Mappings in the Home: Selecting Home Appliances in 3D Space

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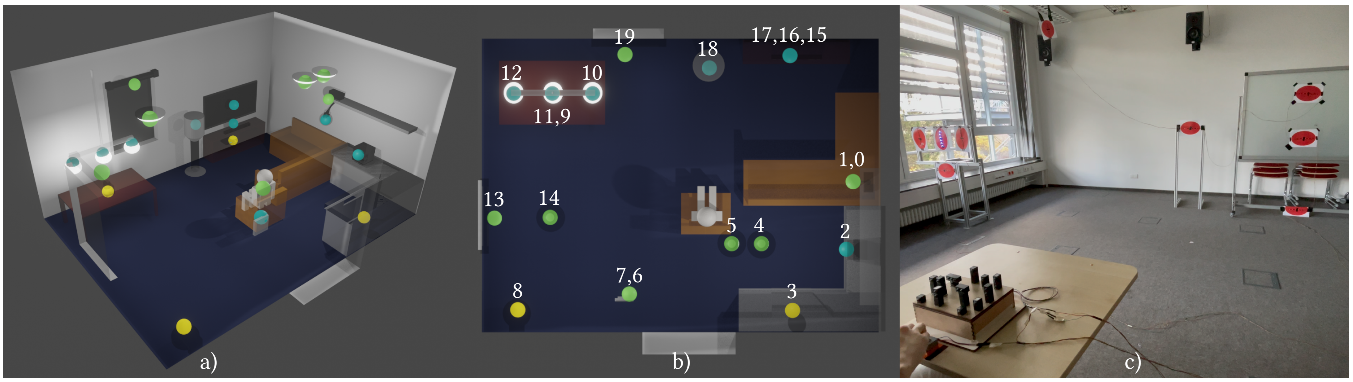

Figure 1: Three views of our test room: an isometric view of the room and the home appliances they represent in our test scenario (a), a top-down view which was used for our Map controllers (b), and the real replication of the room with our light targets that were used in our user study (c). Target colors in (a-b) indicate how high they are placed: <0.95 *m* (yellow), <1.65 *m* (teal), or above (green). In (c), the user is looking at targets 9–12 and 15–19.

ABSTRACT

Unlike voice assistants, remotes, and smartphones, UIs embedded into furniture and other surfaces offer silent, discreet, and unobtrusive control of smart home appliances. However, as the number of appliances grows, fitting individual controls for each onto the surfaces in our environment becomes impractical, making it necessary to select appliances before controlling them. These appliances are placed in 3D at various heights around the room, while traditional controls are laid out in 2D, complicating control-to-target mapping. We compared six UIs using mappings with spatial analogies that are either absolute or relative to the user's position and perspective. Participants used each to select 20 targets in a simplified living room, once while looking and once eyes-free. We investigated performance and participants' ratings for, inter alia, ease of use, mapping comprehensibility, and mental demand. Map-based controllers were most promising, but participants also ranked perspective projection with touch input highly.

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CCS CONCEPTS

• **Human-centered computing → Haptic devices**; **Ubiquitous and mobile devices**; *Empirical studies in HCI*; *Pointing devices.*

KEYWORDS

natural mappings, smart home, haptic, target selection

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1 INTRODUCTION

Smart home appliances are typically controlled using smartphone apps, remote controls, or voice assistants. Since remote controls and smartphones are not physically bound to where they are needed, operating them requires first finding the device and, for smartphone apps, navigating to the app and within it to the appliance to control. While voice assistants avoid those steps, speech commands tend to be loud and indiscreet, and device names are invisible and require memorizing. When placing controls for the smart home onto sofas, tables, or other everyday objects, controls could be placed where they are needed most frequently. This enables users to operate their smart home even without looking, as the location of each control element never changes. Such controls can be embedded aesthetically pleasing to the environment and offer discreet and silent input. In addition, they also grant users who are unfamiliar with or have not set up the system access to smart home functionality. This also enables installations in public places like in hotel rooms.

While numerous projects have explored the design of such tangible controls [3, 6, 11, 14], they usually only show how they are used in isolation for a single application. In modern smart homes, however, there are numerous devices to control, such as TVs, stereos, lights, vacuum robots, blinds, and gaming consoles. To avoid allocating space for each control on the available surface in the environment, such embedded UIs require users to first select a target device before controlling it. However, traditional controls are usually laid out in 2D, which makes it difficult to target appliances arranged in 3D space around the room—especially those located above each other. To address this, we prototyped controllers that implement different target–control mappings based on the principle of natural mappings introduced by Norman [17]. These controllers allow addressing both the horizontal and vertical target positions. Our study participants used them both while looking and eyes-free to select targets in an exemplary living room (Figure 1).

2 RELATED WORK

Norman [17] introduced the concept of *natural mappings* that describe how the layout of input devices can be used to make their effect clear to the user without explanations. One type of mapping he suggests are *spatial analogies* in which the spatial arrangement of the controls and targets is linked (*the left switch for the left light*). Our work builds on this type of mapping, with targets distributed in 3D. Park et al. [18] also found that spatial analogies often break in reality and proposed light switches that dim the lights on contact before the switch is actually toggled. Alternatively, mappings have to be created semantically, e.g., by drawing symbols on surfaces as suggested by Chamunorwa et al. [5] or by letting users bind controls by themselves: Perteneder et al. [19] added mapping symbols to their smart furniture building blocks that provide input and output, and two blocks bound with the same symbol are mapped to each other independently of their spatial arrangement. In AR and VR, 3D selection is often performed by changing the user perspective [10, 21]. In proxemic interfaces like in [2, 12], mappings are addressed using, inter alia, user location and orientation. This, however, requires external tracking and movable controls. Overall, it remains unclear how mappings using spatial analogies can be established without disturbing the calmness of the home with GUI screens or VR displays.

3 TEST ROOM

For our user study, we created a digital exemplary living room including 20 smart home appliances such as lights, media players, blinds, and vacuum robots. Figure 1 (a) shows the imagined layout of this room; the colored balls mark the appliances as targets in our study. The control position was placed so that nine appliances were in front of the user and the remaining eleven above, to the side, or behind them. We replicated this setup in a real-world test room (c). However, we used LED strips to represent the actual appliances to enable uniform feedback for interactions, similar to [18]. In a real-world scenario, such feedback can usually be provided by control LEDs on the appliance. A printed red circle backed the LED strips, and the room was darkened to make the targets clearly visible.

4 CONTROLLERS

We designed six controllers (Figure 2) that use the target's spatial position in their selection mechanism. Inspired by tactile maps like [9], **Map** controllers (a–d) provide a top-view room map (Figure 1b): If a target is placed in the center of the left wall, the map controllers have buttons on the center-left. **Perspective** controllers (e–f) use the target position relative to the user's perspective. In addition to the horizontal mappings, users use the target's perspective height to map them to the input capabilities of the controller (Figure 3).

With our controllers, we wanted to explore a wide range of approaches to address the selection of targets placed above each other. Besides the differentiation in absolute (map) and relative (perspective) mappings, we used repeated clicks (Figure 2a), separated the room into layers (b), introduced a haptic language (c), and used direct 3D-to-3D mapping (d). With perspective controllers, we also investigated the difference between button interfaces (e) and gesture-based touch interfaces (f).

Following simplicity guidelines [4] for haptic interfaces, we only included elements that are indispensable for the working principle of the controller to make the interface as clear as possible for our haptically untrained users, which led to fairly minimalistic hardware designs. Nonetheless, some controllers need their targets to provide feedback on the current selection. Depending on the cause, the targets light up in different colors: If multiple targets can be addressed with the current user input, all candidates light up yellow, a preselected target lights up white, and when the selection is accepted, the target lights up green. If a preselection is set to the task target, it brightens the target color from blue to turquoise.

MapRepeatedClicks (a). To address targets located above each other, the user presses the corresponding button repeatedly to iterate through those targets, which light up yellow. The preselected target lights up white. The selection is accepted when no input is given within one second.

MapLevels (b). This controller consists of three *MapRepeatedClicks* and should help select stacked items by separating the room into three height levels: The top controller only contains targets higher than 1.6 m, the bottom one contains all targets below 0.95 m, and the middle one includes targets in between. As participants familiarized themselves with this mapping, we suggested referring to the height of their own hip and face as reference for these levels.

MapFrames (c). Here, all vertically stacked targets have their own button on the controller, grouped by a surrounding frame. This controller introduces a haptic vocabulary in which a frame indicates that the items within are vertically aligned. The arrangement of the buttons and room targets match according to the spatial analogies from Norman [17].

Map3D (d). Instead of being flat, this map controller consists of pillars at each horizontal target location, which contain buttons for each target. The button height approximately resembles the target

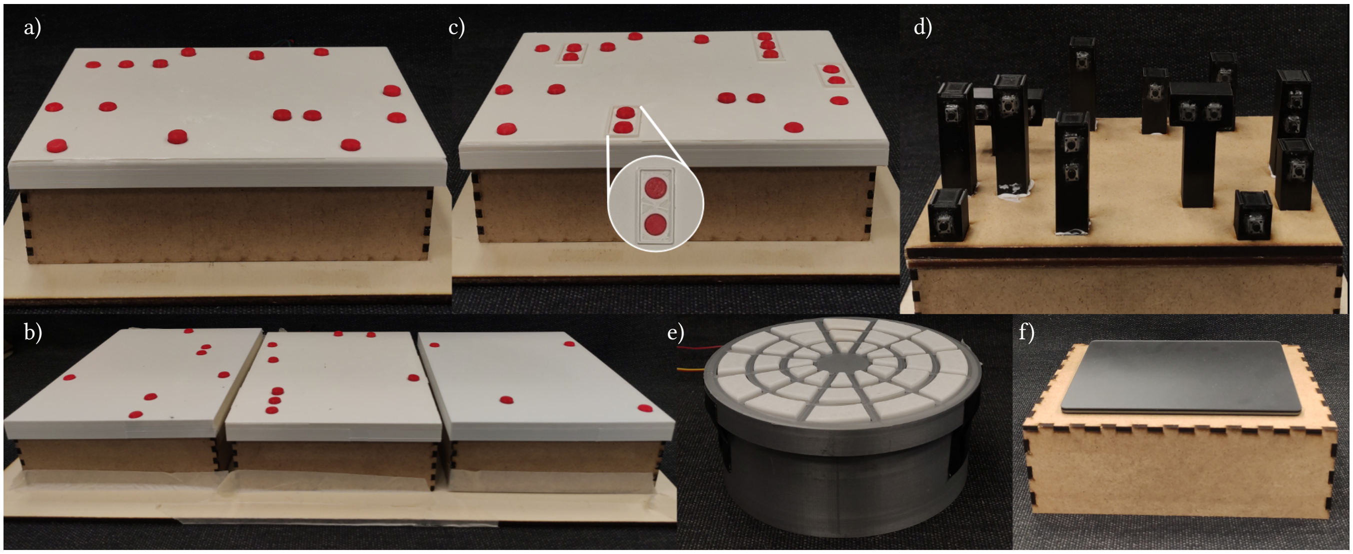

Figure 2: Six controllers to select targets in 3D space: *MapRepeatedClicks* (a), *MapFrames* (b), *MapLevels* (c), *Map3D* (d), *PerspectiveButton* (e), and *PerspectiveTouch* (f). In particular, all controllers select vertically stacked targets differently.

height in the test room. Although this controller is only realizable as a stylized decorative object in a real-world scenario, we added it as "baseline" since it is the most direct application of the natural mappings principle.

PerspectiveButton (e). This controller consists of twelve circle segments, each containing three buttons. Users select a segment based on the direction of the target from the user's perspective. The buttons within a segment are mapped according to a perspective projection of the targets: If a target is the highest target in the user's field of view—which does not have to be the farthest target—, it maps to the button farthest from the center. The button below addresses the second-highest target from that perspective, and so on. Figure 3 (left) demonstrates the mapping. Based on informal testing, we decided to assign the buttons from the outside so that free buttons are in the center. If multiple targets were on the same height within one segment, the grouping mechanism from *MapRepeatedClicks* was used. This would also be necessary if more than three targets were aligned vertically, but this was not the case in our study.

PerspectiveTouch (f). This controller uses touch input to avoid the resolution constraints of the segmented *PerspectiveButton*. Here, the users draw strokes on a touchpad. Users can start the stroke anywhere on the surface. The stroke angle determines the direction of the target in relation to the user, and its length (55 $px \approx 9$ *mm* steps) determines what target in the user's perspective is selected, analogously to *PerspectiveButton* (Figure 3 right). When starting the stroke, the currently selected target lights up white. In preliminary tests, we found this feedback to be crucial as the user had no other help with orientation. If the stroke direction does not directly match a target, the closest target is selected. The target is accepted if the selection does not change for 1 second.

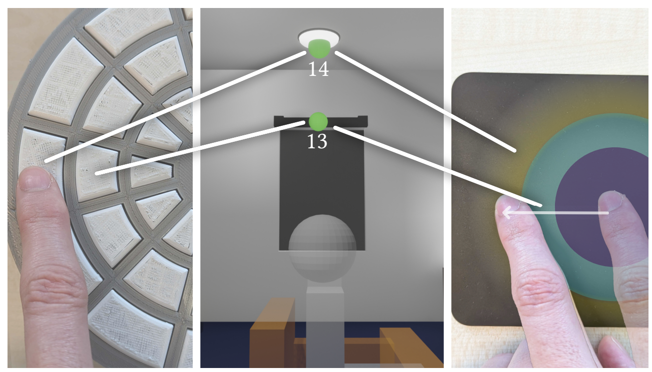

Figure 3: *PerspectiveButton* (left) and *PerspectiveTouch* (right) use perspective height to map user input to devices in the user's vision (center). Therefore, their outer regions map to the closer ceiling lamp (14) while the center regions map to the farther blind on the wall (13).

4.1 Fabrication Details & Apparatus

Except for *PerspectiveTouch*, all controller surfaces were 3D-printed. The map controllers were 20×15 *cm* and *PerspectiveButton* had a diameter of 15 *cm* For *PerspectiveTouch*, we used an Apple Magic Trackpad 2 of 16×11.49 *cm*. All controllers were placed on a 5 *cm* box, which was necessary to connect the buttons. The button dimensions were 3×10×10 *mm* for the map controllers. For *PerspectiveButton*, each "ring" was 13 *mm* large; the button width filled the available space to indicate the range the segment covered and prevent palpation of empty space as suggested by haptic guidelines [4]. The frames of *MapFrames* were raised by 2 *mm*. These sizes and heights were chosen based on related work [4, 15, 20] to create sufficient haptic contrast. We used Adafruit WS2812b light strips controlled by an Arduino Mega 2560 that was connected to an Apple MacBook Pro (16-inch, 2019, 3072×1920 native resolution) set to a resolution of 2048×1280 px.

5 USER STUDY

The goal of our user study was to evaluate the performance of our controllers and to get qualitative feedback on their different approaches to address stacked targets. As one benefit of haptic controllers is their support of eyes-free use, our participants also had to use each controller eyes-free.

5.1 Variables

We controlled CONTROLLER, their VISIBILITY to the participant (*in-/visible*), and the TARGET to select in each trial. The order of CONTROLLER was counterbalanced using a Latin Square while TARGET was randomized. We measured the average *selection time* and *success rate* per participant. Furthermore, we gathered 7-point Likert scale ratings for general and VISIBILITY-dependent aspects. For the first one, we asked how easy the mapping was to *comprehend*, *(initial) ease of use*, and the *reachability* of all controller components. In dependency of VISIBILITY, we investigated how *confident* participants were to select the correct target, how *mentally demanding* using the controller was, and how easily they could *orientate* themselves on the controller. As *PerspectiveTouch* does not offer any orientation cues, we omit the controller for this measurement.

5.2 Task

Before each selection, participants pressed a button for time measurements in front of the controller. This made the target light up blue. After finding the target in the room, they released the button, identified the button/region on the controller, and performed the selection. As we were only interested in the time of operating the controllers and not the time of finding the lights, time measurements were started on button release. When the participant made a selection, the corresponding light turned green and then turned off. A selection was unsuccessful if the user selected the wrong target by misclicking or if the wrong one was preselected after a timeout. After each of the 20 targets were selected, all lit up green. Then, the controller was covered using a large cardboard box with one wall replaced by a drape so that participants could reach into the box. The box was placed so that the drape hung slightly above the measurement button, preventing participants from seeing the controller while the location of the button was clear. The participant repeated the task by operating the controller in the box eyes-free. Participants were asked to verbalize their thoughts and only use their dominant hand.

5.3 Procedure

In the beginning, we ensured that participants were seated such that the targets "13", "14", and "18" were exactly West and North from their perspective. This ensured the angles were correct for our *Perspective* controllers. Before the task started, the current controller was explained and participants completed at least 20 trial selections to familiarize themselves with it. Before switching the controller, participants filled out a controller-specific questionnaire. At the end, participants completed an overall questionnaire with controller ratings.

5.4 Participants

We recruited 18 participants aged 19 to 31 (M = 24.67, SD = 3.36). 11 were female and 7 were male. Except for one left-handed participant, all participants were right-handed. 12 participants studied computer science or related fields, 3 studied in the field of engineering, 2 were HCI researchers, and 1 participant studied chemistry. 5 participants already had experience with earlier iterations of our prototypes from a user study conducted four months earlier.

5.5 Results

For time and success rate analysis, we averaged the measurements per participant, controller, and visibility level. Since our time data was log-normally distributed, we log-transformed it before analyzing it using a two-factor repeated measures ANOVA. For the non-normally distributed *success rate* data, we used a non-parametric analysis of variance based on the Aligned Rank Transform with CONTROLLER and VISIBILITY as factors. Wilcoxon signed-rank tests with Holm corrections were used for post-hoc analysis. If user ratings were dependent on VISIBILITY, they were analyzed analogously. Otherwise, we used a Friedman test with the same post-hoc test.

The ANOVA did not indicate a significant effect on *selection time* of CONTROLLER ($F_{5,192} = 21.65$), but of VISIBILITY ($F_{1,192} = 21.65$, $p < 0.001$). For *success rate*, the test revealed significant effects of CONTROLLER ($F_{5,187} = 32.73$, $p < 0.001$), VISIBILITY ($F_{1,187} = 9.33$, $p < 0.01$), and their interaction ($F_{5,187} = 2.7$, $p < 0.05$). The average performance and results of the post-hoc tests are shown in Figure 4. We found two missing user ratings in our questionnaires, once for *reachability* with *MapLevels*, and once for *mapping comprehension* with *PerspectiveButton*. We removed the participants for the corresponding analysis.

We found significant effects of CONTROLLER on *initial ease of use* ($\chi^2(5) = 43.76$, $p < 0.001$), *ease of use* ($\chi^2(5) = 37.71$, $p < 0.001$), *mapping comprehension* ($\chi^2(5) = 49.77$, $p < 0.001$), and *reachability* ($\chi^2(5) = 35.89$, $p < 0.001$). The means, standard deviations and the results of the post-hoc tests are shown in Figure 5.

Furthermore, we found significant effects on *selection confidence* (CONTROLLER: $F_{5,187} = 36.91$, $p < 0.001$; VISIBILITY: $F_{1,187} = 32.08$, $p < 0.001$), *mental demand* (CONTROLLER: $F_{5,187} = 17.09$, $p < 0.001$) and *orientation* (CONTROLLER: $F_{4,153} = 30.71$, $p < 0.001$; VISIBILITY: $F_{1,153} = 38.47$, $p < 0.001$). Figure 6 shows the means, standard deviations, and the results of the post-hoc tests.

At the end of the study, participants ranked the controllers (Figure 7). Participants liked the frames on *MapFrames* for orientation on the controller and the 1-to-1 relationship of buttons and targets. Interestingly, 3 participants suggested a perspective mapping within the frames. For *PerspectiveTouch*, our participants stated that it was easy and fun to use both in each condition and praised the ability to correct the selection. However, they also found the height mapping difficult. When using *Map3D*, participants appreciated the direct mapping but also mentioned that reaching some targets was difficult due to the other pillars. For *MapRepeatedClicks*, participants liked the simple layout, however, they asked for more

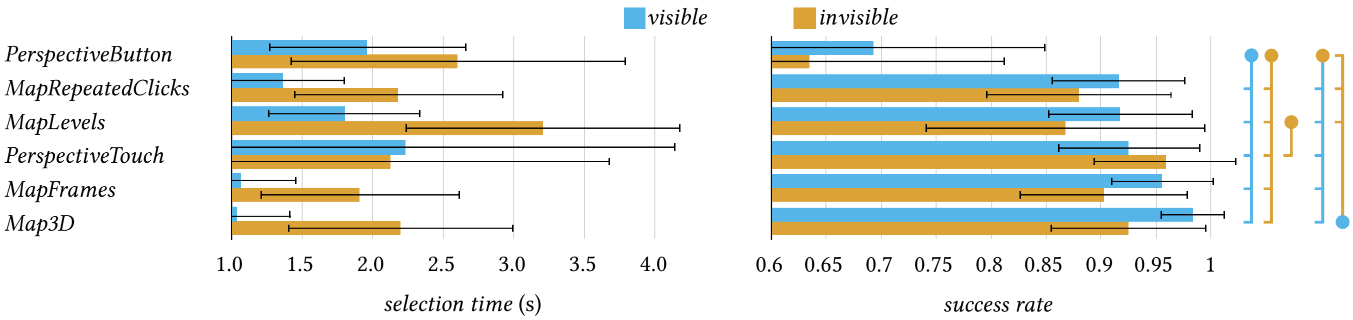

Figure 4: Average *selection time* and *success rate* of Controller dependent on Visibility. Controllers connected with a tick performed significant different to the controller connected with a circle. The colors of the significance lines map to the condition the effects occurred. Two-colored significance lines show interaction effects. Whiskers denote standard deviation.

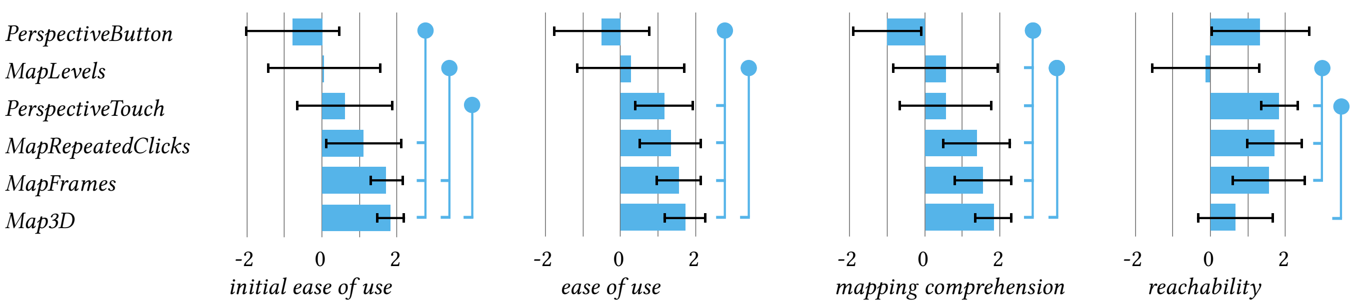

Figure 5: Average participant ratings for *initial ease of use*, *ease of use*, *mapping comprehension*, and *reachability* on 7-point Likert scales from -2 (worst) to 2 (best). Controllers connected with a tick performed significantly differently from the controller connected with a circle. Whiskers denote the standard deviation.

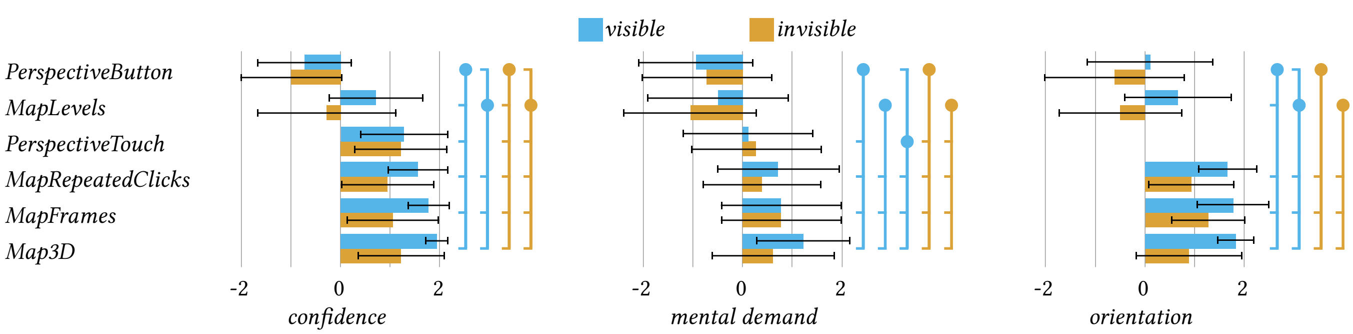

Figure 6: Average participant ratings for *confidence*, *mental demand*, and *orientation* on 7-point Likert scales from -2 (worst) to 2 (best). Controllers connected with a tick performed significantly differently from the controller connected with a circle. The colors of the significance lines map to the condition for which the effects occurred. Whiskers denote the standard deviation.

reference points on the controller. Unfortunately, some participants commented for *Map3D* that the pillars felt sharp when used eyes-free, and for *MapRepeatedClicks*, 3 participants mentioned that some buttons were harder to press, which sometimes occurred when the button covers jammed. Participants were told to inform us about this to repeat the trials if necessary. For *MapLevels* and *PerspectiveButton*, there was no agreement on positive feedback: two participants liked the relative target selections of the latter. Most participants found their mapping unintuitive.

6 DISCUSSION

Overall, all our measurements clearly showed that the concept of *PerspectiveButton* did not work well. Participants found the perspective mapping unintuitive. We observed that especially the targets "4" and "5", which were almost above the participant, were difficult to select using perspective projection. Furthermore, we decided to strictly use the real angles when grouping the targets, which created a split between targets "10" and "11". Although participants did not mention this in the questionnaire explicitly, we could observe this

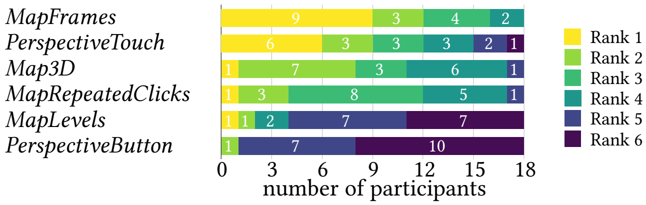

Figure 7: Participant ranking of Controller with 1 being the best and 6 the worst rank.

split to cause frustration when using the controller, which might be one reason why *mapping comprehension* was significantly lower compared to *PerspectiveTouch*.

We expected performance to be the main difference between *PerspectiveButton* and *PerspectiveTouch* as the underlying concept remains the same, and the feedback of the latter should reduce mental effort and increase confidence. While we could observe significant differences for *mental demand* and *confidence*, *selection time* was not significantly different. Regarding *PerspectiveTouch*, we were surprised by the high *selection time* and its wide spread. We informally observed that some participants started the selection without aiming at the target and then corrected their selection. This might explain the high spread since how far away the participants started from the target varied strongly.

The continuous input and feedback of *PerspectiveTouch* also seems to be a crucial factor in understanding the perspective projection since this controller performed significantly better than *PerspectiveButton* for *ease of use*, *mapping comprehension*, *confidence*, and *mental demand*. Although *PerspectiveTouch* was ranked well, we recommend the current implementation only if there is little space on the input surface as *MapRepeatedClicks*, *MapFrames*, and *Map3D* performed significantly better in most ratings.

Of the map controllers, *MapLevels* performed worst. Although we hoped that the familiarization and the orientation by hip and head height would help identify the correct level, the ratings for *confidence*, *mental demand*, and especially *orientation* show that this was not the case. Together with *PerspectiveButton*, those controllers indicate that groupings like separating the room strictly by dimensions like height or angles are not appropriate in our scenario.

We were positively surprised by the good ranking of *MapFrames* as it allows simple, fast, and feedback-free selections. Although this controller did not perform significantly differently to *Map3D* and *MapRepeatedClicks* in any ratings, participants commented on their disadvantage, which is the orientation on the controller when using it eyes-free. Furthermore, *MapRepeatedClicks* requires a feedback channel for the grouping mechanism, which needs to be designed carefully to be visible but also unobtrusive.

7 LIMITATIONS & FUTURE WORK

We tested our controllers in an exemplary living room with an uneven distribution of targets. We did so to create a more realistic scenario. This was also the only way to test meaningful versions of *Map3D* and *MapFrames* as the irregular frames and pillars created haptic reference points for the users. However, it is not clear whether all controllers perform the same in easier or more challenging scenarios. Therefore, future tests should look to incorporate different room layouts.

Participants suggested hardware changes like softer pillar edges on *Map3D* and adding reference points to *MapLevels* and *MapRepeatedClicks*. For future investigations, these should be considered.

Alternative projections could still be investigated in the future for controllers that are not map-based. We used a 1-step projection, especially to make *PerspectiveButton* less cognitively demanding—which turned out to be incorrect in retrospect. As *PerspectiveTouch* was still ranked well, we instead suggest 2-step projections that, for example, first of all use distance for the projection and then, in case of targets above each other, iterate through those stacked targets before continuing with the next, more distant target. However, map controllers could also be improved, for example, by implementing a hover state that preselects the targets similar to [18].

With *PerspectiveButton* and *MapLevels*, we found the grouping of targets to be crucial for the success of the controllers. Future studies should investigate whether controllers that use other algorithmic groupings, e.g., by using clustering algorithms, perform as well as self-configured groupings for those controllers. This could also improve *MapRepeatedClicks*. We believe that groupings are highly relevant in crowded target areas due to the limited space on controllers similar to *MapFrames*. Groupings should also be considered for currently group-free controllers like *PerspectiveTouch* as we received comments of sensitivity being too high to select very close targets like "9"-"12".

One advantage of our perspective controllers is their ability to adapt to new room layouts, while the map controllers can only display static maps. Therefore, future iterations of map controllers should consider using the mechanics of shape-changing interfaces like pin-array displays [13], pneumatic-actuation [7, 8] or textile deformation [1, 16].

8 CONCLUSION

We investigated six controllers to let users address individual targets in 3D in a smart home room. The controllers addressed the problem of targets being placed above each other by using relative and absolute location information, continuous and discrete input, and separation of targets into layers. In our user study, participants selected light-up targets that were arranged according to an exemplary living room, once while seeing the controller and once eyes-free. From comments, ratings, and our performance measurements, we found that maps introducing a haptic vocabulary enable users to make fast and accurate selections and perform similarly to controllers that mimic the room or require the user to iterate through groups of targets. Although our data is mostly in favor of map-based controllers, participants also ranked a controller that uses continuous touch input based on perspective projection well.

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