from the corner of one's eye. This is a known issue of handheld AR (see Chapter 2.1).

Playing the game was fun and proportional to the prototype's simplicity, the GEQ ratings have been quite high, probably for a great part thanks to the new exiting experience of the AR technology. For a richer game the immersion would certainly be stronger. The think-aloud protocol probably also affected the immersion and flow dimensions, because the players did not lose the connection to the world outside the game, while feeling observed and talking to the experimenter. For the GEQ, even though widely used in game research studies [28], no evaluations on its reliability and validity have been published [33]. An analysis of its factor structure [14] indicated that not all items are clearly associated with their assigned category. Thus, some subscales might not measure what they were designed to measure. But apart from these limitations, the GEQ represents a valid tool for measuring the game experience [33].

The results, concerning the ergonomic issues, indicate that the reviewed setup barely satisfies the requirements of a good application. Playing in a standing position with constantly held up arms is a tiring activity. The table height should be adjusted to the player’s body size. Smaller testers could not easily place the last object on its elevated goal position. But within a certain range both interaction techniques allowed users of varying sizes to hold the device at a comfortable viewing angle. Most testers only played for a few minutes, but one tester, playing with the magnet metaphor for 30 minutes, experienced the use as quite tiring. The effort to keep the cursor steady for precise maneuvering is especially straining. A longer game should be designed with enough breaks between these precise movements and also breaks in which the device can be lowered or put aside.

The strain can also be reduced by using the interaction techniques in a seated position with an option to rest the elbows or arms on a solid surface. This also increases the achievable accuracy of the interaction. Otherwise, the accuracy depends on the player’s skill and can be increased by training. The observed user skill levels varied greatly and influenced each player’s game experience. Less skilled users usually preferred the UFO metaphor, because it made them feel more in control.

6 Conclusions

6.1 Summary

Great interest in using AR technologies has been exclaimed from many sides, including game production. Human-computer interaction researchers hope that the border between the worlds in front and behind the screen will disappear and this will lead to new ways to more directly and naturally control technical systems. But progress in AR interaction research is still far from reaching these visions. This work has been conducted to explore a small portion of this gap.

Focusing on the scenario of handheld AR on mobile devices and games as applications, different concepts for appropriate 3D user interaction techniques have been planned. The designed techniques should fulfill four goals (see Chapter 3.1):

1. Preserve the illusion of an augmented reality
2. Be fun to play with
3. Avoid frustration, discomfort or fatigue
4. Support rather general tasks, applicable to many types of games

Using new, but commonly available tools (Unity, Vuforia) and hardware, prototypes for two of the designed interaction techniques have been implemented and evaluated. Both implementations employ a directly controlled 3D cursor as a tool to select, rotate and position objects in 3D space. For the first technique, this tool was designed as a small magnetic sphere. Interactive objects in the scene can be connected to it and manipulated by means of this connection and the object's simulated physical behavior. The second technique uses the metaphor of an UFO that picks and releases objects with its downward-pointing tractor beam. Manipulation of object orientation is controlled with the device's gyroscopic sensor.

A classification of the developed interaction techniques has been performed to point out the metaphors' conceptual differences and characteristics. The taxonomy serves as a base for discussion on the concept's pros and cons and aids to relate them to existing 3D selection techniques.

Prior to the final user study, the implementations have been improved through insights from informal tests. The final survey assessed playing times, subjective ratings on game experience and usability, and recorded players' thoughts during the tests. The test environment was a simple game that could be completed by placing five objects of different shapes correctly aligned on destined goal fields.

Both metaphors can be used in games of different genres and other applications. The survey's results show that they also fulfill the goal of *being fun to play with*. The study did not explicitly measure the players' sense of *presence* in the augmented environment. Therefore, the evaluation of this criterion is still pending. Ratings on the prototype's *usability* indicate that the ergonomic properties of the interaction were acceptable. But this might only be true for the short playing times, reviewed in the study.

Testers recognized the disadvantages and benefits of each metaphor, but none was clearly preferred over the other. In fact, the game experience ratings were quite similar for both techniques. However, the results showed clearly how important a correctly adjusted difficulty level can be for the game. Changes concerning the difficulty decided about the game being either a frustrating or an enjoyable experience.

6.2 Perspectives

Within the scope of this project, the influence of the interaction technique on the user's sense of spatial presence in the AR environment could not be investigated. The described techniques have been designed to better support the AR illusion and lead to a deeper immersion compared to conventional touch screen interactions. It remains an open question, if this intention will be fulfilled. Further studies should employ different interaction techniques as independent variables and measure their influence on perceived presence and immersion to clarify this issue. To perform such studies, new measurement tools need to consider the specific aspects of handheld AR.

Like all mobile AR applications, the two evaluated interaction metaphors would of course benefit from further advances in camera and tracking technology and more powerful mobile devices. More realistic shadows, rendered on markers and table surfaces, together with correct occlusions between virtual and real objects, can create a better illusion and offer helpful depth cues for the interaction.

Compared to a full-fledged game, the prototype offers only little feedback. More visual and auditory feedback in the form of animations and sounds could make the interaction more enjoyable and easier to control. Using a continuous sound to indicate that the UFO is close to the ground could, for example, help to avoid the *Midas Touch effect* [27].

The two implemented concepts could be adjusted in a variety of ways for different application requirements. The following two changes adopt the benefits from the UFO technique to make the magnet metaphor easier to control and at the same time remove the system requirement of a realistic physics simulation:

- Object rotation around the vertical axis is connected to the cursor and will follow the camera perspective.
- During selection the magnet always snaps to the center of the touched object face. Therefore, the selection requires less precision and the selected objects will always be oriented parallel to the ground with the cast shadows being easier to interpret.

A more realistic interaction could be achieved by placing the magnet on a fishing rod. Instead of staying at a constant offset to the camera it would be connected to the end of the fishing line and the camera would move the rod, dragging the line and magnet with it. The movement of the magnetic sphere could then be restricted by solid objects. The dynamic connection to the camera through the elastic line avoids the occurrence of great physical forces.

The UFO metaphor could be improved by:

- Using a volumetric selection tool, such as a cone, instead of a ray.
- Selection could be triggered within a certain range above the target.
- A timed trigger, combined with sound feedback.
- A stabilization mode, keeping the UFO at its current position, if activated. Or even making it follow a target automatically, when activated above the target.

This work discussed only interaction techniques, which use touch input as a binary discrete trigger. But combining conventional touch and alternative techniques could add more functionality and offer many new possibilities.

An interesting direction for further research is the usage of tangible interaction and collaborative AR. For example, the player can hold the device with only one hand (at least for a short period of time) and manipulate real objects with the other free hand. This could also be realized in conjunction with another player.

A possibility to adjust the difficulty level could make the new AR technology more accessible for unexperienced players. It might be implemented via a calibration mechanism prior to starting the actual game or by observing the player performance during gameplay. For example, if the player is repeatedly unsuccessful, the application could automatically adjust the difficulty with or without notification.

6.3 Closing Remarks

The described work demonstrates that convincing AR games can be built with the free and established technology and tools. Common smartphones and tablets can enable interactive AR experiences without using any additional hardware. The following three points are considered important issues for all mobile handheld AR applications, involving 3D interaction:

a) Navigation and depth perception

b) Ergonomic issues of handheld AR

c) Combined camera movement and interaction

Two further aspects are of interest in the design of handheld AR games:

d) Difficulty level

e) Skillful or comfortable

Navigating in an AR environment with the help of a handheld mobile device can be a very intuitive activity. But 3D orientation is not an easy task and cannot be achieved without a correct *depth perception*. To make up for the lower resolution and the non-stereoscopic view on the screen, other depth cues, such as shadows and object occlusion, are vital and should be specifically designed for navigation support.

Ergonomic issues arise, because mobile devices do enable AR applications, but they are not specifically designed to do so. Using common mobile applications does, for example, usually not involve a permanent video recording of the environment. Until the popularity of AR applications rises and the ergonomics for handheld AR are improved, designers of AR applications need to be aware of this challenge, additional to the specific challenges of 3D interaction in free space.

The benefit of multifunctional mobile devices comes with the challenge to handle all these functionalities with a limited set of controls. In the context of handheld AR, this is expressed in the tight connection between *camera movement and interaction tasks*. If moving the device controls selection and manipulation, these interactions cannot be separated from the navigation task, because along with the movement the camera perspective will inevitably change. The application design should therefore consider the use of different states to enable or disable certain interactions during navigation tasks to avoid unintended outcomes.

The *level of difficulty*, in respect to the required accuracy of the interaction, needs to be adjusted to the player’s skill and bodily limitations (hand jitter), associated with the player’s posture (seated, standing, arms rested etc.). The ability to precisely operate a device’s motion can vary greatly, especially among unexperienced players. The player’s should be able to reach the game goals within their means of control and not merely by chance.

Similar to the range from natural to magical interaction techniques, the game interaction can range from *skillful to comfortable*. The interaction can be either designed to challenge the player, requiring skill and leaving room for failure. Or it can be rather comfortable and support the player in reaching the goals faster and with less effort. The decision depends on the specific game.

These issues will probably be approached from two sides. Researchers and designers will find better solutions and maybe reach new standards and guidelines. As AR applications and games become more commercial and widespread, users and players will grow accustomed to their limitations, like they did with other technologies.

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8 Appendix

8.1 Demographic Questionnaire

General information

Age: __________ Gender: ○ male ○ female

Profession/discipline: ____

Questions about your previous experience:

Have you had any previous experience with Virtual Reality?

None	○	○	○	○	○	many
	0	1	2	3	4	

Have you had any previous experience with Augmented Reality?

None	○	○	○	○	○	many
	0	1	2	3	4	

Have you had any previous experience with Computer Games?

None	○	○	○	○	○	many
	0	1	2	3	4	

Have you had any previous experience with Mobile Devices (Tablets, Smartphones)?

None	○	○	○	○	○	many
	0	1	2	3	4	

8.2 GEQ

Game Experience Questionnaire

Please indicate how you felt while playing the game for each of the items, on the following scale:

not at all	slightly	moderately	fairly	extremely
0	1	2	3	4
○	○	○	○	○

1	I felt content	○	○	○	○	○
2	I felt skilful	○	○	○	○	○
3	I thought it was fun	○	○	○	○	○
4	I was fully occupied with the game	○	○	○	○	○
5	I felt happy	○	○	○	○	○
6	It gave me a bad mood	○	○	○	○	○
7	I thought about other things	○	○	○	○	○
8	I found it tiresome	○	○	○	○	○
9	I felt competent	○	○	○	○	○
10	I thought it was hard	○	○	○	○	○
11	It was aesthetically pleasing	○	○	○	○	○
12	I forgot everything around me	○	○	○	○	○
13	I felt good	○	○	○	○	○
14	I was good at it	○	○	○	○	○
15	I felt bored	○	○	○	○	○

not at all	slightly	moderately	fairly	extremely
0	1	2	3	4
○	○	○	○	○

16	I felt successful	○	○	○	○	○
17	I felt imaginative	○	○	○	○	○
18	I felt that I could explore things	○	○	○	○	○
19	I enjoyed it	○	○	○	○	○
20	I was fast at reaching the game's targets	○	○	○	○	○
21	I felt annoyed	○	○	○	○	○
22	I felt pressured	○	○	○	○	○
23	I felt irritable	○	○	○	○	○
24	I lost track of time	○	○	○	○	○
25	I felt challenged	○	○	○	○	○
26	I found it impressive	○	○	○	○	○
27	I was deeply concentrated in the game	○	○	○	○	○
28	I felt frustrated	○	○	○	○	○
29	It felt like a rich experience	○	○	○	○	○
30	I lost connection with the outside world	○	○	○	○	○
31	I felt time pressure	○	○	○	○	○
32	I had to put a lot of effort into it	○	○	○	○	○

8.3 HAR Usability Scale

HAR Usability Scale

Please indicate how much you agree with each presented statement on the following scale:

	1	2	3	4	5	6	7	
strongly disagree	○	○	○	○	○	○	○	strongly agree

1	I think that interacting with this application requires a lot of body muscle effort.	○	○	○	○	○	○	○
2	I felt that using the application was comfortable for my arms and hands.	○	○	○	○	○	○	○
3	I found the device difficult to hold while operating the application.	○	○	○	○	○	○	○
4	I found it easy to input information through the application.	○	○	○	○	○	○	○
5	I felt that my arm or hand became tired after using the application.	○	○	○	○	○	○	○
6	I think the application is easy to control.	○	○	○	○	○	○	○
7	I felt that I was losing grip and dropping the device at some point.	○	○	○	○	○	○	○
8	I think the operation of this application is simple and uncomplicated.	○	○	○	○	○	○	○

8.4 Image Marker