# *Augmented Reality in Hierarchical Micro-Navigation*

Bachelor's Thesis at the
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I hereby declare that I have created this work completely on my own and used no other sources or tools than the ones listed, and that I have marked any citations accordingly.

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*Aachen, March 2015*
*Marcel Lahaye*

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# Abstract

People organize their belongings in hierarchical storage structures like cupboards, shelfs or boxes. Finding objects in such structures can be a time consuming process which can often lead to frustration. Several systems have proposed augmented reality for searching and navigating.

This thesis presents a controlled experiment that compares visual aids which provide two types of spatial knowledge to navigate in a 3D micro navigation task. We compare two types of spatial knowledge which can be used to conceptualize those navigation aids: Route knowledge, which gradually provides step by step instructions and survey knowledge, which gives overview information. Thus route aids enable the user to instantly start the task without any planning, while survey aids provide the user with the ability to think ahead, give an estimation of effort and time and also enable the user to recover from errors.

We use four different visualizations which are based on related work. A set of two visualizations each represents one of the two spatial knowledge types: *Spotlight*, *Icon*, *X-Ray* and *Cut-Away*. We use a cardboard mock-up to simulate the augmented reality system in the user study.

The study data and the participant feedback suggests that both types of spatial knowledge are sufficient to be used as base for augmented reality navigation aids. However with increasing task difficulty route aids begin to outperform survey aids in terms of task completion time and user error rate. This agrees with our hypotheses which expected survey aids to be more error prone and route aids to be more user preferred. The results contradict with our hypothesis that survey aids outperform route aids.

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# Chapter 1

# Introduction

People organize their objects in hierarchical structures like shelfs, drawers, or boxes [22]. If the given information to find the object is insufficient people get stuck and and are not able to finish the search which leads to frustration [27]. In a three dimensional hierarchical structure occlusion may lead to visual clutter and increase the possibility for navigation problems.[6].

People need help with finding their stuff in deep physical hierarchies.

Typically there are three steps in a physical search: First defining the search target, second locating the target and third navigating to the target.

Steps in a physical search.

A navigation task consists of two parts: The *macro-navigation* and the *micro-navigation*. A macro-navigation task demands a translation of the user, because the goal is beyond the user's perception and reach. A micro-navigation task is in-room-navigation, where the target object is within the user's reach [23].

Macro vs Micro Navigation.

Existing systems that are created to help people to navigate, focus on the macro navigation, like Find My Stuff by Knierim et al. [12], or on only two dimensional micro navigation, like the system by Biocca et al. [5]. A structured analysis of a three dimensional micro navigation system is missing so far.

Structured analysis missing.

Visual search: Conspicuity and expectancies.

A visual search can be subdivided into two parts: *Conspicuity* and *Expectancies* [25]. Conspicuity describes how much a target "stands out" from its background and its surroundings, like a red line of text in a book which got marked by a student. Expectancies are where the user expects the item to be, based on her knowledge. For example a user might know that she usually puts her cups on the top shelf in her cupboard in the kitchen, so if she looks for a cup she expects the cup to be there.

We focus on two types of spatial knowledge: Route and survey.

To assist a user to navigate in a visual search task spatial knowledge can be provided. Two types of spatial knowledge, are route and survey knowledge [10]. Route knowledge gradually provides users with instructions of what to do next, like turn-by-turn navigation in car navigation systems. Thus it is supposed to always give the information at the moment the user needs it and therefore tries to reduce any overhead of planning beforehand. With route knowledge it is hard to recover from an error, which the user has made, if the system is not able to provide information on how to recover from this error. Survey knowledge instead gives overview information of the target location, the user's location and the surroundings, like a map application. Therefore it enables the user to plan ahead and estimate effort and task completion time. An overview aid also gives information on how to recover from an error. The downside is that this demands a lot of user initiative and personal investment. We do focus on these two types of spatial knowledge because these are the ones research has shown to be effective [20, 1, 2].

Benefits and challenges of using augmented reality to provide navigation aids.

Augmented reality can provide an unobtrusive way to present such navigation aids while maintaining the direct vision onto the hierarchical structure [9]. However providing a visualization which does not occlude the field of view and does not get cluttered is a challenging task. Especially when dealing with depth [15]. So we consult related work to extract four visualizations which are used to compare survey and route knowledge: *Spotlight* [21], *Icon* [11], *X-Ray* [15] and *Cut-Away* [7]. Spotlight and Icon are both route knowledge visualizations which both gradually give navigation information to the user. X-Ray and Cut-Away are both survey knowledge visualizations which provide an overview of the composition of the hierarchical structure to the user.

User study and first insight data.

The aim of this thesis is to study the efficiency of the two types of spatial knowledge (route and survey) in a 3D micro navigation task and their sufficiency to provide navigation information. To accomplish this we conduct a user study in which the user has to retrieve an object from a hierarchical structure. We measure the task completion time, user errors and the user preference. We use the four navigation aid visualizations to provide navigation information. With this we like to achieve a first evaluation of the performance of the two spatial knowledge types in 3D micro navigation.

# Chapter 2

# Related work

## 2.1 Spatial knowledge

Cousins et al. [8] and Goldin et al. [10] report that navigating needs spatial knowledge. Spatial knowledge can be subdivided into three parts: *Route*, *Survey* and *Landmark*. Route knowledge provides navigation information sequentially. Survey gives the user an overview over the navigation situation. Landmark aids are landmarks which are near the navigation target and can be used to navigate to the target. The work by Peponis et al. [18] suggests that survey and landmark knowledge is simultaneously developed and the user forms something like a *cognitive map*.

Types of spatial knowledge: Route, survey and landmark.

## 2.2 Augmented Reality Navigation Aids

So far structured research of augmented reality navigation aids focuses mainly on 2D navigation and macro navigation. Research like the one by Li et al. [13] shows that Augmented Reality highlights on target objects in a visual search task improve the user performance significantly. They also report a high acceptance from users. Biocca et al. [5] introduce an Augmented Reality visualization technique which should guide the users attention, called "attention funnel". They report that their technique improves user performance and also reduces the mental workload of the user. Schwerdtfeger et al.[20] add more visualizations to guide the users gaze. Akaho et al. [2] present a car navigation augmented reality system which provides route knowledge with a visualization onto the car front window. Their work shows that

Augmented reality navigation aids are able to improve the user performance significantly augmented reality visualizations are able to increase the ease of understanding the navigation aid. This is possible because augmented reality visualizations overlay the real world and do not need to reproduce it with a computer graphic rendering.

Previous work suggests higher user preference of route aids.

Another study by Li et al. [14] compares two navigational Augmented Reality aids, map and arrow, in an indoor macro navigation task. The map and arrow visualization do also represent two types of spatial knowledge, survey and route knowledge. In their study users prefer the map visualization over the arrow visualization, because they have a feeling of "loss of control" with the arrow. Möller et al. [16] do continue the research on indoor navigation techniques by using images of the environment (*visual localization*) to guide the user.

Using the X-Ray metaphor to look into the structure.

Webster et al. [24] evaluate the usefulness of an X-Ray Augmented Reality system which should provide the information of the infrastructure behind a wall for architectural construction inspections. Livingston et al. [15] present a solution to the possibility of visual clutter from the X-Ray visualization. Avery et al. [3] add some techniques to this to improve the X-Ray visualization by adding more visual feedback of the spatial layout of the objects in the field of view of the user.

## 2.3 Object Finding Systems

Systems which do know the location of physical objects in a room are feasible

Yap et al. [26] show that a system which accepts user search queries and knows the location of every object (in a room for example) is feasible, by introducing their system for finding objects in a macro navigation task based on RFID tags. They use a description of the relative location of the container object to give feedback to a user where her target object is hidden. Knierim et al. [12] do continue this approach with their FiMS system. The work by Siio et al. [22] presents Digital Decor objects which are able to keep track of their interior. In our study we assume that such a background system that accepts user search queries and knows the location of every object in the room is present.

## 2.4 Navigating in 3D

Challenges of providing navigation aids in a 3D environment

Burigat et al. [6] look into the challenges of providing navigation aids in a three dimensional environment. They compare three navigation aids (3D Arrow, 2D Arrow and Radar) in a geographic virtual environment and an abstract virtual environment. A significant finding is that the navigation aid needs to be designed for the navigation environment, else it might not bring a benefit for the user even compared to not having any navigation aid.

Cut-Away visualization provides insight into the structure.

A way to look into a structure of objects is presented by Coffin et al. [7]. They show a technique which allows the user to cut into the walls of the structure such that it creates a hole like a window which enables the user to look behind the structure walls.

# Chapter 3

# Navigation Aid Visualizations

We look into related work to evaluate the two types of spatial knowledge —survey knowledge and route knowledge— and create four visualizations based on previous papers. For route knowledge we use the visualizations called Spotlight and Icon. For survey knowledge we use the the visualizations X-Ray and Cut-Away. These visualizations will now be explained in more detail.

Four visualizations for the evaluation: Spotlight, Icon, X-Ray and Cut-Away

## 3.1 Spotlight

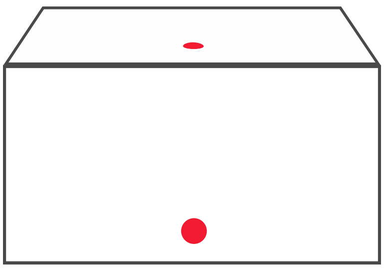


**Figure 3.1:** Conceptual image of the Spotlight visualization.

The Spotlight visualization is based on the simple navigation aid visualizations by Schwerdtfeger et al. [21], Henderson et al. [11] and Li et al. [13] that use simple shapes to highlight objects. The spotlight visualization is a red dot projected onto the object with which the user needs to interact next. So the moment the user

The Spotlight visualization highlights the next object, with which the user needs to interact, with a red dot.

finishes the interaction with one object the Spotlight on this object disappears and it reappears on the next object. The position of the dot correlates with the absolute location of the target object inside the hierarchical structure. So imagine yourself looking onto the container object from the front such that you can see the front side and the top side. The target object is located behind the front of the container in the center area. The dot will then also be located at the lower center area on the front side and more to the front area on the top side (Figure 3.1.

## 3.2 Icon

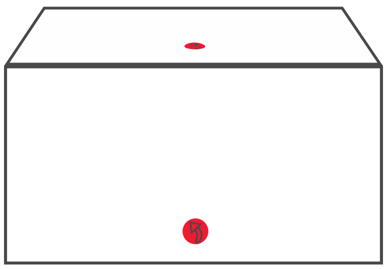


**Figure 3.2:** Conceptual image of the Icon visualization.

The Icon visualization extends the spotlight visualization with instruction icons on the red dot.

The Icon visualization extends the Spotlight visualization with instructions on what to do with the container object in focus. Similar to the projected instructions by Henderson et al. [11]. When you interact with an object in the hierarchical structure then there are two interaction possibilities. Either the container object is occluding or including the target object (if neither of these possibilities is true than there is no interaction needed). To handle the occlusion you simply need to remove the container object and put it aside. If the container object is including the target object than you need to open it and go deeper into its internal structure. With the spotlight visualization the user can interpret the position of the highlight dot to guess what interaction is required to progress further towards the target object. This guessing can be possible source for errors. To avoid these errors and also reduce the mental workload, we introduce the Icon visualization, which provides a set of icons, which visualize the required interaction. The Icon visualization shows a curved left arrow (↶)when you need to open the container object or it shows a straight arrow (↑) if the container object is occluding the target and you need to remove it.

## 3.3 X-Ray

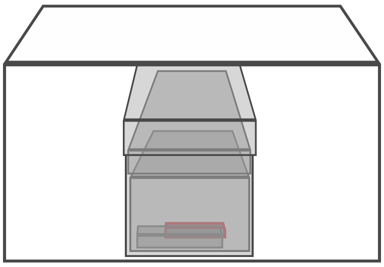


**Figure 3.3:** Conceptual image of the X-Ray visualization.

The X-Ray visualization is based on the publication by Livingston et al. [15] and Avery et al. [3] where they try to solve the problem of visual clutter that can appear when multiple visualization layers occlude each other. The X-Ray visualization itself reassembles the X-Ray method known from the field of health care, where electromagnetic radiation is used to see the internal structure of the human body. In our situation this visualization tries to enable the user to see through the different object layers that are between her and the target object. To achieve this we generate an image of the internal structure as it would be seen at the starting position by the user. In this image the boxes are rendered with a wireframe model and filled with a semi-transparent grey tone (50% opacity). With increasing depth inside the hierarchical structure the intensity of color is reduced by steps of 30 in a 256 RGB scale. The target object is outlined in red to make it easier distinguishable from the container boxes even when it is really deep inside the internal hierarchical structure and therefore occluded by several layers. To avoid visual clutter and to reduce the mental workload only container objects that are on the shortest path to the target object get rendered. The fact that only the objects, with which the user needs to interact with, are rendered gives the user a path leading to the target object. We render the objects in real-life size such that the rendered size is the same as the size of the real object. This provides the user with the ability to make a better estimation of the required effort to get to the target objects since she now knows the correct size of the container objects in the internal structure.

The X-Ray visualization enables the user to see through the structure walls.

## 3.4 Cut-Away

The Cut-Away visualization is based on the publication by Coffin et al. [7]. It describes a vertical cutting plane that cuts through

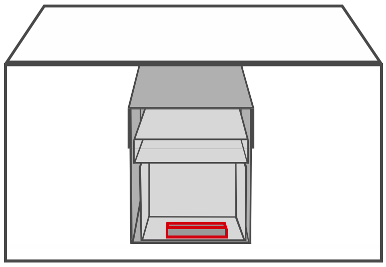


**Figure 3.4:** Conceptual image of the Cut-Away visualization.

The Cut-Away visualization cuts a window into the structure walls and enables the user to see inside.

the container object hierarchy and removes the layers that are between the target object and the user. The Cut-Away visualization only renders objects, with which the user needs to interact with. The reason for this is again to reduce possible visual clutter and reduce the mental workload required by the user. This visualization should have the benefit that the target object is not occluded by semi transparent layers and is therefore easier to see. Again the objects are rendered in real-life size. The image is rendered such that the view perspective is the same as the perspective of the user who stands in front of the hierarchical structure. The container objects were rendered with full opacity, filled with a grey tone, with intensity steps of 30 in a 256 RGB scale for each step of depth in the hierarchical structure. The target object is outlined in red such that it is easier to distinguish it from the container objects.

# Chapter 4

# Prototype

The prototype was required to be as unobtrusive as possible to avoid any confounding side effects in the user study. To achieve this we want the prototype to maintain a hands-free interaction with the prototype such that both hands can be used to interact with objects in the hierarchical structure. Another requirement to the prototype is that it should not limit the field of view of the user since this could again be a confounding factor on task completion time and maybe the user satisfaction. A limitation of the field of view can also result in more errors because the user might miss a detail that would be the hint for her to progress on the correct path to the target object. Another requirement is a good display quality for the visualization. The X-Ray and the Cut-Away method use the difference in intensity of color as an indicator to give cues to the user. Therefore the display quality has to be good to render the intensity difference. This enables the user to identify the difference in intensity of color. We test three different prototypes, which will now be described in detail with their individual pros and cons.

The prototype needs to allow a hands-free interaction, be unobtrusive and provide a sharp rendering of the visualizations.

## 4.1 Head Mounted Display


**Figure 4.1:** The head mounted display prototype.

The head mounted display prototype does allow the hands-free interaction but limits the field of view and may create lag.

The head mounted display prototype consists of a smartphone with a housing that fits onto the face of a user. Optical lenses are used to focus the image correctly. A small piece separates the screen in front of the users eye. The separation is used to have one individual space of the screen for each eye to create a stereoscopic 3D effect. A Holga 3d Lens Set adapter was used to transform the 2D camera of the smartphone into a 3D camera. Thus provides the 3D vision for the user. This installation tries to reassemble more sophisticated head mounted displays like the Occulus Rift [17], which are not available to us during this thesis. This prototype maintains a hands free interaction and allows the user to use her hands to interact with the container objects of the hierarchical structure. The nature of a video see-through head mounted display allows to have full control over what the user sees which can provide a wider range of possibilities for the visualization cues [4]. However this prototype highly limits the field of view for the user and this may influence the user performance during the study. The 3D vision of this prototype is hard to adjust to the user and therefore tends to feel unnatural.

## 4.2 Ceiling Mounted Projector


**Figure 4.2:** Image of concept visualizations projected onto cardboard boxes with a projector.

The next prototype consists of a projector which is mounted to the ceiling of a room. Tho projector displays the visualizations onto the container objects while the user is interacting with them. This prototype provides a hand free interaction with the augmented reality device and allows the user to use both hands for the interaction with the container objects. A problem which occurs with the projector is that different shades of grey are hard to distinguish. Which might lead to errors in the interpretation of the visualization cues. Another problem is that the moment the user moves a container object, the augmentation breaks, if the projection does not adapt to the user movement. Therefore we need to track either the user or the container. Tracking of the boxes is hardly possible because markers on the containers could be a confounding variable in the user study. Image tracking systems like the Vuforia framework by Qualcomm [19] are not reliable enough to provide a fluent projection at the time this thesis gets written. We want to keep the system unobtrusive and therefore we discard using markers on the users body. Also the fact that the grey shades are hard to distinguish discourages using a Ceiling Mounted Projector prototype because it could increase the mental workload of the user.

The ceiling mounted projector is unobtrusive and allows a hands-free interaction but the rendering is not good enough.

## 4.3 Cardboard Mock-up

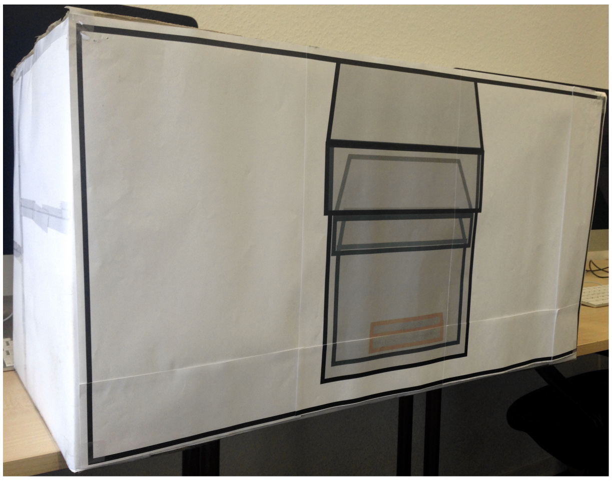


**Figure 4.3:** Image of one of the cardboard mock-up visualizations used for the user study.

The cardboard mock-up prototype reassembles the visualizations with cardboard boxes and transparencies.

The final prototype is a basic cardboard mock-up prototype, which simulates the augmented reality overlay with transparencies, which are attached to cardboard boxes. The cardboard boxes are white to create a clear background which gives a contrast to the visualizations. We expect a white background to enable the user to understand and process the visualization more easily.

### 4.3.1 Advantages

The cardboard mock-up prototype is unobtrusive, allows hands-free interaction and provides a good visualization rendering.

The cardboard mock-up prototype does not have the technological limitations of current devices, which are able to display augmented reality visualizations, and simulates the intended unobtrusive experience of such an augmented reality application. It provides a hands free interaction, does not have lag, does not limit the field of view and modern printers also have such a quality that the different shades of grey can be distinguished. We do not need to attach any device or markers to the user. Any attachments to the user's body could be uncomfortable for the user or limit his movements. This should lead to a minimization of confounding effects. The position of the route visualizations (Spotlight and Icon) does adapt to the movement of the container objects since the transparency are attached to the container objects. This reassembles the behavior which is expected from such an augmented reality visualization.

### 4.3.2 Limitations

A limitation of this prototype is that the visualizations are static. The position of the visualizations moves with the users movement, since they are attached to the container objects but the visualization itself does not adapt to the users movement. Therefore the survey visualizations are fixed to the start position of the user. In a real scenario the user would be able to move around the visualization and it would adapt to the user movement. Effects like *parallax scrolling* (Objects closer to the camera move faster than objects in the background) should allow the user to get a better feeling of what is inside the hierarchical structure and how are the inside objects arranged.

The visualizations of the cardboard mock-up prototype are static, the overview visualization do not adapt to the user movement.

The survey visualizations should enable the user to look inside individual objects of the hierarchical structure. So when she is interacting with a box and wants to know what is inside, the system shows either the X-Ray or the Cut-Away visualization. Changing the visualizations during the study would influence the task completion time and would therefore introduce a confounding factor. So the cardboard mock-up prototype cannot reassemble the omnipresence and the possible interactivity of the survey visualizations without introducing a confounding factor.

The prototype lacks the possibility to interactively look inside individual objects without introducing a confounding factor.

### 4.3.3 Why this prototype?

The cardboard mock-up prototype is a sufficient system for the targets of this thesis.

We choose this prototype over the other prototypes because it enables us to make a first user study and have a first impression for future studies in the field of augmented reality in micro navigation tasks, without dealing with the technological disadvantages of the other prototypes. The evaluation needs to consider that the survey visualizations do not completely represent all possibilities of survey augmented reality visualizations. However this thesis wants to give a a first impression of how the navigation aids will function in an augmented reality system and investigate whether navigation aid visualizations can provide the navigation aid in 3D micro navigation tasks. We expect the cardboard mock-up prototype to be sufficient to give this first evaluation and impression.

# Chapter 5

# User Study

## 5.1 Hypotheses

We want to test three hypotheses with our user study. The first hypothesis **H1** is that survey aids are faster than route aids.The second hypothesis **H2** is that route aids lead to fewer errors than survey aids, but survey aids better support error recovery. The third hypothesis **H3** is that users will prefer the route aids over the survey aids.

We conduct a user study to test our hypotheses.

## 5.2 Task

We conduct a user study to test these three hypotheses. The user actions, which are needed to solve the study task, should replicate the actions a user would do in an everyday micro navigation task. Therefore we create a set of boxes with different sizes and combine them as a hierarchical structure. This should reassemble this situation: A user has placed an object inside this combination of boxes and now she wants to retrieve this object but forgot in which box she placed it. So the task is that the user has to retrieve the object which is hidden inside the hierarchical structure. The participant was asked to show the object and say: "found it!" after she found the target object. This is a scenario where an augmented reality system which uses the presented visualizations could be helpful with retrieving the object in a more convenient way. To measure this convenience we wanted to observe the task completion time, the user error rate and the user satisfaction. These are the dependent variables in our user study.

The study task needs to reassemble the real use case.

## 5.3 Dependent Variables Measurement

### 5.3.1 Task Completion Time

Dependent variables: Task completion time, user error rate and user satisfaction.

The measurement of the task completion time begins the moment the user sees the setup (she has to turn around after a start signal) and ends when she says: "found it!". It is measured in seconds. With this measurement the task completion time consists of the motor execution time and the mental preparation time which the user needs to interpret the visualization. The interesting part is the mental preparation time since we expect this to change with the visualization. The motor execution time should not differ significantly since the time a participant needs to open the correct boxes should always be nearly the same. To reduce the difference in the motor execution time the participants are asked to open the boxes fast and without hesitation. Participants are also asked to put every box aside which is no longer needed and they should not delay themselves with putting the boxes back in the correct order. This should guarantee a minimization of the difference in the motor execution time within each trial. With these requirements should significant differences in the target execution time, between tasks in the same difficulty level, only be caused by differences in the mental preparation time.

### 5.3.2 User Error Rate

Definition of a user error.

To define what counts as an user error imagine a decision tree for the whole hierarchical structure. The structure is designed such that the decision tree has a unique shortest path to the target object. If the participant makes a decision such that she leaves this shortest path than this decision is counted as an error. For example if she opens a wrong container object.

### 5.3.3 User Satisfaction

User satisfaction gets measured with a ranking and a questionnaire.

The user satisfaction gets measured with a simple ranking and a questionnaire (Appendix A). After all trials are solved the participant is asked to rank the visualizations based on her personal preference. If a participant has finished all trials of one of the visualization she is asked to pause the trials and fill out the questionnaire, which consists of questions from the system usability scale, which are adapted to the augmented reality system that gets simulated in this study. There is one of this questionnaires for each of the visualizations.

We conduct an interview, after the trial tasks, with the participant and ask questions (Appendix A) to get some qualitative data and some feedback. We are interested in, whether the user has a search strategy or which device she would prefer to use this system on. These are informations which can help designers in their planning phase when they want to implement such a system.

We conduct an informal interview after the study tasks.

## 5.4 Independent Variables

The independent variables are the difficulty of the task and the visualization. The visualizations are the ones which have already been described before (Spotlight, Icon, X-Ray, Cut Away). The task difficulty is defined by the number of visibility barriers which are placed between the user and the target object. There are two types of barriers in this study: container objects, which surround the target object and need to be opened to access the target object and layers, which are objects that just occlude the target object and need to be removed to access the target object. We conduct a preliminary study beforehand to determine bounds for the task difficulty in which significant differences between the effectiveness of the visualizations should occur. The levels in task difficulty in this study are Easy (task difficulty: one), Medium (task difficulty: three), Hard (task difficulty: five).

Independent variables: Visualization and task depth.

## 5.5 Study Setup and Procedure

The study is conducted with a full factorial subject design with 14 participants (five female, nine male, 20 - 48 years old) with normal or corrected-to-normal visual acuity and no severe known impairments of the motor system (hand tremor, etc.). This results in a number of 168 tasks (14 x 4 x 3 = 168). To counterbalance learning effects of the combinations or other unknown and unwanted effects based on the order of the combinations we use a 24 x 24 latin square. The hierarchical box structure consists of 49 cardboard boxes of different sizes (Figure 5.1).

We have 14 participants, 168 tasks and use a latin square to counterbalance unwanted effects.

Before the participant begins to do the study tasks, we want to make them familiar with the box setup. We do this because we

We familiarize the participant with the setup before we start the study tasks.

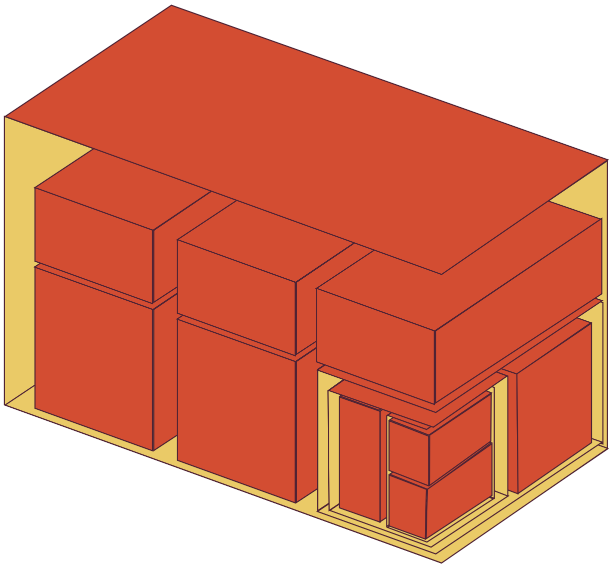


**Figure 5.1:** Setup of the 49 cardboard boxes.

want to avoid any confounding factor which might occur when a participant does not know how to open a specific box for example. This might lead to a situation where the participant needs to stop with what she is doing and gets confused. This situation might lead to errors or affect the task completion time. Therefore a participant is asked to open each box of the box hierarchy setup to get familiar with the whole setup before the study tasks begin. The box setup does not vary between the tasks, only the location of the target object changes.

Survey visualizations are attached to the outside. Route transparencies are attached onto each box that requires an interaction.

The transparencies, which represent the navigation aid visualizations are either attached to the outside of the whole box structure, or onto the outside of each box, with which the user needs to interact with. This depends on the spatial knowledge type which they represent. The survey visualization transparencies get attached to the outside of the hierarchical structure, as if the user is able to look through the structure walls inside the box structure. The route visualizations are attached onto each box, that requires an interaction from the participant to get to the target object. This should reproduce the effect of an augmented reality application, which renders such visualizations onto the boxes. The transparencies are changed between each task. This takes about two minutes.

**Figure 5.2:** Image of how the setup looks during the study.

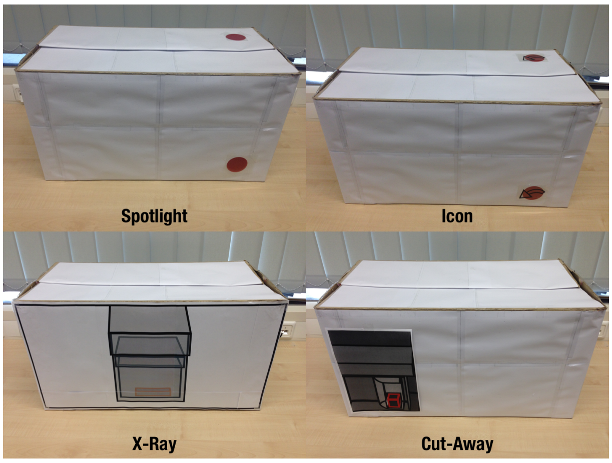



**Figure 5.3:** Image of how the visualizations look with the cardboard mock-up.

After the user is familiar with the box setup, she gets shown all visualizations with a simple trial task. During this trial task all visualizations get explained in detail: What the different colors mean, what the icons mean and how the location of the visualization correlates with the target object location. The participant is encouraged to ask questions until she is sure that she has understand every visualization in detail.

We do some trials tasks to teach how the visualizations work.

The study is video taped to have more insights in the participants behavior afterwards and to enable the participant during the interview to have a look at her actions and remember specific situations, in which she might have come across a special event.

The study gets video taped.

# Chapter 6

# Evaluation

The quantitative data from the study gets analyzed with a full factorial analysis on *Visualization x Task Difficulty* with repeated measures ANOVA and Tukey HSD for post-hoc tests.

## 6.1 Effects on the Task Completion Time

There is no significant effect of the *Visualization* alone on the *Task Completion Time* in the study data ($F_{3,143} = 0.08, ns$). The visualizations performed individually as follows: *Spotlight* ($M = 17.12s, SD = 7.58$), *Icon* ($M = 17.52s, SD = 6.70$), *X-Ray* ($M = 21.09s, SD = 12.67$) and *Cut-Away*($M = 21.76s, SD = 11.68$). These results contradict our first hypothesis **H1** which stated that survey aids will be faster than route aids. This is based on the assumption that planning ahead will give an advantage for the execution of the task. The observation of participants in the study shows that when a participant is confronted with a route aid she immediately begins executing the search task by following the instructions (This was true for all participants). If the participant is confronted with a survey visualization she stops and begins processing the overview image provided by the visualization. After she concludes a plan on how to traverse the hierarchical structure she begins executing her plan (This was again true for all participants). While executing their plan participants sometimes need to step back and have a look at the overview image again. Participants answer that they do this because they forgot the organization of the structure or they misinterpreted the overview image. This stepping back and the fact that the task itself did not take long enough to make the advantage of planning ahead

We found no significant effect of the visualization on the task completion time.

count, may result in the overall increase of the survey aids task execution time.

There is a significant effect of the task difficulty and an interaction effect of visualization x task difficulty.

The results reflect a significant effect of the *Task Difficulty* ($F_{2,143} = 145.27, p < .05$) and a significant interaction effect *Visualization x Task Difficulty* ($F_{6,143} = 2.86, p < .05$) on the *Task Completion Time*. The *Task Completion Time* increases significantly across all levels of *Task Difficulty*: *Easy* ($M = 9.82s, SD = 2.16$), *Medium* ($M = 19.80, SD = 5.09$) and *Hard* ($M = 28.50, SD = 10.11$). The significant interaction effect can also be seen in the graph (Figure 6.1).

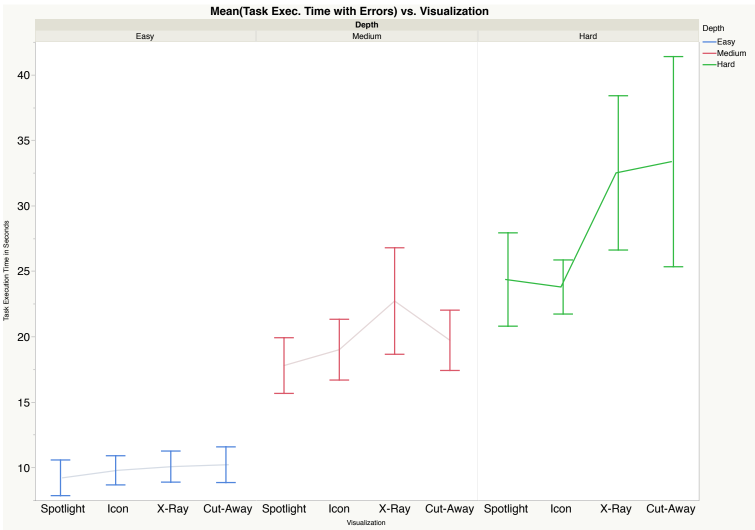



**Figure 6.1:** Task Completion time of the navigation aids at three levels of difficulty.

Post-hoc test supports the significance findings.

With increasing difficulty the higher increase in task completion time of the survey aids compared to the route aids gets more clear. The interpretations of only the graph should be treated carefully because the confidence interval bars indicate that the actual increase might not be as high as the graph suggests. The ANOVA and the Tukey HSD post-hoc test support the observation with a significance finding. The post-hoc test indicates a contribution from the visualizations and the count of errors to this interaction significance. This suggests the interpretation that with increasing difficulty the numbers of errors that are made with the overview visualizations lead to a sharper increase of the task execution time. This again indicates that the advantage of planing ahead is not present in tasks which take only a short amount of time. The time it needs to process the survey visualizations may take too long with increasing task difficulty.

## 6.2 User Error Rate

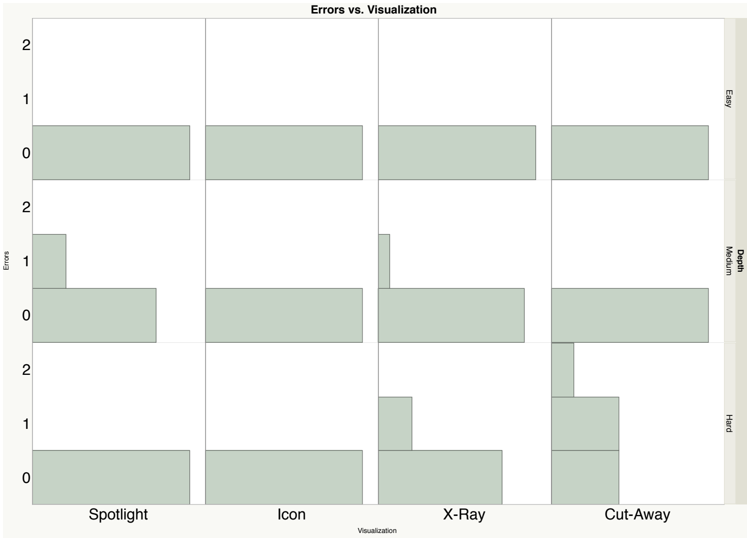



**Figure 6.2:** Distribution of the task on the count of errors.

About 8.90% of the 168 trials included at least one error: *Spotlight* ($M = 0.07, SD = 0.260$), *Icon* ($M = 0.0, SD = 0.0$), *X-Ray* ($M = 0.09, SD = 0.30$) and *Cut-Away* ($M = 0.24, SD = 0.53$). An ordinal logistic regression model shows a significant effect of *Task Difficulty* ($\chi^2 = 18.82, p < .05$) and the *Visualization* ($\chi^2 = 13.59, p < .05$) on the *Count of Errors*. The *Count of Errors* was significant at *Task Difficulty Hard* ($19.64\%$ of all hard trials have at least one error) but not at *Task Difficulty Medium* ($7.14\%$ of all medium trials have at least one error) and *Task Difficulty Easy* ($0.0\%$ of all easy trials have at least one error). A significant difference in *Count of Errors* was found between the *Survey Visualizations* ($14.29\%$trials have at least one error) and the *Route Visualizations* ($3.57\%$ of all route aids trials have at least one error). Overall this reflects a low amount of errors made by the participants of the study. Which leads to the assumption that both types of spatial knowledge may be suitable navigation aids in a micro navigation task. However the more complex the task is the more error prone do the overview visualizations get. In contrast to this the route visualizations seem to be more stable, independent from the task difficulty. That confirms the first part of our Hypothesis **H2** which says that route aids are more robust against errors than the overview aids. However since there are so less errors it is hard to argue about the second part of **H2** which said that survey aids better support error recovery. The direct observation of the participants during the study brings the insight that after participants have made an error they do recover equally fast. In both cases the participants steps back and has

All tasks have a low amount of errors. But with increasing task difficulty get the survey visualizations more error prone.

another view at the visualization to get a sense of the new situation and where she has made the error. They then realize the error, reverse it and continue executing the task. The fact that in a micro navigation task the whole structure is in the field of view of the user may reduce the route aid disadvantage of not giving any overview. In a micro navigation task the whole structure is always visible and provides an overview with both navigation aids.

## 6.3 User Feedback

Participants ranked the route visualizations higher than the survey visualizations.

Participants were asked to rank the visualizations according to their subjective preference (1 to 4). This results in the following overall ranking: #1 *Icon*, #2 *Spotlight*, #3 *X-Ray* and #4 *Cut-Away*. Participants argue that it was easier to follow the route visualizations because they did not demand a lot of cognitive processing of the visualizations. A reason that participants rank the overview visualizations last is: With increasing task difficulty they get hard to process and they prefer the simplicity of the route visualizations because they are easy to follow. Six of the fourteen participants gave the feedback that a benefit of the overview visualizations is: They give structural information on how much effort is needed to get to the target object, how many objects are between the user and the target object and how big the objects are.

Summarization of the answers to the interview questions.

In the informal interview after the trials participants are asked to give their personal opinion on some topics. The questions and answers which have not been covered yet will now get summarized. The overall opinion of the question, whether they think that bot types of navigation aids are equally suitable for ever difficulty of the task, is: With increasing task difficulty the overview navigation aids get hard to interpret (11 of 14 reported depth receiving problems with the overview aids with increasing task difficulty). This agrees with the significance findings in the study data.

Participants have a rough search strategy.

When asked, whether they had a search strategy in the study trials most participants answered that they make a rough area selection based on the visualization and then they try to follow the instructions or try to find a path with the overview visualization in mind.

Usage scenarios: Home, office and store.

They are also asked to describe a situation in which they can imagine themselves using such aids. The participants describe situations like: At home, in a shared office or in a store.

When asked whether they would prefer a phone, a projector or a head mounted display to visualize the navigation aids all of the three get equally preferred because they all have pros and cons. To use a phone may be awkward in a public situation and the display may be too small but today a Smartphone is always available and unobtrusive. The projector enables a hands free interaction and may be able to cover the whole structure with a visualization but is too stationary and has privacy issues in a public area. The preference of the head mounted display depends on the progress of these devices in the future. If they get broader available and are socially accepted they can provide an unobtrusive private interaction.

Possible devices to render the visualizations: Smartphone, head mounted display, ceiling mounted projector.

System usability scale has better results for route aids.

The System Usability Scale favored the route aids with the following results: *Icon* (91.96), *Spotlight* (93.57), *X-Ray* (75.54) and *Cut-Away* (74.29). A System Usability Scale above 68 is above average which is the case for all visualizations. This supports both the statement that both spatial knowledge types are suitable navigation aids in micro navigation task and that users preferred the route aids over the overview aids.

## 6.4 Discussion

Evaluation indicates: Both types of spatial knowledge seem to be sufficient as navigation aids.

The user feedback and the low error count indicates that both tested types of spatial knowledge are sufficient to provide navigation aid in a 3D micro navigation task. With increasing task difficulty the route aids begin to outperform the survey aids in task completion time and user error rate. The survey aids have a sharper increase in task completion time and get more error prone with increasing task difficulty. Users preferred the route aids over the survey aids.

Survey aids being static and not always visible might introduce a confounding factor.

However the following things need to be taken into consideration with the given results. The visualizations are printed on transparencies and are not changed during the task. Therefore they are static and do not adapt to the movement of the user. So for the survey visualizations 3D motion effects like parallax scrolling do not occur. These effects may result in a better understanding of the visualization and a faster task completion time. Additionally the survey aids are only attached to the outside surface of the box structure in contrast to the route aids. So when a participant needs to have another look at the visualization she needs to step back and look onto the outside surface. This may have increased the task completion time for the survey aids.

The unique box setup and the familiarization could be confounding.

As described the arrangement of the boxes in the hierarchical structure is the same for all tasks and is not changed at any point during the study. Each participant is also familiarized with the setup. So the participant is able to create a mental image of the whole setup before the tasks start. This may result in an advantage of the route aids, which usually lack this existence of an overview.

Results may still be valid.

Still the fact that in a micro navigation task the target object is inside the users reach leads to the impression that the user may always have an overview of the situation even without any visualization. This might have threatened the overview benefit of the survey visualizations. Even if the 3D visualization adapt to the user movement, the time it takes to process the visualization may still be a disadvantage for the survey aids.

# Chapter 7

# Summary and future work

## 7.1 Summary and contributions

The target of this thesis is to provide a first impression of how different spatial knowledge aids can be effective in a hierarchical micro navigation tasks. To achieve this we conduct a study which compares two types of spatial knowledge: Route and survey. In the study users have to find a known target object in a hierarchical structure of 49 cardboard boxes. This cardboard mock-up reassembles the scenario of a user using an augmented reality application to find an object inside a hierarchical structure. Four visualizations which represent the two spatial knowledge types are printed on paper, mounted onto the cardboard structure and aid the user with finding the target object. We have three hypotheses that are tested with the user study: **H1** survey aids are faster than route aids, **H2** route aids lead to fewer errors than survey aids, but survey aids better support error recovery. and **H3** users will prefer the route aids over the survey aids because they do not demand a lot of processing and are less error prone.

We conduct a study with a paper prototype to compare survey and route aids in a 3D micro navigation task.

The study data showed a significant effect of the interaction *Visualization x Task Difficulty* and a significant effect of *Task Difficulty* on the *Task Execution Time*. This shows that with increasing task difficulty the overview navigation aids begin to have a sharper increase in the task execution time compared to the route aids. This contradicts with **H1**. Overall both types of navigation aids have a low amount of errors, so both seem to be suitable to aid users with navigating in a micro navigation task. If a micro nav-

With increasing task difficulty the overview aids get more error prone and have a sharp increase in task execution time.

igation task is not complex a designer is not bound to a certain type of navigation aid. However with increasing task difficulty the number of errors with overview aids increases because they demand a lot of processing and memorization from the user. This agrees with **H2**. So one fact a system designer needs to have in mind, while choosing a navigation aid type, is the possible difficulty of his task.

User do prefer the route aids over the survey aids because of low cognitive workload.

A ranking shows that users prefer the route aids over the overview aids because of the expected reasons: They do not demand much cognitive workload and with the instructions of the Icon visualization it is easy to follow them. This agrees with **H3**. Users seem not have a preferred technology which should display the augmented reality visualizations. In fact participants suggested that a designer should consider the benefits and deficits of system and should keep the interaction situation in mind. A special focus should be given to whether the interaction occurs in a private or a public context.

## 7.2 Future work

Future work may use a prototype with adapting visualizations.

One deficit of the study prototype being a paper resemblance is that the visualizations are static and do not adapt to the user actions. If the three dimensional representation would move with the user, effects like parallax scrolling could help the user to understand the structure better and faster. However the user would still have to process the information and come up with a plan how to traverse the structure. This may still take enough time that the route aids keep being faster. So Future work can change the prototype to one which is able to render the visualizations in 3D and also is able to adapt to user movement. Both changes may lead to different results than the one which we found.

Increasing the task difficulty may change the results.

There may also be a point where planning ahead gives an advantage for the task completion time. Future studies can increase the task difficulty to a higher level which may lead to the point where the overview aids outperform the route aids in task completion time.

There may be better visualizations than the ones tested in this study.

The visualizations in this study are either based on existing work or are a basic way of highlighting something in augmented reality. Maybe there exist other visualizations which may lead to different results. Future work may investigate new ways of visualizing a overview navigation aid which are maybe more stable against errors with increasing task difficulty.

In an every day scenario the container boxes would not be empty and the structure would be more cluttered. Future work may consider adding other objects than the target objects to add some clutter and see whether the results change.

We suggest adding more clutter to the structure and observe the results.

We suggest another study with a between-group design, where only one group gets familiarized with the hierarchical structure. This study can evaluate whether the familiarization of the participants in our study is a confounding factor.

Not familiarizing the user may give other results.

# Appendix A

# Feedback Questionnaire

This is the one example questionnaire, which each participant had to fill out after she solved all the trials for one visualizations. The questions are the same for every visualization. Attached after this are the feedback questions for the informal interview which was conducted after all trials have been solved.

# Questionnaire

## Overview X-Ray

1. I think that I would use this visualization frequently.

Strongly Disagree ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Strongly Agree

2. I found the visualization unnecessarily complex.

Strongly Disagree ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Strongly Agree

3. I did understand easily where the searched object is located with this visualization.

Strongly Disagree ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Strongly Agree

4. I think that i would need an explanation of the visualization every time I use it.

Strongly Disagree ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Strongly Agree

5. The visualization helps me to find the object faster.

Strongly Disagree ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Strongly Agree

6. I thought there was too much inconsistency in the system.

Strongly Disagree ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Strongly Agree

7. I would image that most people learn to understand the visualization very quickly.

Strongly Disagree ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Strongly Agree

8. The guidance provided by the system was more cumbersome than helpful.

Strongly Disagree ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Strongly Agree

9. I felt very confident in searching with this visualization.

Strongly Disagree ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Strongly Agree

10. I need to understand a lot of the visualization before I could start searching with it.

Strongly Disagree ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Strongly Agree

## Feedback Questions

After each Hard task:

- What information did you miss while accessing the item?
- Do you have any suggestions on how to improve the visualization, so that it provides more help while accessing the searched object?

1. Please rank the visualizations (Step-by-Step(SbS) Highlight, SbS Icon, Overview(Ov) X-Ray, Ov Cut-Away) such that 1 is the best and 4 the worst in our opinion.
2. Do you prefer the step-by-step style or the overview style of the visualization? Please explain your answer?
3. Did the visualizations help in finding the items? were you faster? in all depths? (justify)
4. Did you have a search strategy? If no, why? if yes, was it influenced by the visualization? (ask also for baseline, derive strategies)
5. In which situations will you need such a visualization? familiar? unfamiliar?(home, office, store)
6. Using what technology will you imagine to use these visualizations? mobile phone? Head mounted display? fixed projector?
7. Do you have any further comment that did not get covered by the previous questions?

# Appendix B

# User Study Protocol

This is the study protocol for the conducted user study of this thesis.

# Final Study Protocol

**Context**

So far, existing indoor search systems facilitate finding physical objects by providing visual cues that illuminate the location of the target [1, 2, 3] or acoustic feedback [1]. These systems assume the target object to be directly visible, or otherwise provide a coarse search result by pointing to the visible structure that is obscuring the target [4].

However, in real-life settings, people use physical structures, e.g., cabinets, boxes, folders, etc., to help organise their objects and expand the storage area of a given space. In turn, using existing search systems would still demand an active search from the user in order to find the target object within a highlighted structure. This could have significant implications on search time if the structure is complex, or when the structure contains private and confidential objects that should not be accessed by the user.

A camera system for finding objects inside boxes was proposed by Komatsuzaki et al. [5]. A camera above the boxes detects the opening of a box and takes a picture of it's content. The user must manually browse through pictures when searching an object, and the system is only feasible when the structure is very simple.

In contrast, we approach the problem of searching within physical structures by extending the feasibility of AR displays, in particular, mounted projectors, and providing more visual information of the precise location of an object within a structure. We referred to research on visualising multiple occluded layers in augmented reality and found tow main approaches: (1) the X-ray vision metaphor [6] (see Fig. 1), and (2) the cut-away metaphor [7] (see Fig. 2). (provide definition for each). These two metaphors mainly vary in the amount of information they provide about a given structure.

In this user study we aim to conduct a controlled experiment to evaluate the benefits of AR visualisations of varying amount of information in searching physical structures.

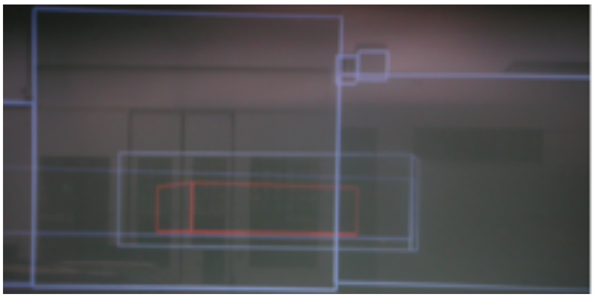


Figure 1

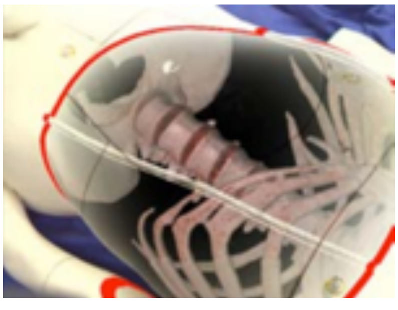
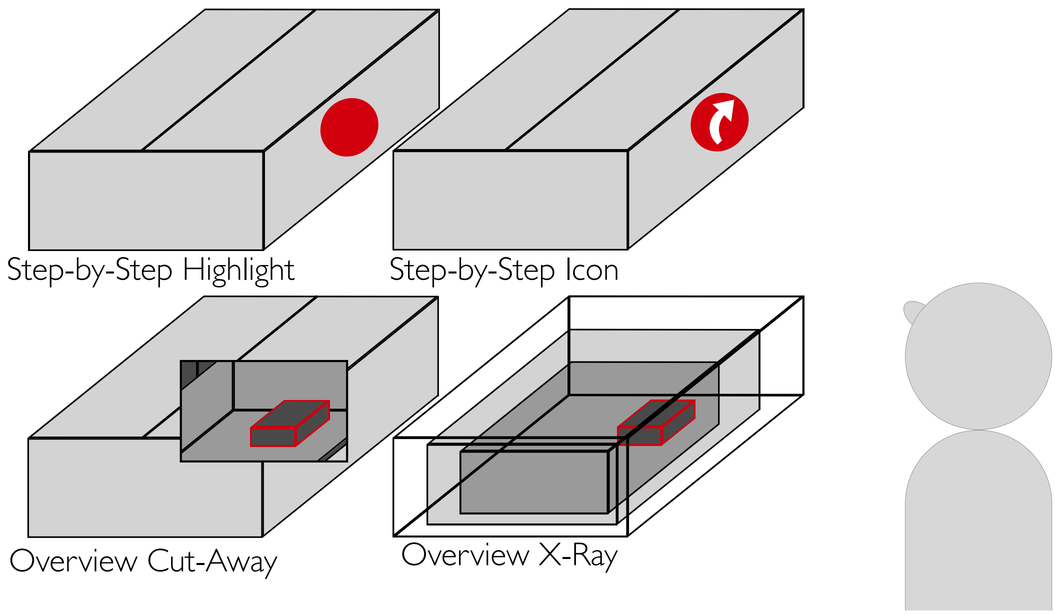


Figure 2

# Visualizations

The overview visualization provides all the information of the object arrangement at once but the moment the user starts the search task the information is no longer visible because it is out of sight. The step-by-step visualization provides the information more in a guidance system style for each step the user needs to do to access the item. The step-by-step visualization is visible at the location of the searched object. So if a circle in the highlight visualization would visualize the location of a box that is located in the lower right corner of a bigger box, then the circle would be presented on the outside surface of the lower right corner of the box that is visible to the user.




- Step-by-Step Highlight: A simple spotlight to highlight the object that the user needs to interact with next.
- Step-by-Step Icon: Adds instructions to the highlight visualizations by providing icons which explain how to interact with the highlighted object.
- Overview Cut-Away: Provides a cutaway to the user that excludes every layer that is between her and the searched. And shows the inside of the object that contains the searched object.
- Overview X-Ray: Provides a simulation of an X-Ray vision that lets the user see through every layer between her and the searched object. The visualization provides a wireframe of the objects and a surface of each object with 50% Opacity. The visualization excludes objects that don't need any interaction from the user to access the searched object.

## Task-Complexity:

Task complexity is defined by the number of visibility barriers that stand between user's field of view (FOV) and the target object. In this study we define two types of barriers: layers, these are objects that cover the target object; containers, these are objects that surround the target object from the FOV of the user.
The lower and upper bound of complexity should be determined in the pilot study, these are the thresholds where visualisation cues are effective in a search task.

## Research Question

How do step-by-step and overview visualizations compete against each other in an indoor physical search task regarding task completion time, user satisfaction and user error rate?

## Hypothesis

- H1: With increasing task complexity will the difference in task completion time, user satisfaction and error rate between the Step-by-Step Highlight and the Step-by-Step Icon visualization increase, favoring the Step-by-Step Icon visualization.
- H2: With increasing task complexity will the difference in task completion time, user satisfaction and error rate between the Overview Cut-Away and the Overview X-Ray visualization increase, favoring the Overview X-Ray visualization.
- H3: With increasing task complexity will the difference in task completion time, user satisfaction and error rate between the Overview visualizations and the Step-by-Step visualization increase, favoring the Step-by-Step visualization.

# Variables

Independent Variables:

1. Task Complexity
   - Levels (3):
     - Easy (Task-Complexity Level: One)
     - Medium (Task-Complexity Level: Three)
     - Hard (Task-Complexity Level: Five)
   - Scale: Ratio
   - Factor Type: within subjects
   - Manipulation Technique: selection
2. Visualization
   - Levels (5):
     - Step-by-Step Highlight
     - Step-by-Step Icon
     - Overview Cut-Away
     - Overview X-Ray
     - Baseline (no Visualization)
   - Scale: Nominal
   - Factor Type: within subjects
   - Manipulation Technique: selection

Dependent Variables:

- Task Completion Time
  - Operationalisation: Measured time between uncovering the object for the user and a clear signal by the user that he has found the item.
  - Measurement: seconds
  - Scale: ratio
  - Levels: [0, unspecified] s
- User Satisfaction
  - Operationalisation: The user satisfaction gets measured with a slightly adapted system usability scale for each visualization which is in the questionary at the end of the study.
  - Measurements: SUS Score
  - Scale: interval
  - Levels: [0, 100]
- User Error Number
  - Operationalism: The setup is arranged as a decision tree while each interaction with an object is a node. So each Interaction opens possibilities to interact with other objects. Also each node has at least two children, so that after each interaction the user has to make a decision which interaction he wants to do next to get to the searched object. There is a fastest path in the decision tree. Each time the user leaves this path this counts as an error. So each time the user chooses an interaction that does not lead fastest to the object this will count as an error.
  - Measurement: number of errors
  - Scale: ratio
  - Levels: [0, unspecified] errors

## Task

Participants perform one task with one trial for each combination of visualization and Task-Complexity (15 combinations). In each trial the user has to find an item in a setup of cardboard boxes. The setup is always the same setup but the object for each trial hidden at a different place in the box structure such that this represents the specific task complexity (easy, medium, hard). The location of the object is then represented with a visualization (Step-by-Step Highlight, Step-by-Step Icon, Overview Cut-Away, Overview X-Ray, Baseline) that is simulated with paper or transparencies that get attached to the cardboard boxes. The participants have to find the object inside the box setup as fast as possible and indicate clearly to the supervisor when they found it by saying “found it!”. While searching the participant will be provided with an empty table on which she can place boxes that she already has interacted with. Participants are advised to not close boxes again or to put them back in place after they made an error, but to put them aside so that they are not in their way.

## Participants

- Count:
  - 15-30
- Background Information:
  - No Payment
  - Age: young adult to middle aged adult
  - Recruited in family/friends or at the University campus
  - Normal or corrected-to-normal visual acuity
  - No severe known impairments of the motor system (hand tremor, etc.)

## Experimental Design

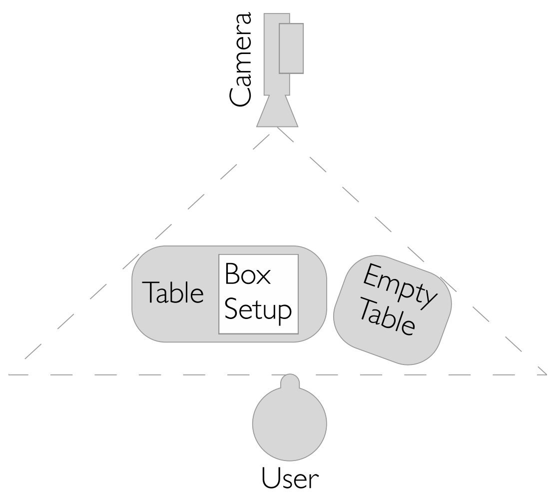
- full factorial within subject design
- One trial for each of the 15 combinations
- One questionary to collect information typical socio-demographic variables (age, gender, handedness, visual acuity, etc)
- One post-experiment questionary
- To counterbalance learning effects of the combinations or other unknown and unwanted effects based on the order of the combinations we use a 24 x 24 latin square
- Estimated duration per participant: up to 60minutes

# Experimental Procedure:

- BEFORE arrival of participant:
  1. Set up and test equipment
  2. Perform trial run of experiment
  3. Print/Prepare questionary and consent form
  4. Provide food and drinks
  5. Prepare the setups as much as possible
  6. Mark a place on the ground where each participant has to start from.
- AFTER arrival of participant:
  - Request participant to read and sign consent form
  - Explain experimental tasks to participant (not bias, no insights)
  - Enquire about any relevant handicaps or injuries
  - Training phase:
    - Explain each visualization with an easy task and make sure the participant understands the meaning of each visualization and is familiar with it.
    - Show the participant the box setup and show him how to open each box.
    - Explain the purpose of the second table to the participant.
    - Ask her to be as fast as possible and advise her not to waste time with closing boxes or putting boxes pack in their place.
    - Show the participant a duplicate of the object she has to look for.
    - Instruct the participant to say “found it!” if they found the searched object.
  - Testing phase:
    - participants perform the task in each trial.
- After experiment:
  - obtain qualitative data per post-experimental questionary
  - provide them the video recording of their participation so they could easily refer to certain events.
- End of experiment:
  - Inform participant about actual aim of the experiment
  - Ask the participant whether she has any questions/comments
  - (Hand out contact details if not known)

# Setup

- Box combination setup on one table and an empty table aside of it.
- camera above the tables to capture the user.
- behind a curtain (or something that brakes vision to the participant) an assistant or the supervisor who prepares the next combination setup to reduce time between each trial.
- MacBook that records from the camera to provide the video to the participant while she fills out the questionar



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# Latin Square

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| 2 | 3 | 1 | 4 | 0 | 5 | 14 | 6 | 13 | 7 | 12 | 8 | 11 | 9 | 10 |
| 3 | 4 | 2 | 5 | 1 | 6 | 0 | 7 | 14 | 8 | 13 | 9 | 12 | 10 | 11 |
| 4 | 5 | 3 | 6 | 2 | 7 | 1 | 8 | 0 | 9 | 14 | 10 | 13 | 11 | 12 |
| 5 | 6 | 4 | 7 | 3 | 8 | 2 | 9 | 1 | 10 | 0 | 11 | 14 | 12 | 13 |
| 6 | 7 | 5 | 8 | 4 | 9 | 3 | 10 | 2 | 11 | 1 | 12 | 0 | 13 | 14 |
| 7 | 8 | 6 | 9 | 5 | 10 | 4 | 11 | 3 | 12 | 2 | 13 | 1 | 14 | 0 |
| 8 | 9 | 7 | 10 | 6 | 11 | 5 | 12 | 4 | 13 | 3 | 14 | 2 | 0 | 1 |
| 9 | 10 | 8 | 11 | 7 | 12 | 6 | 13 | 5 | 14 | 4 | 0 | 3 | 1 | 2 |
| 10 | 11 | 9 | 12 | 8 | 13 | 7 | 14 | 6 | 0 | 5 | 1 | 4 | 2 | 3 |
| 11 | 12 | 10 | 13 | 9 | 14 | 8 | 0 | 7 | 1 | 6 | 2 | 5 | 3 | 4 |
| 12 | 13 | 11 | 14 | 10 | 0 | 9 | 1 | 8 | 2 | 7 | 3 | 6 | 4 | 5 |
| 13 | 14 | 12 | 0 | 11 | 1 | 10 | 2 | 9 | 3 | 8 | 4 | 7 | 5 | 6 |
| 14 | 0 | 13 | 1 | 12 | 2 | 11 | 3 | 10 | 4 | 9 | 5 | 8 | 6 | 7 |

0 X-Ray Easy

1 X-Ray Medium

2 X-Ray Hard

3 Cut-Away Easy

4 Cut-Away Medium

5 Cut-Away Hard

6 Icon Easy

7 Icon Medium

8 Icon Hard

9 Spotlight Easy

10 Spotlight Medium

11 Spotlight Hard

12 Baseline Easy

13 Baseline Medium

14 Baseline Hard

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