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Designing Tactile Guides for Smart Home Controls

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Abstract

In this thesis, we investigated how users search naturally using only their sense of touch in the context of smart homes. This serves as a pre-study to explore how to best guide the user with the help of guiding markers to the targeted smart home controls. We investigated the effects of the `surface`, the `surface position`, the `target size`, and the `target position` on the haptic search of the user. The participants of the study exhibited behavior of a systematic search strategy and starting point. Three search strategies named **wave lines with both hands**, **wave lines with one hand**, and **circular motions** were mainly employed. The starting point was always in the *front or top margin*. This position was also preferred by the participants for possible controls. Therefore, we propose to place such controls either in the middle or the corners of the *front or top margin*. The `target size` significantly influenced the easiness of the search. No other significant effects were found. However, in our qualitative analysis, we found that the `surface position` affects the search strategy. Because the *small* target was easy to miss, we propose a target height greater than 1 mm. Moreover, a target size of 13 mm should not be undercut. As for possible positions for the guiding markers, we propose the margins (at least for the initial guiding marker), especially the *front or top margin*. Because most participants swiped, it is unlikely for the user to miss any guiding markers by tapping over them.

Überblick

In dieser Arbeit haben wir untersucht, wie Benutzer im Kontext von Smart Homes auf natürliche Weise nur mit ihrem Tastsinn suchen. Dies dient als Vorstudie, um zu erforschen, wie man den Benutzer mit Hilfe von fühlbaren Markierungen am besten zu den gewünschten Smart Home-Bedienelementen führt. Wir untersuchten die Auswirkungen der Oberfläche, der Position der Oberfläche, der Größe des Ziels und der Position des Ziels auf die haptische Suche des Benutzers. Die Teilnehmer der Studie zeigten das Verhalten einer systematischen Suchstrategie und eines Ausgangspunktes. Drei Suchstrategien mit den Bezeichnungen **Schlangenlinien mit beiden Händen**, **Schlangenlinien mit einer Hand** und **kreisartige Bewegungen** wurden hauptsächlich verwendet. Der Ausgangspunkt befand sich immer im *vorderen oder oberen Rand*. Diese Position wurde auch von den Teilnehmern für mögliche Bedienelemente bevorzugt. Daher schlagen wir vor, solche Bedienelemente entweder in der Mitte oder in den Ecken des *vorderen oder oberen Randes* zu platzieren. Die Zielgröße hatte einen signifikanten Einfluss auf die Leichtigkeit der Suche. Andere signifikante Effekte wurden nicht gefunden. In unserer qualitativen Analyse haben wir jedoch festgestellt, dass die `Oberflächenposition` die Suchstrategie beeinflusst. Da das *kleine* Ziel leicht zu verfehlen war, schlagen wir eine Zielhöhe von mehr als 1 mm vor. Außerdem sollte eine Zielgröße von 13 mm nicht unterschritten werden. Als mögliche Positionen für die fühlbaren Markierungen schlagen wir die Ränder vor (zumindest für die erste fühlbare Markierung), insbesondere den *vorderen oder oberen Rand*. Da die meisten Teilnehmer mit dem Finger wischten, ist es unwahrscheinlich, dass der Benutzer fühlbare Markierungen übersieht, weil er über sie tippt.

Acknowledgements

First and foremost, I would like to thank my supervisor Oliver Nowak for the tremendous support throughout the process. Secondly, I would like to thank my friends and colleagues for participating in my study. Thirdly I would like to thank René Schäfer and Sören Schröder for supporting me during Oliver's vacation. Fourthly I give my Thanks to Esra Gueney for showing me the FabLab. Lastly, I would like to thank my boyfriend for always listening to my problems and helping me stay motivated.

Conventions

M = Mean
SD = Standard deviation

Chapter 1

Introduction

More and more technology has been integrated into our households (Zielonka et al. [2021]). The smart home has arrived, but its end state has not been reached yet. One possible next step is integrating technology into our everyday surfaces (Brauner et al. [2017]). However, this integration should be as less invasive as possible since the technology integrated into, e.g., furniture, is not their primary function. Therefore once this technology has been integrated, it might not be obvious where to find it, especially for the first-time user, e.g., in a hotel room or at a friend's house. Possible applications are, e.g., integrating a TV remote or light switches into a couch or a bedside table. These are also applications where the user is, at least for some time, in a dark room, where his vision is impaired. Therefore it would be especially hard to find less invasive controls. The only thing the user could rely on in this situation is his sense of touch. Thus tactile guides which lead the user to these controls would be helpful. But to provide such tactile guides, one first needs to know how users naturally seek objects using only their sense of touch. Tactile guides designed for this type of interaction will also prove helpful in scenarios where the user can see because visual attention might be needed elsewhere, e.g., while the user is talking to someone face to face or observing the lights one wants to change. Sometimes tactile controls might also be more efficient and intuitive than visual ones (Challis and Edwards [2001]). Moreover, tactile controls do

not exclude visually impaired users (Challis and Edwards [2001]).
Our user study will investigate how users naturally seek objects using only their sense of touch. The next step in future research would then be to investigate which shapes (guiding markers) can be used to guide the user to the target. In a subsequent study, one could compare letting the users seek without help, following a continuous path to the targets, or allowing them to seek using guiding markers.

Chapter 2

Related work

Little research has been conducted on how people search naturally using only their sense of touch in the context of smart homes and smart home controls. However, outside the smart home context, researchers in the field of psychology investigated the search by touch only. Their results will be presented in the first section.
As mentioned in the introduction, the next step after knowing how users search using only their sense of touch would be to investigate how to best guide the users to the target using guiding markers. To design these guiding markers, one first needs to know what the actual interfaces may look like. Therefore in section two, we present different textile interfaces. In section three, multiple examples for other areas show that tactile feedback that helps the user interact with the interface eyes-free is beneficial even when the user can see the interface. Finally, in section four, other researchers' design principles are provided, which one should consider when designing the guiding markers.

2.1 Insights from psychology

Metzger et al. [2021] explored a five-finger search on a table. The participants had to search for a particular configuration of symbols on a rectangular tactile display. They observed that participants moved their hands parallel to the edges of the tactile display. They thought this might help participants to orientate themselves within the search space. Moreover, they found that the index and middle fingers were mainly used during target analysis. Furthermore, the index and middle fingers slowed down for target exploration.

In the study by Overvliet et al. [2007], participants had to identify a target (cross) among multiple non-targets (circles) using only the index finger in the first experiment or three fingers in the second experiment. All the items were placed in straight lines. The total search time depended on the target position (the participants stopped once they found the target) and the separation between targets. However, the time in contact with an item did not vary for different separation sizes. If the separation was short, the movement of the participant's finger was smooth compared to jerky when the separation was large. When more fingers were used, the total search time and the time in contact with an item increased.

van Polanen et al. [2011] investigated the search strategies of participants in a haptic search task for a target among a varying number of distractors. There was not always a target present. The target was either anchored or movable. If the target was anchored, the distractors were movable, and if the target was moveable, the distractors were anchored. Fluent movements (sweeps and circles) were observed for the movable target. On the other hand, a more detailed search in scribbles was employed for an anchored target. The search time did not increase for the movable target when the number of distractors was increased, unlike for the anchored target. This indicates a parallel search strategy for the movable target and a serial search strategy for the anchored one. To conclude, the search strategy is influenced by the conditions and target salience and less by target presence and size.

Overvliet et al. [2012] investigated whether the Gestalt laws of similarity, proximity, and good continuation for visual tasks are transferable to haptic search. They found that the principles of similarity and good continuation could also be applied to haptic search, unlike the principle of proximity.

In the study by Theurel et al. [2012], the participants (blindfolded or blind subjects) had to identify different shapes by touch only. The blindfolded sighted subjects recognized prototypical shapes faster than non-prototypical shapes.

2.2 Textile interfaces

Post and Orth [1997] first introduced the integration of conductive thread into fabric.
"The Textile Interface Swatchbook" by Gilliland et al. [2010] gives researches guidelines on how to manufacture textile GUI(Graphical User Interface)-like widgets using conductive embroidery. The benefit of GUI-like widgets is that users should be familiar with them from the start. Moreover, the researchers developed a hybrid resistive, capacitive touch sensing technique that tolerates a flexible fabric base.
Project Jacquard by Poupyrev et al. [2016] proposes manufacturing technologies to produce interactive textiles at scale. They investigated new textile materials that can be made inexpensively with existing textile weaving technology and equipment. Moreover, they propose new techniques for connecting woven interactive textiles to inexpensive electronics that endure washing and drying.
Brauner et al. [2017] investigated the usability and acceptance of three different textile controls for an armchair and compared them to a standard remote. They found that the acceptance was higher for textile controls than for the standard remote, even though the standard remote's pragmatic qualities (efficiency, fluidity of interaction, and reliability) were better. They concluded that hedonic quality and attractiveness influence acceptance more than pragmatic qualities. Moreover, the attractiveness of the textile controls profited from the direct and nearly invisible integration into the armchair.
Heller et al. [2016] designed a motorized curtain with an integrated capacitive textile sensor. The curtain could be opened and closed through gestural input.
In the study by Rus et al. [2017], they constructed a couch that recognizes different postures using integrated smart

textiles. They propose that in the future, this information, in combination with other information, could be used to adjust the user's surroundings automatically.
Ziefle et al. [2014] studied the users' preferences for textile interfaces in a home context. Overall the researchers reported a high openness to the use of smart textiles. However, the acceptance was higher for more familiar objects like clothes or armchairs than carpets or curtains. Concerning the function and place of such controls, neutral and public functions (like media control, lights, window blinds, not locks, and not heating) along with non-personal locations (living room, office, not bedroom, and not bathroom) were preferred. The more intimate the place and the more critical the function, the lower the reported suitability of smart textiles. Moreover, they said that aesthetics, (perceived) durability, and the tactile sensation of the fabrics were essential aspects of smart textiles.
In Hamdan et al. [2016b], the researchers proposed a different type of interaction with textiles than through buttons and sliders. They used the affordance of textiles to fold and move the fold as an interaction technique. Moreover, their interface could also recognize stroke gestures. This technique could minimize accidental input while supporting eyes-free interaction and low device acquisition time. Additionally, their approach showed a similar movement speed and accuracy to touch screens. Hamdan et al. [2016a] extended their research by using this technique for menu selection. They based the design of their menu on marking menus. "The selection of a menu item is performed by grabbing a fold at a specific angle while changing value is performed by rolling the fold between the fingers"(Hamdan et al. [2016a]). In their study, users could grab fabric with an accuracy between 30 and 45 degrees. This would make up to six different menu options possible. Moreover, they found that different fabric types did not influence the users' performance or comfort.

2.3 Insights from common areas

In a study by Colley et al. [2016], the researchers constructed transparent Perspex with cut-outs which were

then attached to a touch screen. The cut-outs in the form of sliders guided the interaction with the touch screen. Although the total interaction time with the touch screen did not change, the guided touch screen condition provided better ease of use. In addition, the participants reported better eyes-free usage for the guided condition.
Weiss et al. [2009] manufactured SLAP Widgets, a translucent layer made out of silicon or acrylic, which can be relabeled dynamically through rear projection, to put on multi-touch tabletops to generate tactile feedback. As a result, the widgets improved input accuracy and overall interaction time. Moreover, they support eyes-free interaction.
Multiple papers also investigate wearable interfaces. One of them is the paper by Zeagler et al. [2021]. They examined how good users could locate textile interface touch points on their forearms, eyes-free and whether the addition of active touch embroidery and passive touch (with or without vibrotactile stimulation) nubs helps. They reported that touch points at the end of the interface were easier to locate accurately than in the middle. Moreover, vibrotactile stimulation increased the accuracy. Therefore they recommended placing often-used functions at the edges of the interface and functions which should not be triggered accidentally in the middle. Moreover, they found that users thought that textile interfaces have low mental, physical and temporal demands on top of not requiring too much effort. Additionally, they are not frustrating to use. However, the users were not confident in the accuracy of their interactions with the interface.

2.4 Design principles

Challis and Edwards [2001] presented a set of design principles for tactile interfaces in their paper. These principles were:

1. "A consistency of mapping should be maintained such that descriptions of actions remain valid in both the visual and the non-visual representations."

2. "The tactile representation within an interface should focus on data that is static."

3. "Height should be used as a filtering mechanism."

   After their user study, conducted with blind participants, they extended these principles:

4. "Good design will avoid an excess of ‘empty space’ as this is a significant source of confusion."

5. "A simple visual-to-tactile mapping is likely to produce many problems and is therefore unlikely to be the most efficient design strategy."

6. "Good design practice should, whenever possible, encourage a specific strategy for the exploration of a particular display."

7. "Double-clicking is an inappropriate form of interaction within static displays."

8. "A display should be sized and orientated such that users are not expected to overreach to discover the full extent of the display."

9. "Tactile objects should be simple."

Moreover, they noted that a maximal display area is approximately the size of a standard piece of paper.
Oakley and Park [2007] also investigated some general design principles for eyes-free interaction. They identified five design principles.

1. The user should be able to monitor his input.

2. The input motions should reflect bodily constraints and be comfortable.

3. The interaction models should apply a simple mapping, and metaphors should be minimized.

4. The feedback should be immediate.

5. The interface should provide novice users with a way to use the system from the beginning and seamlessly transition into expert users..

Mlakar and Haller [2020] extended the more general design principles of Challis and Edwards [2001] and Oakley and Park [2007] with specific principles for textile interfaces. They found that elements of different heights were the easiest to differentiate, different shapes the second easiest, and different textures the hardest. Moreover, they found that visual symbols are very hard to recognize by touch only. In the end, they propose five design recommendations. First, "Use explicit contrast to imply differentiation. The easiest tactile contrast to recognize is height.". They further specify that the height difference should be at least 1.6 mm, the difference between shapes should be edges vs. round shapes, and the difference between textiles should be smooth vs. rough surfaces. Second, they propose 13 mm (the size of a fingertip) as an optimal target size and 6.5mm as a minimum size. Third, "Concave surfaces are also perceived as interactive. A combination of a convex and a concave element can be used for opposite commands.". Forth "Use the shape of an element to indicate required interaction.". A small shape afforded to be pressed and a straight line sliding over it. Fifth, they state that all shapes and the interface should be as simple as possible and visual symbols should not just be copied. They also note that "Textile icons should not focus only on shape, but should include other tactile properties. For example, an exit or stop command can be achieved with a shape of an 'X', a height difference, and a very stiff surface texture." (Mlakar and Haller [2020]).

The paper by Sjöström [2001] presented design guidelines for blind users. These guidelines included that the interface should provide reference points that are easy to find, and the reference system should not be changed if not necessary. Moreover, sharp edges should be avoided as it is easy for the user to lose contact with the object each time he passes a sharp edge.

Chapter 3

User study: How do people search for objects using only their sense of touch?

So far, no study has been conducted concerning the effects of different surfaces or surface positions on haptic search. Moreover, in most studies, the participants were instructed to use only one hand or specific fingers and could not choose freely which part of their hands to use or if they wanted to use both hands. We will extend this research by exploring the natural search behavior of users on different surfaces and surface positions typically found in homes and their effect on how the users search. For this, we will explore the search *on the table*, *underneath the table*, and *on the side of the couch* on a *smooth* and *rough* surface. Because of their possible effects on the haptic search, we will also investigate different target sizes and target positions.

The following sections describe the questions we want to answer with our study, the independent variables we choose and their levels, and the experimental setup. After that, the construction process of our setup, the setup, the execution of our user study, and the measurements and feedback are described. Before our actual study, we executed a pilot study to identify potential flaws in the execution of our user study, which is not described in detail as it does not vary significantly from our actual user study. However, the changes we made after our pilot study are mentioned in the corresponding sections. Last but not least, we describe the gender, age, and handedness of the participants in our study and note the time it took to complete our study.

3.1 Aim

In this user study, we aim to investigate how users search for objects naturally using only their sense of touch. More specifically, the following questions will be answered:

- With which part of their hand do the users seek?
- Do they tap or swipe?
- Do the users have a specific search strategy to cover the whole surface?
- Do the users have a specific starting point?

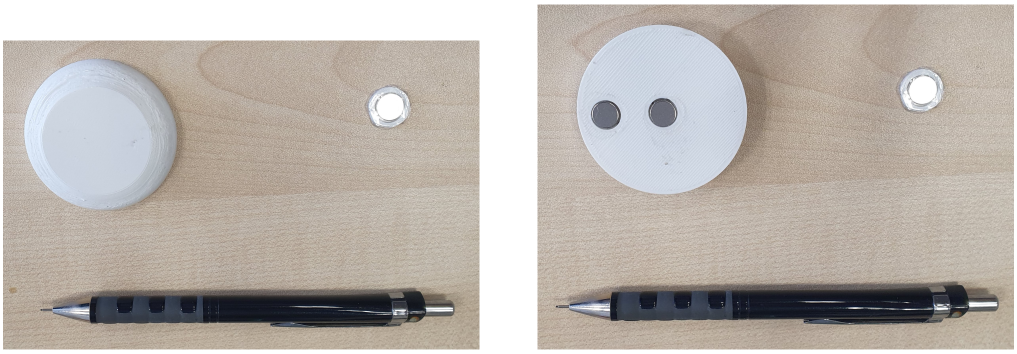
3.2 Variables

We have four independent variables in total, as shown in Table 3.1. The first independent variable is the type of

Independent variable	**Level**
`surface`	*rough, smooth*
`surface position`	*on the table, underneath the table, on the side of the couch*
`target size`	*small, big*
`target position`	*middle, front or top margin, left or front margin, right or back margin, far region*

Table 3.1: Independent variables and their levels

`surface`. In the study, we use two different surface types which appear in most homes. One surface is supposed to be *rough*. For this, couch fabric is used. The other surface



(a) **(b)**

Figure 3.1: Targets (a) from above and (b) from underneath

is supposed to be *smooth*. For this, plexiglass is used. We think users might be more likely to tap for the *rough* than for the *smooth* surface. The second independent variable is the `surface position`. We investigate all possible positions for controls that are likely to appear in future smart homes and have different affordances: *On the table*, *underneath the table*, and *on the side of the couch*. The third independent variable is the `target size`. We use one *small* and one *big* target. Naturally, the big target might be easier to find, so that the user might search differently for it. Both targets are round and 3D-printed. To have great difference between the *small* and the *big* target, the *small* target should be as small as possible and the *big* target should not be possible to overlook. The *small* target has a diameter of 13 mm, approximately the size of a fingertip, and a height of 1 mm, the minimal height of a required magnet. (Mlakar and Haller [2020] also suggested 13 mm as the optimal target size for a target.) The *big* target has a diameter of 5 cm and a height of 1 cm. The targets are shown in Figure 3.1.
The fourth independent variable is the `target position` in order to find the most comfortable position for the user to place smart home controls. For this, we divide the surface *on the table* and *underneath the table* into five regions:

- the *front margin* (region closest to the user)
- the *left margin*
- the *right margin*

- the *middle*
- the *far region*

On the side of the couch the regions are called differently, but have the same size, as can be seen in Figure 4.2.:

- the *top margin* (region closest to the user)
- the *front margin*
- the *back margin*
- the *middle*

The "near corner" is defined as the corner of the *top margin* next to the *front margin* and the "far corner" as the corner next to the *back margin*. To the regions, we assigned multiple target positions. In the middle, we have six, in the front margin eleven, in the left and right margin each seven, and in the far region, four possible positions *on the table* and *underneath the table*. *On the side of the couch* in the middle, we have six, in the top margin eleven, and in the front and back margin each seven possible positions. The different positions for the targets *on and underneath the table* can be seen in Figure 3.3. For the positions *on the side of the couch*, one only needs to rotate this visualization. The *far region* is only used for *on the table* because it would be out of reach *underneath the table* and *on the side of the couch*, forcing the user to uncomfortably twisting himself.
The surface size is fixed at 55 cm×55 cm, the size of a typical bedside or couch table. Furthermore, we only investigate *the side of the couch* for the dominant hand.
The dependent variable is the search strategy of the user.

3.3 Experimental Setup

We use a mixed design. The participants will only interact with the *smooth* or *rough* surface, due to the scalability of the study. Thus the `surface` is the between-group factor. The

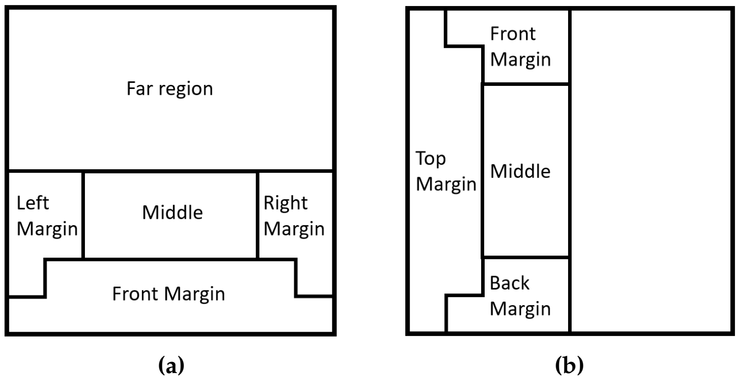


Figure 3.2: The regions for (a) on the table and underneath the table and (b) on the side of the couch

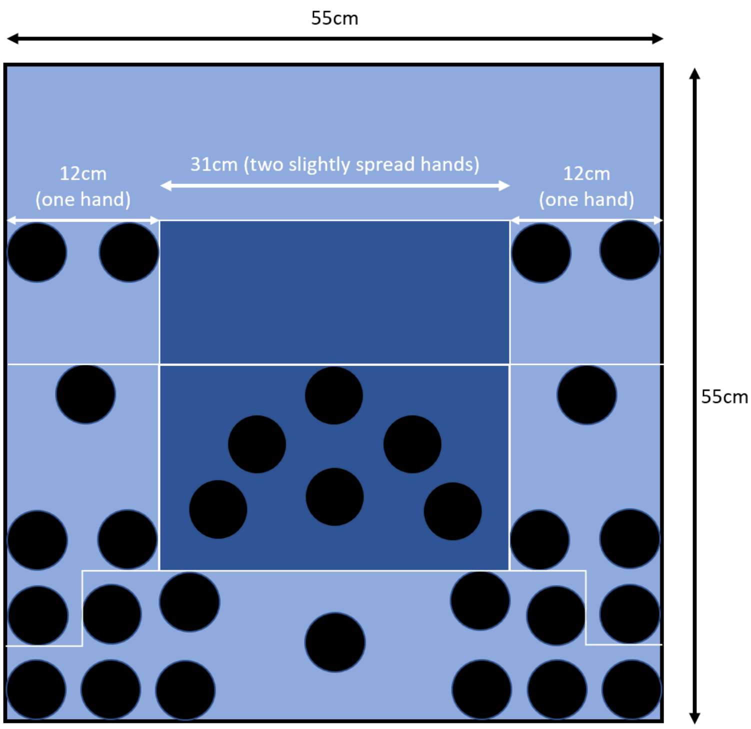


Figure 3.3: Different positions for the targets for on and underneath the table

rest of the independent variables are within-group factors. Using a Latin Square design, the `surface position` is counterbalanced against the order effect. The `target` and `target position` are randomized. We conduct two trials for each region (*middle*, *front margin* or *top margin*, *left margin* or *front margin*, *right margin* or *back margin*, *far region*). However, the *far region* is only investigated for *on the table*. For the other conditions it would be out of reach. A factorial design is used. Therefore 3 (`surface position`) $\times$ 8 (`target position`) + 2 (*far region on the table*) = 26 trials per participant are executed in total. The experiment is a Think Aloud experiment, meaning the participants should voice there thoughts during the study.

3.4 Construction of the surfaces and targets

We glue couch fabric on a wooden plate for the *rough* surface. The wooden plates have a size of 55 cm$\times$55 cm and a height of 5 mm. For the *smooth* surface plexiglass with the same size as the wooden plates is used. The edges of the plexiglass were mentioned as sharp in the pilot study. Therefore, we put silicone tape on the edges to make them more comfortable for the user while searching, as shown in Figure 3.4.

To hold the targets in place even *underneath the table* or *on the side of the couch* and still be able to switch their positions quickly, we glued magnets to the targets and surfaces. To keep the form factor, the targets are 3D-printed with appropriate holes, into which we then glue magnets. Into the *big* target we glue two neodymium magnets N52 with a diameter of 8 mm, a height of 3 mm, and an adhesive force of 2.6 kg. Into the *small* target we put one neodymium magnet N52 with a diameter of 9 mm, a height of 1 mm, and an adhesive force of 1 kg. We use sellotape to hold the magnet in place. The resulting targets are shown in Figure 3.1.

The counterpart to the magnets in the targets are magnets integrated into a wooden plate which is put underneath the surface. The wooden plates have a size of 55 cm$\times$55 cm

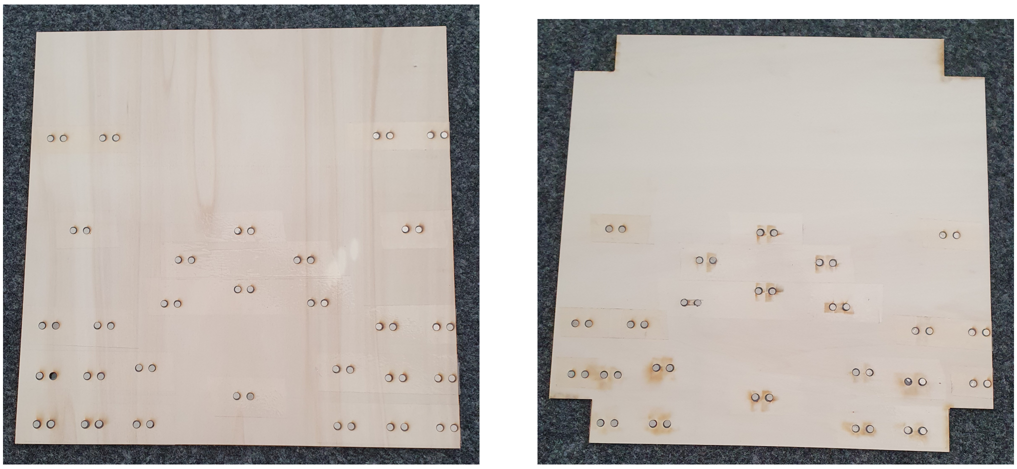
Figure 3.4: Plexiglass for on the table

and a height of 5 mm. The holes for the magnets are laser cut and the magnets hold in place by packaging tape. The magnets used for the wooden plates are also neodymium magnets N52 with a diameter of 8 mm, a height of 3 mm, and an adhesive force of 2.6 kg. The wooden plates are shown in Figure 3.5.

To blindfold the user during the search we took safety goggles and glued duct tape to them. The safety goggles are shown in Figure 3.6.

3.5 Setup

The user is placed on the couch with a table in front of him or at the side of the couch. On or underneath the table is the wooden plate with integrated magnets. On top of that,



(a) (b)

Figure 3.5: Wooden plates with integrated magnets for (a) on the table and on the side of the couch and (b) underneath the table

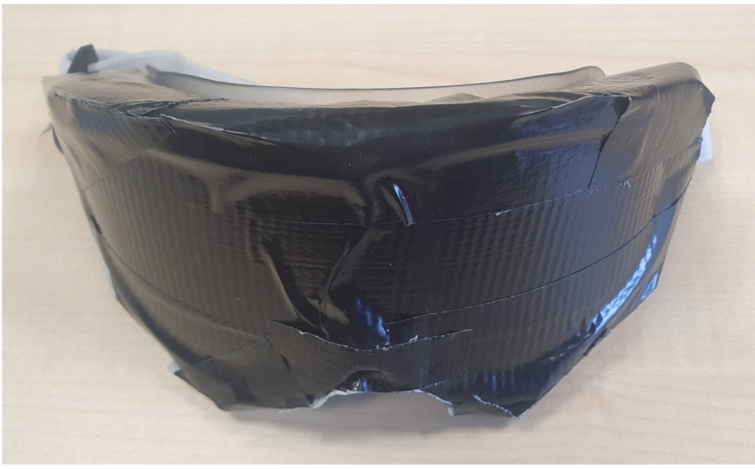


Figure 3.6: Safety googles used to blindfold the user

the plexiglass or the wooden plate with the couch fabric glued onto it is placed. All plates have the same size as the table (55 cm×55 cm). The final table height is 46 cm. The plates are held in place by clamps to be able to switch the setup quickly. On or underneath the table, we then place the targets. During the search, the user is blindfolded. The user's interaction with the surface is documented by two cameras positioned at a right angle to each other, which

(a) (b)

Figure 3.7: Setup (a) underneath the table and on the side of the couch for the rough surface, and (b) on the table for the smooth surface

also record audio. The cameras are placed so one can see when the user touches the surface and with which part of their hand. The setup can be seen in Figure 3.7.

3.6 Execution

When the participants signed up for the study, they were asked whether they were right or left-handed. We then placed the surface on the side of the dominant hand *on the side of the couch*. At the beginning of the study, the participant was asked to read and sign the consent form (see Figure A.1). The participant was told that if he had any questions, the experimenter would be happy to answer them. As soon as possible questions had been answered, the experimenter told the participant to voice any thoughts he had during the search. The experimenter reminded the participant of this multiple times during the study. The participant was also told that he could remove his glasses and take a break at any time between the trails. Next, the participant was informed whether the target would be placed *on the table*, *underneath*, or *at the side of the couch*. He was also informed when this changed. Furthermore, the experimenter emphasized that the target will be small or big randomly and that the participant only has to search for a single target. The participant was then asked to put on the glasses.
In the pilot study, we found that participants tried to and

could hear or at least roughly estimate where we placed the target and searched in that region. To avoid this, we decided to put three targets of the same type in our actual study and remove two of them concurrently. Therefore, the experimenter next placed three targets and removed two concurrently. The participant was then asked to search for the target. As soon as the participant had found the target, the new targets were placed, and two of them were removed. The participant was then asked to search again. This was repeated multiple times till all trials were finished. During those trials, the experimenter always placed the targets standing on the same side of the table.
After the experiment, the user was asked to fill out a questionnaire (see Figures A.2 and A.3) concerning demographic information and his perception of the experiment. The user was told that if he had any questions concerning the questionnaire, the experimenter would be happy to answer them. Moreover, the experimenter told the participant that he was free to do so if he wants to feel the surface or the targets again.
The user was not allowed to see the targets till the end of the study. The surface, however, he saw even before the first trial began. If the user asked whether he could use both hands or had to use a specific hand, he was told that he could use both hands or either of his hands but that he is supposed to do what is most natural to him. Otherwise, the participant was not told that he could use both hands. Furthermore, throughout the study, the participant possibly heard slightly distracting sounds coming from people walking by or the street through an open window, which leads to a more realistic setting, as it will usually not be totally quiet at home.

3.7 Measurements and Feedback

As mentioned before, the experiment was filmed with two cameras. The videos were analyzed by hand. After the experiment, the participants had to fill out a questionnaire with multiple 7-point Likert scales and free text questions to capture their study experience accurately. In the free-text questions, the participants are asked to describe their search strategy, their starting point, and their preferred region for the target. In the 7-point Likert scale questions, the participants are asked to rate how comfortable the `surface`, the `targets`, each `surface position` and each `target position` were. They were also invited to rate how easy it was to find the targets, how well they could reach all regions, and how much they were guided by the sound, which occurs when positioning the targets.

3.8 Participants

We did not have specific requirements for our participants because any person could be a user of smart home controls. Our participants were a mix of colleagues, friends, and, in total, 17 people. Eight participants were male, and eight participants were female. One participant did not disclose his gender. Sixteen participants reported being right-handed, and one participant was left-handed. The age of the participants ranged between 21 and 29 (M(Mean) = 23.63, SD(Standard deviation) = 2.5). One participant did not disclose his age.

3.9 Duration of the study

The study took approximately 30 min to 45 min (M=37.35, SD=6.87) per participant. Many participants stated that the study was relatively quick and fun. Although we did not stop the time, each trial took approximately under 10 sec, except for a few outliners (0-2 per participant).

Chapter 4

Results

The following chapter presents the results of our qualitative analysis and the statistical tests we conducted. The conclusions we draw from these results are shown in Chapter five (Discussion). First, we describe the observed search strategies for the different `surface positions` and compare them. Then we present the self-described search strategies by the participants and compare them to the search strategies we observed. After that, we describe the observed starting point of the participants and the self-described starting point and compare them. Next, we describe the participants' preferred regions for the targets and mention the influence of the sound occurring when placing the targets. Last but not least, we show the result of the statistical test we conducted on the answers to the questionnaire and present other comments made by the participants.

4.1 Observed search strategies

4.1.1 On the table

On the table, most participants (ten out of 17) used a variant of **wave lines with both hands** shown in Figure 4.1. Three out of the ten participants executed this movement

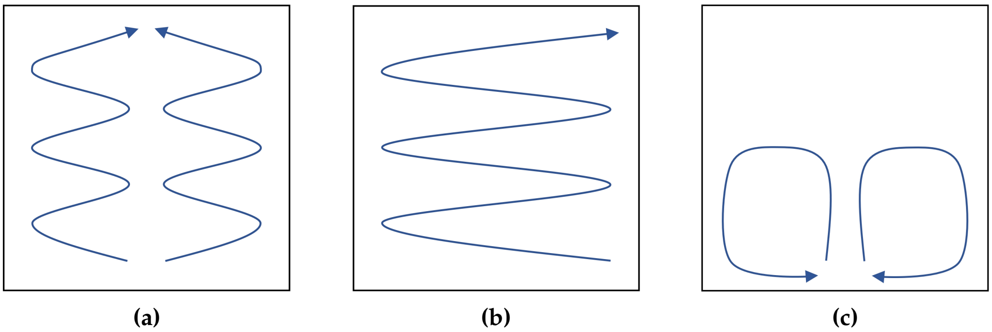


Figure 4.1: Movements called: (a) wave lines with both hands, (b) wave lines with one hand, and (c) circular motions

forwards and backward (standard variant). Two out of ten participants only had another starting point. One participant always started in the left and right corners of the *front margin*. . One of the ten participants lifted his hands to start at the front edge again. One of the ten participants always moved his hands in a straight line and right angle away from the front edge and then executed this movement on his way back. Two participants moved their hands in a straight line and right angle away from the front edge to perform the **wave lines with both hands** only on some occasions and otherwise executed the standard variant. One of those participants also always started in the left and right corners of the *front margin*. One participant did not only sometimes first move his hands in a straight line and right angle away from the front edge but also sometimes used only his dominant hand to execute **wave lines with one hand** shown in Figure 4.1.

Wave lines with one hand, in general, were the second most executed movement. Six out of 17 participants performed a variant of this movement. Four of the six participants completed this movement forwards and backward (standard variant). One participant started in the left corner of the *front margin* and then went to the right corner of the *front margin* first. Another participant sometimes moved his hand in a straight line and right angle away from the front edge and then started executing this movement.

One last participant had a strategy of his own. He first moved his hands in a straight line and right angle away

from the front edge till he reached the clamps and then checked the left and right edges on his way back. If he did not find the target in the first run, he moved his hands in a straight line and right angle away from the front edge and then checked the part of the table behind the clamps. Two of the 17 participants first checked the table's measurements the first time by running over all the edges. One participant did so with both hands and the other with only one, although both used both hands in the consecutive search.
Twelve of the 17 participants mainly swiped *on the table*. However, three of the twelve participants sometimes tapped for a very short time. One participant sometimes tapped or crawled. Two participants sometimes moved only their fingers a bit during the search to better glide over the surface. Four participants tapped in general. But still, three of them occasionally swiped. Two of those three swiped whenever they could not find the target by tapping. One participant showed a mix of swiping and tapping with no clear preference. The distance between the taps was only a few centimeters and did not increase or decrease over time. This remains true for all `surface positions`.
Seven of the 17 participant used their whole hand for the search *on the table*. Six participants used their fingertips and their palms. Four participants used only their fingertips. One participant switched from using his whole hand to using only his fingertips when he could not find the target. One participant switched from using his whole hand to using only his fingertips and palms when he switched from tapping to swiping.

4.1.2 Underneath the table

For *underneath the table*, nine out of 17 participants used a variant of the **wave lines with both hands** shown in Figure 4.1 to find the target. Four of those participants consistently executed the standard variant. One participant performed the standard movement, except that he started at the left and right corners in the *front margin*. One participant always lifted his hands to start at the front edge again. Two participants permanently moved their hands in a straight line and right angle away from the front edge and then only on their way back used **wave lines with both hands**. One participants moved his hands in a straight line and right angle away from the front edge to then execute the **wave lines with both hands**. Whenever he could not find the target, this participant switched to swiping **wave lines with one hand** using only his dominant hand. . Another participant often completed the standard variant but sometimes switched to **wave lines with one hand** using only his dominant hand.

Six out of 17 participants executed a variant of the **wave lines with one hand**. Two participants completed the standard variant. One participant started in the left corner of the *front margin* and than went to the right corner of the *front margin* first. Three participants began in the middle of the front edge and then went to the left or right with no clear preference.

Two out of the 17 participants introduced a new movement shown in Figure 4.1; we call this **circular motions**. However, one of those participants sometimes switched to **wave lines with one hand** using only his dominant hand.

Four out of the 17 participants sometimes leaned forward to embrace the table from the sides and search the *left and/or right margin*.

Eleven of the 17 participants mainly swiped *underneath the table*. Three of these eleven participants sometimes tapped for a very short time. One participant each sometimes crawled and tapped or crawled. One participant also tried to glide better over the surface by moving his fingers a bit during the search. Three participants tapped mostly. However, all of them sometimes swiped. One of those swiped whenever he could not find the target by tapping. Another one used one hand only for swiping when he used two hands before for tapping. One participant showed a mix of swiping and tapping, and another two, a combination of tapping and crawling with no clear preference.

Thirteen of the participants used only their fingertips *underneath the table*. Three used their fingertips and their palms. One participant used his whole hand.

4.1.3 On the side of the couch

For *on the side of the couch*, 14 out of 17 participants used a variation of **wave lines with one hand** for their search. Eight of those participants first moved their hands to the far corner. Four of those eight participants started their search in the near corner. Three started in the middle of the top margin, and one participant started anywhere in the top margin. One of the participants who started in the near corner sometimes also moved his hand downwards in a straight line right angle from the top margin first. Two out of the 14 participants started in the far corner and first moved to the near corner. Four of the 14 participants first moved to either the near or far corner with no clear preference.
Three of them started in the middle of the top margin, and one either in the middle or the near corner. Three out of the 17 participants each showed a unique but similar search strategy. They all mainly searched by going over all the margins. One of those participants always checked the margins first, and he checked the middle only if he could not find the target there. Another of those participants always checked the margins but only those in front of the clamps. This participant sometimes let his hand first run downwards in a straight line at a right angle to the top margin till it was at the height of the clamps. The last of those participants was also the only one who used two hands *on the side of the couch*. This participant used his non-dominant hand to search the near corner and his dominant hand to run downwards in a straight line at a right angle to the top margin and then check all the margins. Five of the 17 participants first checked the measurements of the surface the first time by running over all the edges. Two of them, however, did not go all the way to the ground but stopped their search at the clamps.
Twelve out of the 17 participants many swiped *on the side of the couch*. Two of them sometimes tapped, and one sometimes tapped or crawled. Three participants tapped in general. However, all of them occasionally swiped—one of them when he could not find the target. One participant showed a mix of tapping and swiping with no clear preference. Another one showed a combination of tapping

and crawling. However, this participant also switched to swiping when he could not find the target.
Eight of the 17 participants used only their fingertips for the search. Six used their fingertips and their palms. Only three participants used their whole hands.

4.1.4 Comparisons

One can see the direct comparison of search strategy, hand motion, and part of the hand used *on the table*, *underneath the table*, and *on the side of the couch* in Tables 4.1, 4.2, and 4.3.

Search Strategy	On the table	Underneath the table	On the side of the couch
Wave lines with both hands	10	9	0
Wave lines with one hand	6	6	14
Circular motions	0	2	0
Other	1	0	3
Additionally check measurements	2	0	5

Table 4.1: Comparison of search strategies

Hand motion	On the table	Underneath the table	On the side of the couch
Swiping	12	11	12
Tapping	4	3	3
Swiping and Tapping	1	2	1
Tapping and Crawling	0	1	1

Table 4.2: Comparison of hand motion

Part of hand	On the table	Underneath the table	On the side of the couch
Whole hand	7	1	3
Fingertips and palm	6	3	6
Fingertips	4	13	8

Table 4.3: Comparison of the part of hand used

If one compares the participants' strategies *on and underneath the table*, one can see that the participants use similar techniques for both scenarios. Six out of 17 participants used the same method. Seven out of 17 participants only changed the hand part they used. To be more specific, four participants who used their fingertips and their palms and three who used their whole hand *on the table* used only their fingertips for *underneath the*

table. One participant used a different variant of **wave lines with both hands** for *on and underneath the table*. Two participants switched between **wave lines with both hands** and **circular motions**, one in each direction. Only one participant switched his search strategy and the part of the hand he used. He switched from **wave lines with both hands** using his whole hand to **circular motions** using only his fingertips.
If we look at which part of their hand the participant used to swipe or tap, we can see that participants who tapped used their whole hand in three cases and their fingertips along with their palms in one case *on the table*. *Underneath the table*, participants used only their fingertips in two cases and their whole hands in one case. *On the side of the couch*, the participants used their whole hand in two cases and their fingertips along with their palms in one case.
Next we look at the participants who swiped. *On the table*, four participants used their whole hand, five their fingertips and their palms and three only their fingertips. *Underneath the table* most (nine) participants used only their fingertips and one participant each either their whole hand or their fingertips along with their palms. Finally, *on the side of the couch*, seven participants who swiped used only their fingertips and five participants their fingertips and palms.

4.2 Self-described search strategies

Next, we will describe, the feedback the participants gave in the questionnaire (see Figures A.2 and A.3) and their statements during the study. But first, we want to note that the participants only considered some aspects of their search strategy in the questionnaire. Thus their answers are not complete. Two participants claimed to use **wave lines with both hands**. Two participants claimed to use **wave lines with both hands** *on and underneath the table*. Three participants claimed to use **wave lines with both hands** or **wave lines with one hand** depending on how many hands they used. One participant claimed to use **wave lines with both hands** starting in the left and right corner or **wave lines with one hand** starting in the right corner. Thus, four out of 17 participants claimed to use **wave lines with both**

hands and four participants claimed to used **wave lines with both hands** and **wave lines with one hand**.
Two participants claimed to use **wave lines with one hand**. Two participants each claimed to use **wave lines with one hand** starting in the right or left corner. Thus six participants claimed to use only **wave lines with one hand**. One participant claimed to use half circles. Only one participant claimed to use **circular motions**. One participant only wrote that he used symmetrical movements for both hands when possible. Another participant claimed to use the sound of the targets when being placed towards the end of the study and otherwise to search only in the front half.
Three participants stated that they used only one hand *on the side of the couch*. One participant claimed to use his dominating hand more *on the side of the couch*. Two participants stated that they sometimes embraced the table for *underneath the table*. Three participants stated that they checked the measurements of the surface the first time in their search. Only one participant mentioned to tap.
Four participants emphasized trying to make their hands as big as possible. One participant stated that he tried to maximize contact with the surface. Three participants claimed to use only their fingertips. One of those three participants wrote that he first tried to use his whole hand. Only one participant claimed to use his fingertips and his palms. Two participants claimed to use slight pressure to move quicker or feel more, especially for the small target. One participant also mentioned moving his fingers a bit during the search to move quickly over the surface. Another participant said to use his thumb to check the corners behind the legs under the table. One participant also mentions using his forearms to check the surface under the table.
Seven participants said to hear whether the target was small or big. One of those participants mentioned searching more subtly for the smaller target. One participant mentioned searching with more speed for the bigger target. One participant noted that he lifted his hand higher off the plate when he searched for the bigger target, along with more speed and a less subtle search. Another participant mentioned not switching his search strategy after hearing whether the target was small or big.

Three participants said they only searched in the nearer half of the table (in front of the clamps) or avoided the space behind them. They only searched there when they could not find the target elsewhere because the part behind the clamps was not well reachable. Another participant stated that the *back margin* was not reachable *underneath the table*. One participant also mentioned searching only in the nearer half because all the targets were placed there. One participant also noted that when he could not find the target, it was because it was behind the clamps and the small one. Another participant stated that the targets behind the clamps were hard to find. One participant mentioned that he oriented himself at the clamps to know where he was *on the table*, especially when he searched for the *small* target.
One participant said to first search roughly and then more thoroughly. Another participant stated to first search for the big and then the small target. One participant mentioned that he first roughly scanned the surface. One participant also noted that the plexiglass's edges helped him orient himself.
One participant noticed that he got quicker in his search over time. Another participant mentioned that he would typically have used **wave lines with one hand** from the front to the back, then to the front and the back again, etc., but the clamps prevented him from doing so. Thus instead, he chose to go from left to right. In the videos, we could also see that he first tried the described movement before switching to go from left to right.

4.3 Comparison of self-described and observed search strategies

Let's compare what participants said during the experiment and wrote down in the questionnaire to what we could observe. We can say that what the participants described matches our observations very well. Of course, we surveyed more than what the participant described. Out of 59 statements, the participants made our observations contradicted only ten.

Three of these deviations related to which part of the hand was used. In one case, the participant stated to use only his fingertips. However, we observed that he also used his palms *on the table*. In another case, the participant claimed to use his whole hand when he only used his fingertips and palms *on and underneath the table*. Finally, in the last case, the participant stated to use his flat hand when he only used his fingertips.
Five of the deviations concerned the search strategy. Two participants reported to use only **wave lines with both hands**. However, they used **wave lines with one hand** *on the side of the table*, and one of them also *underneath the table*. One participant claimed to use **circular motions**, when he really moved his hands in a straight line and right angle away from the edge and then executed **wave lines with both hands** on his way back. However, these movements are very similar. Finally, another participant claimed to search in **wave lines with one hand** from right to left. However we could not observe a preference for a first movement to the right or left side.
One participant mentioned searching more subtly for the smaller target. However, we could not see a difference in the videos. Another participant noted that he lifted his hand higher off the plate when he searched for the bigger target, along with searching with more speed and less subtle. We could not confirm this either.

4.4 Starting point

4.5 Observed starting points

On the table and *underneath the table* all of the 17 participants actually started in the *front margin*. Most of them (eight out of 17 for *on the table* and 13 out of 17 for *underneath the table*) started in the middle of the *front margin*. For *on the table* another four out of 17 participants started in the right corner of the *front margin*. For *underneath the table* only one participant did so. For both surface positions, one participant started in the left corner of the *front margin* and

one participant either in the right corner or the middle of the *front margin*. Two out of 17 participants for *on the table* and one participant for *underneath the table* started in the left and right corner of the *front margin* simultaneously.
For *on the side of the couch* all of the participants started in the *top margin*. Most of the participants (eight out of 17) started in the middle of the *top margin*. Five of the participants started in the near corner of the *top margin* and two in the far corner. One participant started either in the middle of the *top margin* or the near corner.
The observed starting points can be seen in Table 4.4.

Starting point	**On the table**	**Underneath the table**	**On the side of the couch**
Front or top margin	1	0	1
Middle of the front or top margin	8	13	8
Right or near corner of the front or top margin	4	1	5
Left or far corner of the front or top margin	1	1	2
Right and left corner simultaneously	2	1	0
Right corner or middle of the front margin	1	1	0
Near corner or middle of the top margin	0	0	1

Table 4.4: Comparison of the starting point

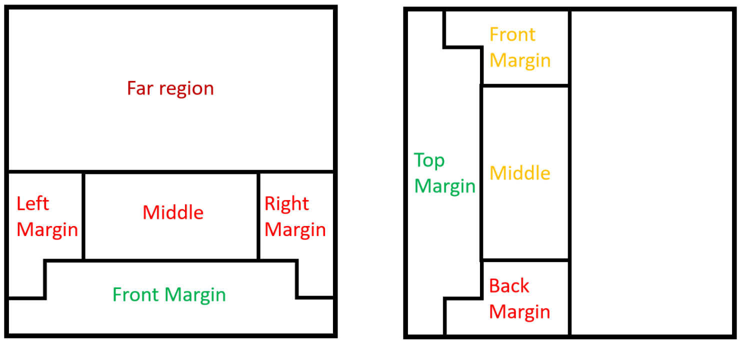
4.6 Self-described starting point

On and underneath the table, participants reported to start their search in the *front margin* 15 out of 17 times. Some specified this further. The participants stated to begin in the middle or the right corner of the *front margin* four out of 17 times each. One participant stated to start in the left corner of the *front margin*. However, this participant was not left-handed. Another one stated to start in either of the corners of the *front margin*. Only one participant reported choosing his starting point based on the sounds he heard when the targets were placed towards the end of the study. Another one said to start in the middle.
On the side of the couch, only 13 out of 17 participants wrote down their starting point. Twelve out of these 13 participants reported to start in the *top margin*. Here some also specified this further. Three out of 13 participants stated to start in the far corner. Two out of 13 participants each reported to start in the middle of the *top margin* or the near corner. Only one participant said again to choose

his starting point based on the sounds he heard when the targets were placed towards the end of the study.
Eight out of 17 participants also specified that their starting point was always the point closest to them. One participant also mentioned always starting close to the point where he found the last target.
In the questionnaire, participants were also asked whether they chose the starting point consciously or unconsciously. Only 14 out of 17 of the participants answered this question. Of those 14 participants who answered, seven chose the starting point consciously and six unconsciously. One participant wrote that sometimes he chose it consciously and sometimes unconsciously. Two participants also noted that they decided on the starting point unconsciously the first time but after that consciously.

4.7 Comparisons of self-described and observed starting point

If we now compare the participants' statements to what we saw in the videos, one can see that the participants were quite self-aware. If we use one-to-one comparisons, the participants were right 20 out of 47 times. This might seem low. However, 15 out of 47 times, the participants reported starting point was simply more general than what we saw, e.g., the participant said that he started in *top margin*, when he started in the middle of the *top margin*. In ten out of 47 times, the participant was only slightly off. E.g., the participant said he began in the far corner of the *top margin* when he started in the middle of the *top margin*.
If we compare the starting point to the number of hands used during the search (only the primary search strategy is considered), we can see a correlation between the starting point and the number of hands. Because *on the side of the table*, only one participant used both hands, we only looked at *on and underneath the table*. *On the table*, eight out of the eleven participants who used both hands, started in the middle of the *front margin*. Two participants began at the corners of the *front margin* and one participant anywhere in the *front margin*. Of the six participants who used only their



(a) **(b)**

Figure 4.2: The preferred regions for (a) on the table and underneath the table and (b) on the side of the couch, green = preferred by >8, orange = preferred by 3-4, red = preferred by 1-2, dark red = preferred by 0

dominant hand, three started in the left corner and two in the right corner of the *front margin*. Only one participant started either in the middle or the right corner of the *front margin*.

Underneath the table ten out of the eleven participants who used both hands started in the middle of the *front margin*. Only one participant started in the corners of the *front margin*. Three of the participants who used only one hand started in the middle of the *front margin*. One participant each started in the right or left corner of the *front margin*. Finally, one participant started in the *front margin's* middle or right corner.

4.8 Preferred region for the targets

On and underneath the table, people preferred the *front margin*. Thirteen out of 17 participants *on the table* and eleven out of 16 *underneath the table* stated that preferred the *front margin*. Some specified this further. Three out of 17 participants *on the table* and two out of 16 *underneath the table* stated that preferred the middle of the *front margin*. Two participant each *on and underneath the table*, said they preferred the right corner of the *front margin*. However, two out of 17 participants *on the table* and one out of 16 *underneath the table* stated that preferred the *right margin*. Furthermore, one out of 17 participants *on the table* and two out of 16 *underneath the table* indicated that they preferred the *left margin*. Lastly, one out of 17 participants *on the table* and two out of 16 *underneath the table* stated that preferred the *middle*.

On the side of the couch, nine out of 17 participants preferred the *top margin*. Few specified this further. One participant each preferred the near corner, the far corner, the middle, and either the middle of the *front margin* or the far corner. Four out of 17 participants actually preferred the *front margin*, and three out of 17 the *middle*. One participant preferred the *rear margin*.

If we compare the preferred region and the actual starting point for each participant, we can see that they are precisely the same eleven out of 51 times. The starting point was in the preferred region an additional 23 out of 51 times. Three out of 51 times, the preferred region was part of the regions used as a starting point. In 14 out of 51 times, the starting point and the preferred region do not match. However, in general, it is visible that the preferred region and the starting point align in most cases.

4.9 Influence of sound

One participant claimed to hear where the targets were placed towards the end of the study and thus just checked these locations. In one case, the participant heard that the target was further away but did not believe it. The participant also stated that the *big* target was easier to hear than the *small* one. We were able to confirm this for some trials with the videos. However, most of the time, the participant still had to search a bit. Nevertheless, because of this, we excluded the trials where this was visible from our evaluation.

Seven other participants claimed to hear whether the target was big or small, but not its location. Three of them stated to change their search strategy according to this. They searched with more speed and less subtle for the *big* target. One participant explicitly said not to change his search

strategy. However, for all seven participants, a difference in the search strategy was only visible for two. These two participants searched with more speed for the bigger target. However, the difference was minimal.
Five participants claimed that hearing did not help because it was not reliable (two participants), one had to search nevertheless (one participant), or they could not get any information out of it (two participants).
Three participants also claimed that hearing only partially helped. One participant mentioned that one could hear the targets less well *underneath the table* than *on the table*. Thus *on the table*, the participant was more influenced by the sound than in the other surface positions. Another participant stated that the target's sound, when placed, did not affect him much and only in the front area.
On a 7-point Likert scale, the average of the participants' answers to whether they were influenced by the sound when the targets were placed was 3.56 for the *rough* and 4.38 for the *smooth* surface, which roughly corresponds to neutral. The standard deviation was 2.65 for the *rough* and 1.06 for the *smooth* surface.

4.10 Effects of the independent variables

In this section, we test the Likert scale questions of the questionnaire for significant differences. Because of the mixed design of our study, we executed the Friedman and Wilcoxon Signed-rank tests for the *smooth* and *rough* `surfaces` separately. To test whether the `surface` significantly affected any of the questions, we used Kruskal-Wallis rank sum tests. The mean and standard deviation for most of the questions in the questionnaire can be seen in Figures 4.3, 4.4, 4.5, 4.6, 4.7, and 4.8. For the question of whether the surface was comfortable, the mean for the *rough* surface was 5.22, and for the *smooth* surface, 5.5. The standard deviations were 1.3 for the *rough* and 1.69 for the *smooth* surface.

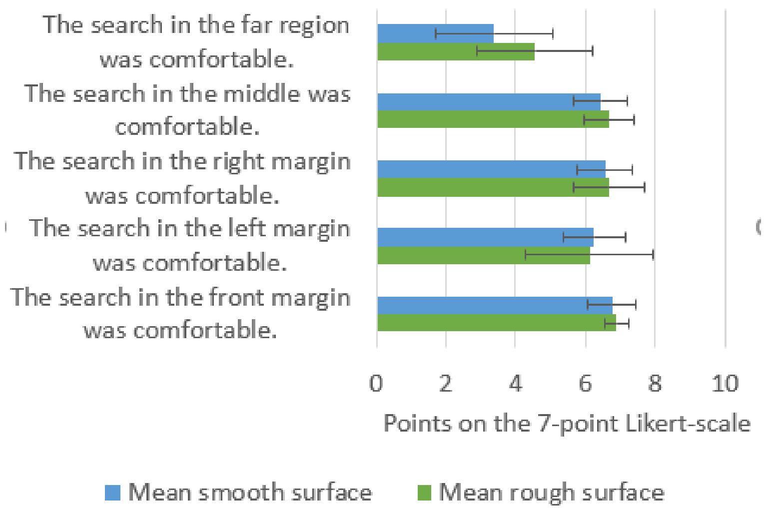


Figure 4.3: Mean +/- standard deviation for the effect of target position on the table

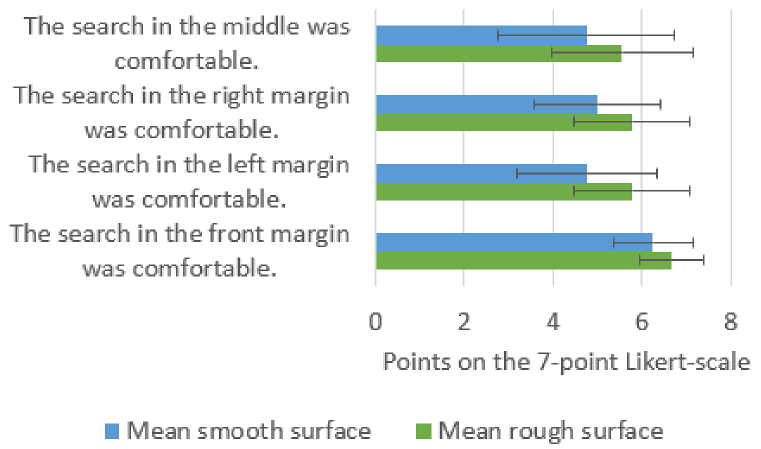


Figure 4.4: Mean +/- standard deviation for the effect of target position underneath the table

4.10.1 Rough surface

A Friedman test revealed a significant effect of `target size` on the easiness of finding the target ($\chi^2(2)$ = 6, p $<$ 0.02). A post hoc test using the Wilcoxon signed-rank test with Holm correction showed a significant difference

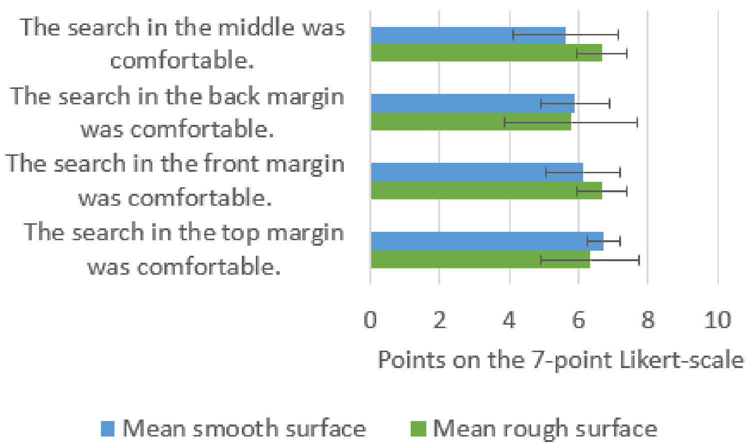


Figure 4.5: Mean +/- standard deviation for the effect of target position on the side of the couch

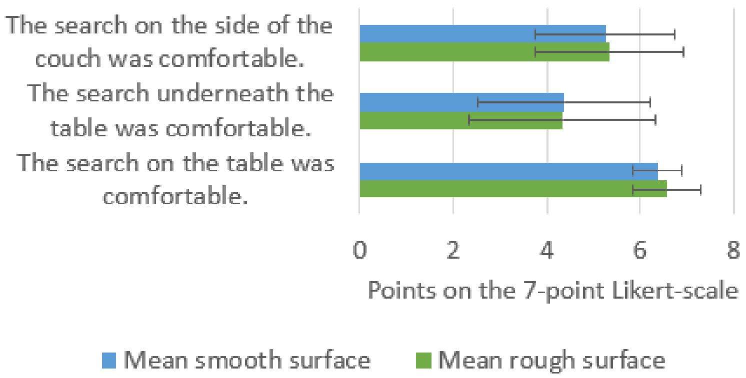


Figure 4.6: Mean +/- standard deviation for the effect of surface position on search comfort

between the *small* and *big* target ($p < 0.04$). Another Friedman test revealed a significant effect of `target size` on the comfort of feeling the target ($\chi^2(2) = 6$, $p < 0.02$). The post hoc test using the Wilcoxon signed-rank test with Holm correction showed a significant difference between the *small* and *big* target ($p < 0.04$).
We found no significant effect of the `surface position` on the ability to reach all regions. We also found no significant effect for neither `surface position` nor `target position` on the comfort of the search.

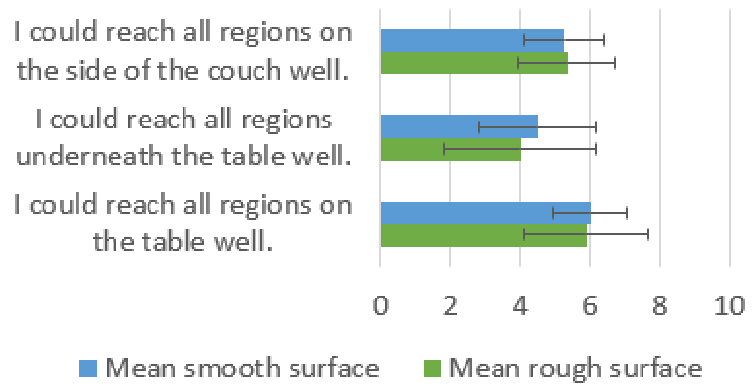


Figure 4.7: Mean +/- standard deviation for the effect of surface position on the ability to reach all region

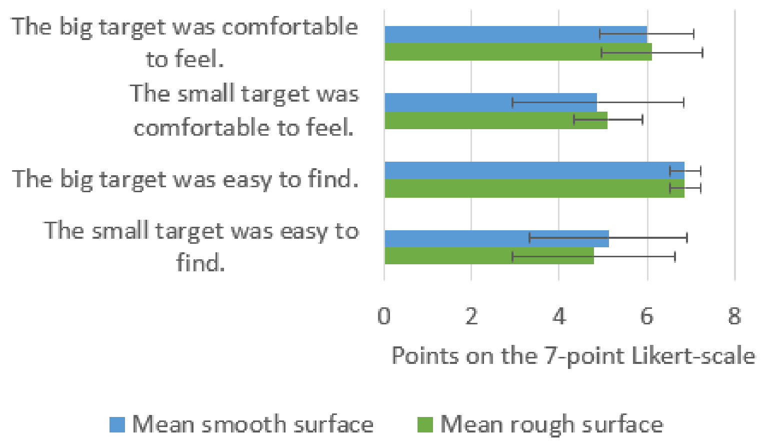


Figure 4.8: Mean +/- standard deviation for the effect of target size on the easiness to find and the comfort to feel the target

4.10.2 Smooth surface

A Friedman test revealed a significant effect of `target size` on the easiness of finding the target ($\chi^2(2) = 6$, $p < 0.02$). A post hoc test using the Wilcoxon signed-rank test with Holm correction showed a significant difference between the *small* and *big* target ($p < 0.04$).
A Friedman test showed no significant effect of `target size` on the comfort of feeling the target. Likewise, we

found no significant effect of the `surface position` on the ability to reach all regions. We also found no significant effect for neither `surface position` nor `target position` on the comfort of the search.

4.10.3 Surface comparison

The Kruskal Wallis tests revealed no significant effect of the `surface` on easiness or comfort of the search nor on reachability.

4.11 Other comments of the participants

One participant mentioned that he did not have a strategy the first time he searched and just hoped to be in luck. Another participant stated to search like he would in real life. One participant described his search *on the side of the table* as more intuitive and unsystematic. The participant stated to search more in the middle in form of half circles. However, another participant mentioned that searching *on the side of the couch* was less intuitive. Moreover, he did not see the surface beforehand and therefore did not have a picture of it in his head.

One participant mentioned that he found one hand to be safer than two. One participant also used his second hand for support. Another participant noted that he moved his hands synchronously; otherwise, coordination would be challenging.

One participant mentioned that one is likelier to catch the target with one's fingertips than palms. Another participant stated that the *small* target was difficult to detect because of its thinness. However, the sellotape made it easier to feel the *small* target with the palms. One participant mentioned that the *big* target was easier to find than the *small* one and that this effect was stronger *on the table* than *on the side of the couch*. Two additional participants confirmed that the *big* target was easier to catch and the search for it more comfortable.

One participant mentioned that he had no fear of destroying anything and was, therefore, able to cover more space more quickly. On the other hand, one participant philosophized that he might be faster without the clamps, but he might not want to throw anything off the table in real life.

Two participants mentioned that the search *on the side of the couch* was most comfortable and *underneath the table* was least comfortable. One participant mentioned that to search *on the side of the couch* with one hand is comfortable. *On the side of the couch* one participant found it more comfortable to approach from the *back margin* than the *top margin*; only the corner made this approach less comfortable. Another participant mentioned that that the targets were more challenging to find *underneath the table* than *on the table*.

Chapter 5

Discussion

In this chapter, we will derive conclusions from the results presented in chapter four. First, we will consider the influence of sound, as this is a critical point in our analysis. Then the search strategies and starting points are mentioned, followed by possible positions for controls and the evaluation of the statistical tests. Last but not least, we will make some suggestions for the design of guiding markers.

5.1 Influence of sound

Concerning the influence of sound, we can safely say that most of our participants were not or only slightly influenced by the sound the targets made when they were placed. Therefore our analysis of the natural search behavior of possible users of smart home controls is still valid. However, one should keep this problem in mind for future studies.

5.2 Search strategies and starting points

We saw that all participants systematically searched and chose their starting point and could find the target quickly, especially if it was in the nearer half of the surface. We observed that the participants had different search strategies and starting points for different `surface positions`. Therefore we can say that the `surface position` influenced the search. Interestingly the participants used similar techniques *on and underneath the table*, but not *on the side of the couch*. Moreover, the participants described behavior matches our observations and therefore shows that the participants were quite self-aware. However, as we can derive from the question in the questionnaire which asked the participants whether they consciously chose their starting point, they might not always have chosen their search strategy on purpose and certainly not always their starting point.

5.3 Possible positions for controls

Since all participants started their search in the *front or top margin*, this region is particularly interesting for possible controls because it allows the participant to find the controls there quickly. Moreover, this region does not require the participant to move much to reach the controls or twist himself. Additionally, it allows for the central space of the table (the middle) to be used typically without any restrictions. Furthermore, this is consistent with the preferred region of the participants.
As particular points of interest in the *front margin*, we propose the corners and the middle. Especially the right corner is predestined for controls *on the table* as many participants started their search there and named it their preferred region. Moreover, the corners of tables are usually barely used. Therefore, the left corner would be the second best option because it does not disturb the regular use of the table as well. However, one must remember that we only had one left-handed participant, which is not representative of the whole population. But still, in general,

there are more right than left-handed people, which is why this conclusion should remain valid but has to be considered with care. Finally, the third option would be the middle, as many participants also started there. However, it might restrict the regular use of the table.
Underneath the table the middle is especially interesting, since over 75% of the participants started there, and multiple named it their preferred region. Therefore, the next best option would be the corners of the *front margin*, with the right corner preferable to the left because more participants started there and named it their preferred region. However, here applies the same as *on the table*: the conclusion must be considered carefully because we only had one left-handed participant.
If it is not possible to place the controls in the *front margin*, the *left or right margin* would be the next best option as it was also named by multiple participants and does not disturb the regular use of the table. Here the right margin is preferred over the left margin by the participants and would also most likely be more intuitive since more participants started in the right than in the left corner. This notion should also be considered with care because we only had one left-handed participant. We also saw that, especially *underneath the table*, no controls should be placed in the *far region* since this would force the user to twist himself or even get up. Also, *on the table*, this would pose the problem of an item possibly being in the way and accidentally knocking something over.
On the side of the couch we propose the *middle* of the *top margin* as the best location for controls as it allows them to be found quickly since many participants started there. Moreover, the user does not need to twist himself to reach it. The next best option would be the near corner, as many participants also started there, and the user does not need to twist himself to reach it. The third best option is the far corner because multiple participants also started there.
The next best option to the *top margin* would be the *front margin*, as multiple participants proposed it, and the user also does not need to twist himself to reach it. The *back margin* margin is not recommended because it is not well reachable. In general, positions behind the center of the body should not be used except the far corner. Multiple participants also proposed the middle. Because this part

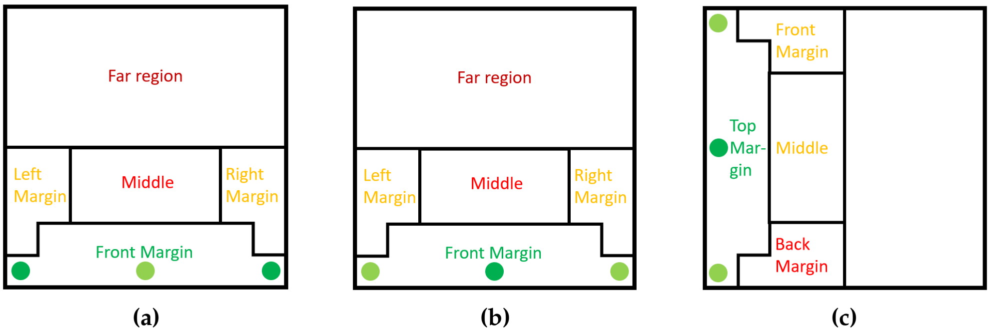


Figure 5.1: Recommended positions for controls: (a) on the table, (b) underneath the table, and (c) on the side of the couch, green = highly recommended, light green = recommended, orange = alternative, red = not recommended, dark red = definitely not recommended

is still easy to reach and the side of the couch is not used for anything else, this would be the third best option. However, this might interfere with a table placed next to the couch. Finally, the *far region* is not recommended to be used since this would force the user to twist himself.
The recommended positions for the controls are shown in Figure 5.1.

5.4 Effects of the independent variables

The only revealed significant difference in the tests was the difference between the *small* and the *big* targets. Therefore we can say with certainty that the `target size` influences the easiness of the search. Moreover, we can say that no `surface position` is clearly a better place for possible controls than another `surface position`. However, controls *on the table* might interfere with its regular use. Since the tests revealed no significance for `target position` the same can be said about it. However, the qualitative analysis provided some insights into what `target positions` are better suited for controls, as seen above.
The significant difference for `target size` was expected and also noted by the participants multiple times, who

sometimes missed the *small* target, but this never happened for the *big* target. The participants missed the *small* target because their hands had run over it without detecting any difference from the surface. In contrast, the *big* target was mainly detected by the side of the hand crushing into it. If the target were higher, it would, therefore, most likely not be so easy to miss it. Thus we propose to choose a height greater than 1 mm. Investigating a specific height with the optimal balance between the easiness of target detection and unobtrusive design is possible future work. Since the statistical tests showed no difference between the *smooth* and *rough* surface and we could not observe any difference in our qualitative analysis either, one can say that the `surface` does not influence the search of targets.

5.5 Design of guiding markers

As already said, a second user study should be conducted concerning how to best guide the user via guiding markers to the target. Concerning the design of such guiding markers, first of all, the proposed target size by Mlakar and Haller [2020] of 13 mm should not be undercut because already targets of this size were hard to find for the participants. The same suggestion for the targets also applies for the guiding markers that their height should be greater than 1 mm so that the user can easily detect them. Additionally, we propose placing such guiding markers in the *front or top margin*, because this is most likely the user's starting point. Furthermore, the margins generally seem an excellent place to place such guiding markers since the edges themselves provide a good reference point to follow the guiding markers in a straight line. This will be especially helpful if the targets are placed in the margins. In addition, putting the guiding markers in the margins will help the user to find the markers again, should he lose them. If it is impossible or desired to place the targets in the margins, we still recommend putting the initial guiding marker in the margin and the following guiding markers in a straight line from it to the target. Because most participants swiped, we can be sure that the user should not miss any guiding marker by tapping over it.

Chapter 6

Summary and future work

6.1 Summary and contributions

This thesis investigated how people search naturally using only their sense of touch and is the first step into discovering how to best guide users eyes-free to smart home controls. The effects of the `surface`, the `surface position`, the `target size`, and the `target position` on the haptic search of the user were investigated.
We found that the users mainly employed three different systematic search strategies named **wave lines with both hands**, **wave lines with one hand**, and **circular motions**, see Figure 4.1, with individual variations. *On the table*, only **wave lines with both hands** and **wave lines with one hand** were used. **Wave lines with both hands** were used more often. *Underneath the table*, all search strategies were employed. **Wave lines with both hands** were used the most and **circular motions** the least. *On the side of the couch*, only **wave lines with one hand** were used. However, three participants showed individual search strategies. In general, most participants mainly swiped, but some tapped. A few participants also showed a mix of swiping, tapping, and crawling. The distance between

the taps was only a few centimeters and did not increase or decrease over time. *On the table*, participants maximized contact with the surface, while *underneath it* they did the opposite. *On the side of the couch*, participants showed no clear preference for maximal or minimal contact. These observations were confirmed by the participants' self-described search strategies and showed that they were self-aware. The different search strategies depending on the `surface position` show that this factor influences the search.

Moreover, we found that most participants start in the middle of the *front or top margin*. *On the table*, some participants also preferred the right corner of the *front margin* as their starting point. *On the side of the couch*, multiple participants also chose the near corner as their starting point. This was also confirmed by the participants' self-described starting point and showed that they were self-aware, although they did not always choose their starting point on purpose.

For all `surface positions`, most participants preferred the *front or top margin*. *On the side of the couch*, multiple participants also preferred the *front margin* and the *middle*.

As for possible positions for controls, we propose the *front or top margin*, more specifically, the corners and the middle of them. *On the table*, we prefer the corners, especially the right one, while *underneath the table* and *on the side of the couch*, we suggest the middle. If this is not possible, the right or near corner is preferred. *On the side of the couch* positions behind the center of the body should be avoided.

The statistical tests revealed a significant effect of *target size* on the easiness of finding and the comfort of feeling the target for the *rough* surface. For the *smooth* surface, the statistical tests only revealed a significant effect of *target size* on the easiness of finding the target. No significant effects were found of the `surface` on the easiness or comfort of the search or reachability, the `surface position` on the comfort of the search or reachability, and the `target position` on the comfort of the search. Therefore we can say that the `target size` influences the easiness of the search. Additionally, the `surface` does not affect the search because we could not observe any difference for different `surfaces` in the qualitative analysis either. Furthermore, one can conclude

that no `surface position` nor `target position` is preferable for possible controls. However, our qualitative analysis, suggested where to best place the controls for different `surface positions`.
Because the *small* target was easy to miss, we propose a target height greater than 1 mm. Also, the target size of 13 mm proposed by Mlakar and Haller [2020] should not be undercut. This also applies to potential guiding markers to guide the user to the target. We suggest placing such guiding markers in the margins because this makes it easier for the user to find them again, should he lose them. Moreover, the edges provide a reference point to follow the guiding markers in a straight line. Especially the *front or top margin* would be an excellent place for guiding markers, as this is most likely the user's starting point. Even if it is impossible to place all guiding markers in the margins because the target is in the *middle*, the initial guiding marker should be put in the margin and the following guiding markers in a straight line from it to the target. Because most participants swiped, it is unlikely for the user to miss any guiding markers by tapping over them.

6.2 Future work

First, the effect of additional variables on the search strategy can still be investigated, like surface size, target reactivity (avoid false activation), and experience. We did not explore these independent variables due to the scalability of the study. Moreover, in our research, there was always only one target the participants could find. Therefore, the effect of multiple targets and the distances between them was not investigated. If one uses multiple targets, the task of distinguishing between them could also be explored depending on the physical difference between them. As already mentioned in the discussion, the optimal target height could also be investigated, or as proposed by one participant, the effect of other things placed on the table one does not want to knock over.
As already mentioned in the introduction, a second user study still needs to be conducted on how to best guide the user to the target. For this second user study, we

Figure 6.1: Possible guiding markers

propose investigating different guiding markers and their effect on how long people can follow them and how far they deviate once they cannot follow them anymore. We offer to study different types and sizes of guiding markers with varying distances between them. Different types and sizes may afford a better sense of the direction in which they lead, and if the distance between those markers is too great, the participant may have to start his search anew. Additionally, we would investigate the effect of regular, recessed, and raised guiding markers, because this showed a big difference for sliders in the study by Nowak et al. [2022]. As for the different types of markers, we would investigate, it would be interesting to see which part of the markers the users use to get a sense of direction and whether long horizontal bars as part of the guiding markers provide better support for the user. Therefore we propose to investigate four types of markers shown in Figure 6.1.
In a third user study, one could then compare guiding the users via a continuous path vs. with the help of guiding markers to letting them seek blindly.

Appendix A

Documents

Einverständniserklärung

Studientitel: Wie suchen Menschen nach Objekten nur mit ihrem Tastsinn?

Protokollführer: Michelle Mirus

Beschreibung: Sie sind eingeladen worden, um an einer Forschungsstudie teilzunehmen, welche sich damit beschäftigt wie Menschen nach Objekten nur mit ihrem Tastsinn suchen. Während der Studie werden Sie auf einer Couch sitzen und einen Couchtisch vor sich haben, auf welchem sie blind nach Objekten suchen. Sie werden ebenfalls seitlich der Couch nach Objekten suchen. Um zu gewährleisten, dass Sie sich nur auf ihren Tastsinn verlassen, werden Sie während der Studie eine blickdichte Brille tragen. Sie werden nach 2 verschiedenen Objekten suchen (ein kleineres und ein größeres) und das auf einem Untergrund (Stoff oder Plexiglas). Die gesuchten Objekte werden sich entweder auf der Ober- oder Unterseite des Tisches oder seitlich der Couch befinden. Während des Suchens wird Ihre Hand von 2 Kameras, die auch Audio aufnehmen gefilmt werden. Die Videoaufnahmen werden sicher und anonymisiert gespeichert werden. Sie sind auf den Videos nicht zu erkennen. Nach der Studie werden Sie noch einen Fragebogen ausfüllen, in welchem Sie gebeten werden Ihr Alter, Geschlecht und Links- oder Rechtshändigkeit anzugeben. Außerdem werden Ihnen Fragen bzgl. Ihren Erfahrungen während des Suchens nach Objekten gestellt. Auch die Fragebögen werden sicher und anonymisiert aufbewahrt. Die Ergebnisse der Studie werden in einer Bachelorarbeit und eventuell in wissenschaftlichen Veröffentlichungen verwendet werden.

Zeit: Die Studie wird vermutlich ca. 45min dauern.

Risiken und Vorteile: Die Studie beinhaltet keine Risiken oder Vorteile für Sie.

Bezahlung: Sie werden keine Bezahlung für die Teilnahme an der Studie bekommen.

Rechte des Teilnehmers: Wenn Sie diese Einverständniserklärung gelesen haben und sich entschieden haben an der Studie teilzunehmen, beachten Sie bitte, dass die Teilnahme freiwillig ist und Sie das Recht haben Ihre Einverständnis jederzeit zu widerrufen oder die Teilnahme abzubrechen. Die Alternative ist nicht teilzunehmen. Sie haben das Recht sich zu weigern bestimmte Fragen zu beantworten. Ihre Privatsphäre wird geschützt in jeglichen veröffentlichten und geschriebenen Dokumenten, die aus der Studie hervorgehen.

Kontaktinformation:
Fragen: Falls Sie irgendwelche Fragen, Bedenken oder Beschwerden bzgl. der Studie, deren Verfahren, Risiken und Vorteilen haben, kontaktieren Sie Michelle Mirus (michelle.mirus@rwth-aachen.de).

Ich bin damit einverstanden während der Studie mit Audio gefilmt zu werden:
Zutreffendes bitte ankreuzen: ☐ Ja ☐ Nein

Ich habe alles gelesen und erklärt bekommen:
Zutreffendes bitte ankreuzen: ☐ Ja ☐ Nein

Unterschrift ______________________________ Datum ____________

Figure A.1: Consent form

Fragebogen

Teilnehmernummer:

Bitte geben Sie zunächst an:

Alter:

Geschlecht:

Links-/Rechtshänder: ☐ Links ☐ Rechts

Beschreiben Sie bitte ihre Suchstrategie:

Falls Sie ihr Suchstrategie teilweise verändert haben, beschreiben Sie bitte wie und unter welchen Umständen (z.B. am Ende anders als zu Beginn):

Falls Sie einen spezifischen Startpunkt für ihre Suche hatten, beschreiben sie bitte wo und wieso. Gebe sie bitte außerdem an ob dieser bewusst oder unbewusst gewählt wurde:

Figure A.2: Questionnaire

Fragebogen

Teilnehmernummer:

	stimme überhaupt nicht zu	stimme nicht zu	stimme ehr nicht zu	weder noch	stimme ehr zu	stimme zu	stimme voll und ganz zu
Die Oberfläche war angenehm.							
Das kleine Target war auf der Oberfläche gut zu finden.							
Das große Target war auf der Oberfläche gut zu finden.							
Das kleine Target war auf der Oberfläche angenehm zu erfühlen.							
Das große Target war auf der Oberfläche angenehm zu erfühlen.							
Ich konnte **auf** dem Tisch alle Bereiche gut erreichen.							
Ich konnte **unter** dem Tisch alle Bereiche gut erreichen.							
Ich konnte **seitlich** alle Bereiche gut erreichen.							
Die Suche **auf** dem Tisch war angenehm.							
Die Suche **unter** dem Tisch war angenehm.							
Die Suche **seitlich** war angenehm.							

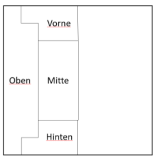
*Wenn Sie **auf** dem Tisch gesucht haben:*

	stimme überhaupt nicht zu	stimme nicht zu	stimme ehr nicht zu	weder noch	stimme ehr zu	stimme zu	stimme voll und ganz zu
Die Suche **vorne** war angenehm.							
Die Suche **links** war angenehm.							
Die Suche **rechts** war angenehm.							
Die Suche in der **Mitte** war angenehm.							
Die Suche **hinten** war angenehm.							

*Wenn Sie **unter** dem Tisch gesucht haben:*

	stimme überhaupt nicht zu	stimme nicht zu	stimme ehr nicht zu	weder noch	stimme ehr zu	stimme zu	stimme voll und ganz zu
Die Suche **vorne** war angenehm.							
Die Suche **links** war angenehm.							
Die Suche **rechts** war angenehm.							
Die Suche in der **Mitte** war angenehm.							

*Wenn Sie **seitlich** gesucht haben:*



	stimme überhaupt nicht zu	stimme nicht zu	stimme ehr nicht zu	weder noch	stimme ehr zu	stimme zu	stimme voll und ganz zu
Die Suche **oben** war angenehm.							
Die Suche **vorne** war angenehm.							
Die Suche **hinten** war angenehm.							
Die Suche in der **Mitte** war angenehm.							
Das Geräusch, das die Objekte beim Positionieren gemacht haben, hat mich in meiner Suche geleitet.							

Beschreiben Sie ihre präferierte Region für das Target (in Abhängigkeit von der Position der Oberfläche):

Figure A.3: Questionnaire continuation

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