Designing Motion Matching for Real-World Applications: Lessons from Realistic Deployments
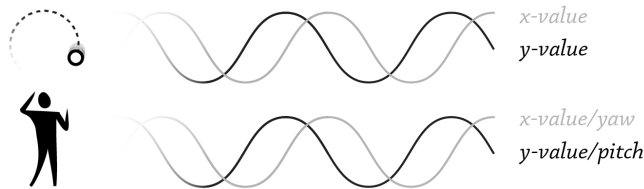

Figure 1. Motion Matching is an embodied interaction technique that allows interaction based on mimicking (displayed) targets, resulting in matching movement characteristics (such as axes) between target and user. Depending on implementation, input modality ranges from fingers and arms to eyes and heads.

ABSTRACT

Amongst the variety of (multi-modal) interaction techniques that are being developed and explored, the Motion Matching paradigm provides a novel approach to selection and control. In motion matching, users interact by rhythmically moving their bodies to track the continuous movements of different interface targets. This paper builds upon the current algorithmic and usability focused body of work by exploring the product possibilities and implications of motion matching. Through the development and qualitative study of four novel and different real-world motion matching applications — with 20 participants — we elaborate on the suitability of motion matching in different multi-user scenarios, the less pertinent use in home environments and the necessity for multi-modal interaction. Based on these learnings, we developed three novel motion matching based interactive lamps, which report on clear paths for further dissemination of the embodied interaction technique's experience. This paper hereby informs the design of future motion matching interfaces and products.

ACM Classification Keywords

H.5.2. User Interfaces: Input devices and strategies, Interaction Styles

Author Keywords

Motion matching; motion correlation; smart watches; touchless interaction; gestural input.

INTRODUCTION

The ability to remotely control the increasing number of smart devices is a recurrent challenge in HCI. This challenge has often been addressed by using tangible proxy devices, such as remote controllers [3, 15, 55]. Alternatively, researchers have explored input systems that leverage people's sensorimotor skills to provide intuitive, embodied and direct interaction, for example using body movement or gestures [5, 17, 28]. A recent class of such embodied interaction techniques, broadly described as *motion matching* [20, 46, 54], allows users to interact with digital systems by imitating a moving entity using bodily movements (e.g. moving one's hand to match a circular motion, see Fig. 1) [9, 11, 21, 48]. Compared to other touchless embodied interactions, motion matching is seen as better suited for spontaneous interaction [51], as it does not require gesture discovery and memorization.

Related works have developed and studied a variety of technical implementations of motion matching interaction, using web-cams [11, 12], depth-sensors [9], eye-trackers [18, 25, 37, 48, 51], magnets [39], and inertial measurement units (IMUs) embedded in smart-watches [49], phones [4], and AR headsets [19]. These implementations are supplemented with work on further algorithmic developments and novel deployments [10, 16, 21, 27, 29, 47]. Taken together, these laboratory studies have shown that people are able to accurately interact with motion matching interfaces after a very short learning period. Given these promising developments, an important next step is to further explore how motion matching is experienced in broader real-world scenarios [13, 51], and in which settings it would be most valuable.

To support and promote the future design of motion matching products and interfaces — contrasting technical or algorithmic developments — we present the study of 20 participants who sequentially experienced four novel real-world motion matching implementations in a controlled environment. These four implementations explore existing anticipated uses for motion matching, as seen in prior work, for parameter control (e.g. [39, 18]), and (multi-user) scenarios at home (e.g. [11, 50]) or in public spaces (e.g. [14, 51]). This allows us to draw design relevant insights for the scenarios reflected in our implementations: smart home control, interactive television, smart classrooms, and public displays. Our findings demonstrate that motion matching seems more suitable for (semi) public spaces and focused interactions, and less pertinent for use in scenarios at home — particularly for simultaneous multi-user control. They furthermore indicate the necessity for multi-

modal interaction for seamless integration of the technique in everyday life. We finalize this paper by exemplifying how these considerations could be put into practice. To this end, we present three novel product designs (interactive lamp) which implement motion matching interaction and discuss practicalities for future integration of motion matching in consumer products.

RELATED WORK

Touchless Embodied Interaction

The advances in real-time body tracking have spurred the creation of a rich set of interaction techniques that rely on body movement and gestures as means of user input [30, 43, 44]. These techniques generally involve pointing-based approaches, where users control on-screen cursors through body or hand movements [31, 53]; gestural systems, where user input takes the form of discrete (semaphoric) mid-air gestures [2, 43, 53]; or an hybrid of the two [24, 28]. But while effective, pointing-based (ray casting) techniques tend to require rather larger body movements when dealing with larger interaction spaces (e.g., large displays or smart environments [23, 40]), and displaying cursors for multiple users has been found to lead to confusion in non-collaborative tasks [9]. Gestural systems, on the other hand, have users perform discrete, mid-air gestures with their arms, hands, or fingers [8]. These systems allow users to interact with smart spaces in a relatively scale- and orientation-free manner, but also requires them to learn and memorize the system's gestures and corresponding commands [1, 2], often leading to false activations [45]. Additionally, others have noted that several of these systems rely on gesture sets that are not entirely natural or intuitive [32, 33]. In sum, in domains where spontaneous interaction is necessary, such as in public spaces or in any unfamiliar smart environment, designing for motion-matching interaction might address many of these challenges.

Motion Matching

The concept of motion matching was inspired by the early work of Williamson et al. [54], Fekete et al. [20], and more recently, Vidal et al. [51]. In motion matching, users interact not by pointing, nor by performing a discrete gesture, but by using their body to track the continuous and singular movements of different interface targets, see Fig. 1. User input and target movements are compared on their phase, speed, and direction — not on their position or scale. Because of this, interface targets can be positioned very close, or even super-imposed onto each other [18]; and a small tracking motion is sufficient to interact with targets trajectory of any size or distance, leading to a less fatiguing experience when compared to interfaces that require pointing over large surfaces [11]. Furthermore, targets in motion matching interfaces encode the necessary input information in their singular movement. This makes for interfaces that are "self-revealing and highly discoverable" [11, 51], ideal for spontaneous interaction [14, 51]. This is particularly important in maintaining a consistent experience across various smart devices and smart environments, otherwise relying on a broad set of input gestures [48].

Current work on motion matching interfaces has explored a variety of ways to capture user input, with the majority relying on optical tracking. Examples include systems that track users' eyes as these follow a moving target [18, 25, 27, 48, 51]; depth-cameras that track users' hands [9, 21, 22]; and systems that rely on off-the-shelf web-cams to capture any input motion in their field-of-view (FOV), be it performed by the users' hands, feet, or even their heads [11]. But due to inherent limitations of computer vision, such as being restricted by their FOV (interaction space), being susceptible to changing light conditions and occlusion, and introducing privacy concerns when used in the context of smart homes [7], recent work looks at other forms of input sensing for motion matching. Examples include passive magnets that capture the user's thumb movement [39], or inertial measurement units (IMUs) that capture users' head (AR headset [19]), arm (smartwatch [49]), or phone-based [4] rotations when following a moving target.

In addition to exploring different technical implementations of the technique, related works have also validated motion matching through a variety of lab studies. These have established the technique's accuracy [49], usability [18], and preference when compared to, e.g., pointing-based input [9]. But despite its promise and appeal, very little research has explored the use of motion matching in realistic, every-day scenarios. The few exceptions available describe how, when deployed in a real public display, motion matching facilitates discovery and rapid learning (Vidal et al. [51] describes 87.5% successful interactions with no guidance or instructions). With a high anticipated potential for this technique in a breadth of everyday scenarios — often envisioned in the related work — this leaves an important gap between research and product integration towards exemplifying motion matching product, and thus a crucial next step for this growing research area. This paper builds on the work described above and reports on the user experience across four realistic demos covering different use cases.

FOUR MOTION MATCHING DEMOS

The complexity and 'bulkiness' of integrating motion matching in every day interactions at its current state is a delimiting factor for testing user experiences for motion matching. With the aim to inform the design and deployment of future motion matching systems, this study explores the user experience with the technique in different application scenarios, through four fully functional demos in a semi-controlled environment. These demos represent scenarios in personal and public spaces, single and multi-user control and individual and collaborative interactions, which allows us to draw design relevant insights for a broad spectrum of future potential implementations. We hypothesized the four demos (presented below) to elicit functional, attractive, and pleasurable experiences, whilst each scenario explores a different real-world setting. We varied the (graphical) implementation of the interaction technique amongst these demos to elicit different challenges that motion matching interfaces might encounter in future deployments. In this section, we introduce our technical implementation of motion matching, and present our four demos.
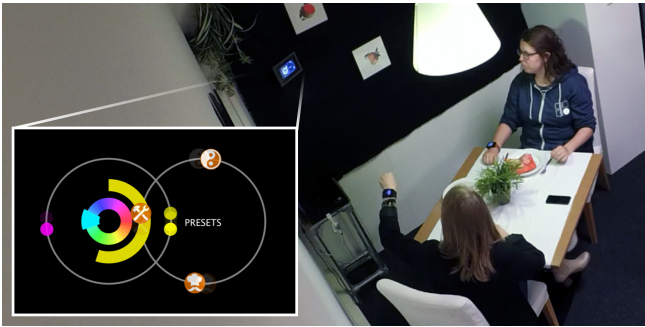
Figure 2. Smart Lighting Demo. Left: clockwise tracking of the moving yellow target increases light intensity (counter clockwise decreases), whilst tracking the purple target navigates through the HUE color spectrum. Right: three room lighting presets.

Motion Matching Implementation

As addressed in the related work section, various technical implementations of motion matching interaction are possible, each with their own benefits and limitations. The aim of this work is to generalize insights that designers of future motion matching applications can build further upon. Therefore, we found it important that our implementation would rely on affordable, off-the-shelf hardware and could be used in a variety of real-life scenarios. To avoid the FOV limitations and privacy concerns of optical tracking, our implementation relies on the inertial measurement unit (IMU) in a smart-watch to track user's arm movements. In particular, we adopted the 'WaveTrace' implementation presented by Verweij et al. [49].

In line with the WaveTrace implementation, each of our four demos depicts rotating targets on a display. Each target is distinguishable by its own unique rotational phase and direction. To interact, users track the rotating movement of the target they wish to select with their arms, which is captured by a 9-DOF IMU (triple axis gyro, accelerometer, and magnetometer) embedded into an Android smart-watch (Sony Smartwatch 3) and represented as Euler angles (yaw, pitch, and roll). Using a 'rolling' window of 1500ms (~195Hz, ~192 data points for each axis), this data is then matched with all moving targets through a Pearson's correlation between the user's (the yaw/horizontal and pitch/vertical movements of the arm) and each target movement (respectively x- and y-axis). If the correlation coefficient, a value between -1 and 1, is above 0.8 in both axes, the target is selected. Continuous input is supported when users continue to track a target after the initial selection (to, e.g., increase playback volume). Whilst prior work has shown that variety of target trajectories are possible [9], we opted to constrain our implementation to circles, so as to remain comparable to the majority of related work on motion matching.

Demonstrators

Based on ideation amongst the authors we developed four demos: the 'smart home control' aims to (seamlessly) blend a motion matching interface into users' smart homes (Fig. 2); an 'Interactive Television' demo aims to augment smart-TV interfaces with moving targets for co-located control (Fig. 3); a 'Smart Classroom' demo implements smart-watch use for classroom (Fig. 4); and, lastly, a 'Public Display, demo (Fig. 5)
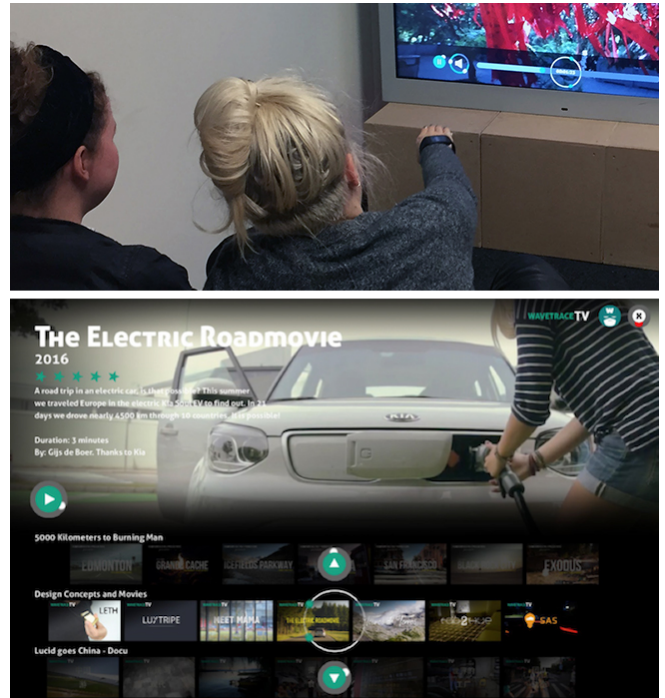

Figure 3. Interactive TV Demo. Top: the playback menu with five moving targets for basic video functionality. Bottom: the main menu with six moving targets. Both menus contain two targets which allow for horizontal scrolling.

integrates motion matching with the aim to better facilitate the switch between implicit and explicit interaction [52] in public and personal interaction spaces. Each demo consists of a custom Processing [38] application running on a laptop, which receives users' motion data over Wi-Fi. Each demo has a display appropriate for the context of use, which depicts the moving targets and provides feedback when a target is selected. To minimize false positives with everyday movements, an initial gesture needs to be performed to display (and activate) the targets. Kerber et al. [26] showed that a double flick of the wrist is a highly uncommon accidental movement. Applying such a delimiter also minimizes the amount of movement on the interface when no interaction is required. Unfortunately, using an Android-based smart-watch, a double flick requires the gesture recognition to be turned off due to conflicting with existing system gestures. Rather than building our own gesture recognition algorithm, we opted for using a single flick to represent the suggested double flick — which allowed us to use the built-in gesture recognition. All demos support up to two users interacting in tandem (each wearing a smart-watch) and vary in their interface design.

Demo 1 — Smart Home Control

In the first demo, we present an example of a smart home dashboard using a motion matching interface (Fig. 2), allowing control over a Philips HUE smart lighting system [36]. A 5-inch display, embedded in a picture frame, displays a photo when the system is idle, attempting to hide the system in 'plain sight'. Upon activation, a motion matching menu is displayed. On the left, three (abstract) targets are displayed that manage the lights' brightness and color. The intensity

Figure 4. Classroom Demo. Students choose an answer for in-class quiz questions. Each question differed in the implementation of moving targets (Q1-4) to explore their usability and experience.
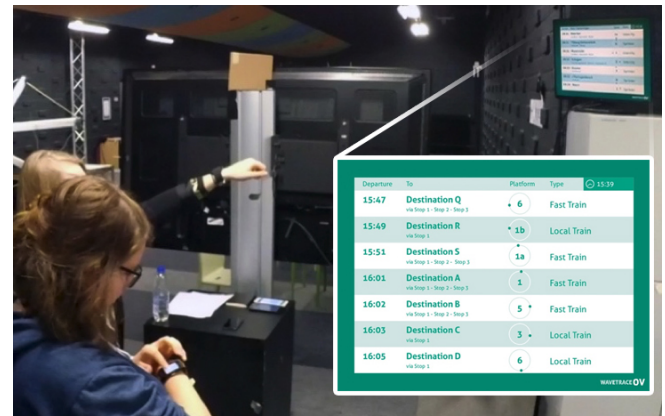

Figure 5. Public Display Demo. By matching the motion of a certain train departure, users are provided with additional information about that trip on their smart-watches.

of the lights increases or decreases upon continuous tracking of respectively clockwise or counterclockwise moving yellow targets. Continuous tracking of the purple target enables navigation through the HUE color spectrum. On the right, three (iconic) targets are displayed that once selected enable pre-defined light settings. Selection and the current light status is confirmed through brightness and color wheels displayed on the left.

Demo 2 — Interactive Television
In the second demo, we present a motion matching interface for interactive television (Fig. 3), particularly focused on multi-user interactions in such a social setting. We developed a video on demand (VOD) application, with a login, main and playback menu. Moving targets were implemented in several ways. For example, four out of six targets in the main menu (Fig. 3 - bottom) allowed for discrete navigation such as up, down, play, and exit; whilst two other targets allowed horizontal navigation using continuous input. The volume targets in the playback menu (Fig. 3 — top) display a clockwise and counterclockwise continuous target for respectively increasing or decreasing the volume, whilst the volume status is highlighted in the target's trajectory. Input from either user is received on a first-come-first-serve basis, where discrete input (e.g. 'play') disables any other input for 1.5 seconds to minimize accidental selection in the transition to a new view or state.

Demo 3 — Smart Classroom
In the third demo, we explore the use of motion matching in a public setting: a classroom. Here, the benefits of our cho-

sen wrist-worn motion sensor approach to motion matching become apparent, as capturing input on a classroom scale and complexity becomes feasible. The demo (Fig. 4), displayed on a large presentation screen, is an interactive quiz that leverages motion matching to collect user input, whilst additional haptic and graphical information can be conveyed through the used smart-watch. Again, moving targets were implemented in several ways through the four types of questions: Q1 presented an individual target for each multiple-choice answer; Q2 displayed two targets moving in opposite direction on one trajectory; Q3 randomly assigned users a selection color to minimize shoulder surfing (Fig. 4 — F1), resulting in 16 displayed targets; and lastly Q4 assigned an answer via the users smart-watch screen, which they were asked to 'position' on a 5-point presented scale using motion matching. Aggregate results are displayed on the large presentation screen, individual results on each user's smart-watch (if applicable).

Demo 4 — Public Display
Finally, we developed a train station departure board to explore motion matching use around public displays in busy areas, and the benefit of cross-device interaction through users' own smart-watches (Fig. 5). Each platform icon in the departure board is a moving target which, upon selection, uploads additional information about the selected trip to the user's smart-watch — allowing for later retrieval of information.

USER EXPERIENCE STUDY
We aim to evaluate current and potential future applications for motion matching interfaces. We are particularly interested in studying the suitability of the technique in the four application scenarios described above, and in generalizing our results to further practical application areas and to motion matching implementations other than WaveTrace [49].

Setup and Procedure
We conducted a user evaluation with 20 participants (11F), aged between 19 and 30 (M = 23.7, SD = 2.83), to gather feedback and to invite participants to envision how these prototypes could be used in their everyday lives. Participants took part in the study in pairs of two, and were paired with friends, family, acquaintances, or colleagues. This was done

deliberately to promote open and frank discussions during the study, and to elicit honest opinions and experiences. Using a five-point Likert scale, participants rated their experience with computer technology and mobile devices as high (M = 3.95, SD = 0.89), and with wearable technology as average (M = 3.00, SD = 1.03). Most participants were students at a local institution (N=18), and none reported limited mobility. Each pair experienced each of the four demos consecutively. The Smart Home Control and Interactive Television demos were set up in a room furnished as a living room. The Smart Classroom and Public Display demos were set up in a hall-way of a university building, to try and increase 'ecological validity'. Right before the study, all participants took part in an individual training session to get accustomed to motion matching — similar to the performance study in [49].

We evaluated the demos using the Co-Constructing Stories method [34], a qualitative evaluation technique specifically geared towards evaluating the user experience of concepts or demos before they are turned into commercial products. The technique consists of a sensitization and elaboration phase, and is especially meant to help people imagine experiencing the demos in potential future use contexts. Before interacting with each demo, the researcher shared a simple fictional story that introduced the application scenario. To ensure *sensitization* with this scenario, participants were asked to recall their most recent (and where possible similar) experience related to that story. Participants were then invited to interact with the demo and all its functionalities. Afterward, participants engaged in a group (duo) discussion about their experience — the *elaboration* phase. In addition to any remarks or feedback on their experience with the demo, participants were asked to project it onto the experience they had described during the sensitization phase, and to reflect on this prospective experience. To provide a usability benchmark, we also asked each participant to individually fill in the System Usability Scale (SUS) [6] after using each demo and before each discussion.

The order in which pairs used the four demos was balanced using a Latin Square. Each demo, including both phases and the SUS, took on average 30 minutes, resulting in a 2-hour session for each pair of participants. Upon request, participants were allowed to interact with any of the demos for a longer period of time. Finally, participants were compensated with a $30 gift voucher. We recorded audio and video of all sessions for further analysis.

RESULTS
The System Usability Scale (SUS, [6]) is a 10-item Likert scale questionnaire that assesses the perceived usability of an interface. Participants reported the highest scores in the Smart Classroom demo (M = 83.6, SD = 12.1), followed by Public Display (M = 81.5, SD = 14.2), Smart Home Control (M = 64.0, SD = 18.3), and lastly, the Interactive Television demo (M = 61.5, SD = 21.5). Compared with over 5000 scores from previously assessed products and systems [41], this puts the demos ahead of 94%, 92.5% (both grade 'B'), 38% and 32% (both grade 'D') of previously assessed systems, respectively. These numbers reflect participants' shared view on these demos which we elaborate on below.

Qualitative Findings
We extracted 547 quotes from the interviews' audio recordings, which address the overall user experience with the demos, motion matching, the context of the experience, envisioned user experiences, and suggested improvements. We analyzed the quotes using open coding [42]. To minimize bias, we divided the 547 quotes across one of the authors and two other independent researchers. Each researcher first clustered half of their set independently, after which the emerged clusters were discussed and a intermediate set was agreed upon. The remaining quotes were collaboratively accommodated, whilst continuous discussion allowed for the clusters to evolve — resulting in eight clusters. Based on the findings from these clusters, we now present our findings (numbered using F#) along three topics: *effort and social dynamics*, *application areas*, and *interface designs*. Finally, the quotes included below were translated to English where necessary.

Effort and Social dynamics
A recurring theme in the discussions revolved around the general use of motion matching, and, due to our choice for wrist-worn sensors as implementation technology, often around the use of arm movements. Ten participants noted that tracking a moving target requires mental and visual effort. This was not deemed too problematic, especially in scenarios where the input and output share the same required focus space (F1)(e.g. the Smart Classroom or the Public Display demo). For other scenario's, seven participants emphasized that the moving target and interaction distracted from the task at hand (F2), for example, whilst scrolling through videos on the television. Overall, six participants expressed how they quickly got the hang of the interaction. They reasoned that using the technique has a (relatively) short learning curve. Only two participants expressed their concerns with physical fatigue, related to the stretched arm position .

Regarding moving targets as used in our interfaces, six participants envisioned that disambiguation through different trajectory shapes and speeds for different (type of) controls would assist in the technique's learnability and recognition of those controls (F3). Relatedly, eight participants reported that the current target speed (and thus the required arm movement speed) for particular continuous targets were uncharacteristic. This means that the input speed for, for example, changing a light's brightness felt too slow, and often did not match the output result (F4)(i.e. the speed of changing brightness). Ensuring a correct and characteristic translation between target movement and effect, due to the continuous selection of the targets, is also advocated by Esteves et al. [19] in their findings. Nine participants reported feeling unsure about whether the system was accurately capturing their input (F5). This is because most motion matching interfaces do not offer a hover state (doing so would increase acquisition times) — input feedback was provided purely upon selection as haptic feedback on participants' smart-watches. In cases of anonymous input (in the public domain demos), visual feedback was intentionally left out. Five participants suggested adding additional output to confirm their bodily actions — P9: *'You want to know that the system knows you are aiming. That it understands that you are aiming but that you are not yet there'*. They believed this

would increase their confidence in the selection mechanism. Relatedly, five participants explicitly reported that, because the technique does not include something akin to a cursor, they were not able to determine what the other participant was selecting, and as such, the transparency in the multi-user input control distribution was hampered (F5). This ability for multiple users to simultaneously interact caused ten participants to foresee issues if no priority system was implemented, particularly at home. In any case, these participants indicated that their selection concerns were mitigated over time, as they became more confident about how the demos responded to their input (and matching haptic feedback).

The visibility of the physical interaction to others (sometimes strangers) elicited discussions with thirteen participants on its social effect, especially on its potential awkwardness. Three participants expressed they felt awkward during the study when people actually passed by. When discussing whether the interaction would stay awkward in the future, 14 participants indicated it would depend on the location (e.g. at home or at the train station) or on how commonly known the interaction would be (F6). For example, P15 elaborates:*'[in a classroom] everyone needs to do the interaction and I think that that will slightly remove the awkwardness'*. It was furthermore mentioned by nine participants that the visibility of interaction was a means to perceive other users' actions and decisions. As such, four participants anticipated that the technique could motivate engagement, especially in a classroom or presentation setting, as they could see if and when the other participant was engaging (F7). Alternatively, five participants commented on the negative effect of this visibility — for instance, the pressure when you are the last one to make a choice on a class quiz.

Application Areas
Regarding the usefulness of the technique in the home domain, four participants discussed the need for simplicity (F8), and reported that there were too many targets, some of which were deemed redundant. They did, however, think it would be useful if they could use the technique to control multiple smart devices throughout the house, including an extractor hood (e.g. turn it off whilst eating dinner), lights, or the oven (e.g. to acquire a video feed from inside and check the state of the food).

Five participants expressed particular interest in extending the functionality to control their sound system through the dashboard interface as used in the Smart Home demo; they deemed it more useful than a lighting interface, which is not so commonly used. However, the physicality of the interaction was envisioned to become distracting for the casual environment of the home by six participants (F2). P13 states: *'... as we have used it now [in the study], it is totally distracting from the contact we have during dinner'*. Participants considered that this would not be an issue after the technique's adoption in the future, yet, it was deemed too distracting due to the visibility of the movement.

Participants moreover concurred on the usefulness of the motion matching interaction in the public domain, as reflected by the SUS scores. Seven participants envisioned that, in a classroom, the physicality and required focus aids in the engagement of the audience. This was emphasized by eleven participants who predicted that the physical movement would affect a lecture or presentation positively (F7). They envisioned the physical input to draw listeners out of their comfort zone and introduce interactive breaks, contrasting the envisioned distraction in the home domain. Seven participants reflected that regardless of functionality, the interaction would only prove its usefulness for public displays if passers-by have some time to spare (F2) — particularly in order to stand still. This reflects the limitation for interaction with public displays, regardless of the choice of (mid-air) input technique.

Interface Designs
Whilst most participants were pleased with how the moving targets (seamlessly) augmented the interface in the Public Display demo, some commented on the lack of consistency between target movement, color, or size amongst the demos. Participants appreciated the haptic feedback as additional output in the public domain demos, with five participants indicating that this needs to be carefully considered to avoid unwanted distractions. The Perceived effort of the input technique, when compared to other input solutions, was also discussed. Eight participants considered the Public Display and Classroom demos to be more efficiently controlled using motion matching, while nine participants considered that existing input techniques were better suited for the Smart Home Control and Interactive Television demos (F9) — especially for menu navigation in the latter. Furthermore, the integration of the second screen (due to the use of a smart-watch) was considered useful and an advantage over current information sources by eight participants, especially for users in unknown places, such as whilst traveling. Finally, participants also expressed their interest in alternative input devices (e.g. fitness trackers), and in using traditional gestures in combination with the motion matching technique (F10).

DISCUSSION
The purpose of this work is to support designers and researchers of motion matching through observations into the user experience of the technique, and its applicability in the four demos described. The discussion below offers design insights that can drive motion matching development for broader systems and domains.

Everyday Use
Overall, participants were positive about interacting in (semi) public spaces (F1,7,9). Both the Smart Classroom and Public Display demos were rated high in the SUS which was qualitatively confirmed in the discussions with the participants. The two demos for the home elicited mixed responses (F2,5,8,9), highlighted by a low usability assessment. Participants reported they would not use the Smart Home or the Interactive TV demos due to their complexity (for their purpose), and because they were seen as too fatiguing or distracting. The TV demo also elicited a known limitation of motion matching interfaces: the lack of a cursor or hover state, making it challenging for users to know the system is aware of their input (F5). This was considered specifically challenging in multi-user scenarios with shared control (TV demo). These

Figure 6. Three interactive lamps directly inspired by the results of the qualitative study. F.l.t.r.: the wall-, ceiling- and standing-lamp. For the wall-lamp (left), tracking a blue or red LED traversing across the border of the lamp either increases or decreases the amount of light emitted.

comments are common critiques of general gestural interfaces [32], and similar to what has been reported by other motion matching researchers [9]. Interestingly, the classroom demo, which allowed for multiple users to interact at once, did *not* allow for simultaneous control of shared parameters and thus did not elicit this critique. Instead, participants envisioned the embodied interaction in such a regulated context to be beneficial; to motivate participation and — even though individually tasked — collaboratively acted upon (F6,7). These findings suggest that the technique is particularly suitable in cases where it introduces new interaction possibilities (e.g. in the classroom or for public displays), or as an efficient interaction mechanism (e.g. turning up the volume whilst remain seated on the couch) — not as a replacement for (all) existing interaction modalities. This strengthens reflections from prior work on motion matching being predominantly useful in specific scenarios of use [14, 18, 19, 35, 39], where they effectively extend their current interaction space (e.g. when hands-free interaction is required).

The aforementioned challenges become more apparent in the relaxed atmosphere of the home, in which participants preferred more straightforward interactions, even if this, for example, meant getting up and walking towards the light-switch (F2,8,9). Noticeably, participants' examples of other home control systems that could benefit from motion matching were based on these being out-of-reach, and enabling a smaller number of actions. This suggests that motion matching interfaces are most suitable for out-of-reach on-the-fly selection, as part of a multi-modal interaction flow. This contrasts prior implementations of motion matching input techniques that were designed to support precise parameter control [11, 19], or sustained interactions with public displays [9, 14].

Interaction Model
In the design of the four demos above, we purposefully tried to vary and iterate on prior implementations where targets travel the contour of a 'button'. As a result, participants commented that conveying input information through motion was useful, but could be enhanced by having trajectories that are (more) tightly coupled with their interaction metaphors (F4)

— a round trajectory is suitable for knob-like actions such as increasing the volume, but not so much for perceived linear actions such as scrolling. The reported conflicts for continuous selection, such as potential physical fatigue or lack of input feedback, left us wondering whether continuous input is suitable for motion matching interfaces. Even though improvements in input feedback and algorithm optimization might improve the experience, these conflicts mirror findings by Esteves et al. [19] suggesting that IMU based motion matching is more suited for quick and discrete interaction. As several participants commented on a combination of motion matching and coarse gestures for continuous control, the multi-modal approach discussed earlier presents great potential for future implementations (F10).

FROM RESEARCH TO DESIGN
In light of the findings from the experience study we argued to develop three interactive lamps. Not only were interactive lamps chosen to challenge the technique's applicability for the home domain, it simultaneously allowed us to focus on the consumer market (rather than community technologies such as public displays) and thereby follow the trend in connectivity in the home. As such, we have developed a refined product family of three interactive lamps: a wall-, standing- and ceiling-lamp, each with different output functionalities and different form-factors (Fig. 6). The design choices and features respond to the earlier reported findings (see **F1-F9**), in addition to additional challenges due to the input technique. Their design is a concrete example of applying our research into practice, which can inform future developments. To emphasize the ease of implementation of motion matching using off-the-shelf hardware, and to further disseminate this body of work, we provide full supplementary materials (illustrator files, system design, source code and instructions) via the ACM Digital Library and GitHub (*current hidden for anonymous submission*).

Design Process and Implications
All three interactive lamp designs were built using RGBW LED strips that both emit light and any moving targets — with added engraved Perspex for light refraction. We also opted for
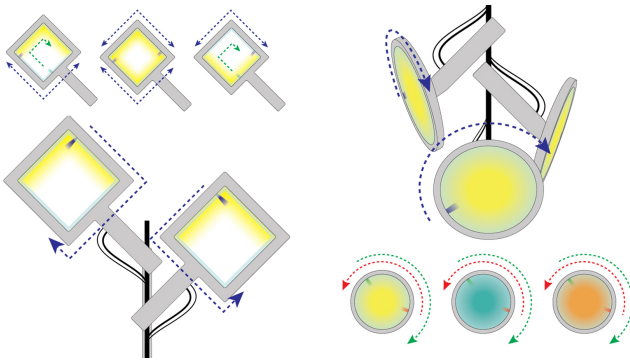
Figure 7. All lights initially show their 'selection' target (large versions). Upon selection, a new set of targets is shown to interact with the selected light (miniature versions) - effectively providing a finite set of interaction possibilities (F8). The shown lights allow you to, respectively, direct light downwards, upwards or both; or change the color temperature of the light.

using indirect light, as direct light sources would have been uncomfortable during prolonged use. These choices effectively enabled an input and output space that was tightly coupled (F1) — something that was strongly suggested in the qualitative study. The basic interaction followed the same principle as before: after a flick of the wrist, the lamps display individual moving targets that enable their selection. Responding to participants' request for multi-modal input (F10), a tilt of the wrist (>23 degrees) in a clockwise or counterclockwise fashion would respectively increase or decrease the overall brightness of a selected lamp. After this, users simply need to lower their arms to deselect the lamp, and disable all moving targets (F2).

Trajectory and Product Shape
To further illustrate that motion matching techniques support a variety of target trajectories, and to aid in target disambiguation (F3), the standing-lamp was made from rhomboidal shapes. This lamp can be set to direct its lights downwards (top sides LED's on), upwards (bottom sides LED's on) or both (all sides LED's on), see Fig. 7. To better support the interaction metaphor, the targets that trigger these behaviors respectively traverse back-and-forth on the top LEDs, on the bottom LEDs, or circulate on all LEDs. These implementations aim to adhere to how motion as input is reported to be more intuitive when the movements correspond to an expected functionality — i.e. it should use known interaction metaphors (F4). In addition, we envision the design of future systems to display moving targets on locations other than the 'main' display (if any) by incorporating indirect LEDs (e.g. around a button or perhaps embedded in the product logo). Therefore, future motion matching devices can be designed such that their shape is distinctive. This aids in their branding, but also in their input movement disambiguation from other (motion matching) devices. Alternatively, a transparent screen could be considered to allow more flexible placement in the intended environment. In such implementation, much like our see-through standing-lamp, the user potentially sees moving targets in a mirrored manner. The correlation algorithm, therefore, must accommodate for mirrored user input, and requires careful target disambiguation.

Omni-directional Field of View
Whilst ensuring a high flexibility of use, we noticed embedding motion matching in consumer lighting products surfaced a few challenges. Firstly, all designs used in prior motion matching work, including our own demos, display moving targets in a 2D plane, often with an opaque background. As this limits placement due to the field of view and thereby the user's interaction space, the modules of the standing-lamp are open (i.e. see-through), mainly possible due to the indirect light source. Secondly, and similarly to the ceiling-lamp, the standing-lamp consists of three modules, each spaced 120 degrees from each other to improve visibility from any angle. Lastly, in case of the ceiling-lamp, the modules are additionally angled down (roughly 45 degrees). Since the aforementioned 2D plane for a ceiling lamp would not contain a y-dimension (only x and z), a one-to-one correlation as used before would be impossible without additional sensing approaches. The angled modules reintroduce the y-dimension to maintain this accessible implementation. Future motion matching products that are not placed on or against a wall, should thereby carefully consider their potential placement in the design of their motion matching interface.

Discussion
The development of motion matching based consumer products allowed us to implement the learnings from the experience study. Although the reported practical challenges emerged due to our aim to explore physical designs (compared to screen-based solutions), they have potential to inform and inspire other researchers and practitioners to — at least — consider exploring integrating the technique in their physical design.

FUTURE WORK AND CONCLUSION
Despite our best efforts to study motion matching in realistic environments, there is arguably more to learn from an in-the-wild deployment of our prototypes, including the latter, refined smart lamps. We are particularly keen in further exploring the response to different combinations of user input (e.g. motion matching and discrete gestures or speech commands), and to different forms of selection confirmation during discrete and continuous control. In sum, this paper contributes an in-depth, qualitative analysis of four motion matching implementations for a wide range of domains, reflecting upon these techniques as an appropriate input approach for spontaneous and touchless control of smart environments. In particular, the translation from theory to practice, both through the screen-based demos and interactive lamps, elicits considerations for future motion matching products and services, including the design of targets and their movement. The findings indicate the suitability of motion matching in different multi-user scenarios, the less pertinent use in casual environments and the necessity for multi-modal interaction. This work pursued motion matching using a wrist-worn motion sensor, which we can advocate due to its relatively cheap and fast implementation, yet highlights the potential of exciting future work where motion matching is combined with other forms of input and output to create user experiences that draw on the strengths of different input techniques for interaction with a wide set of devices.

REFERENCES

1. Christopher Ackad, Andrew Clayphan, Martin Tomitsch, and Judy Kay. 2015. An In-the-wild Study of Learning Mid-air Gestures to Browse Hierarchical Information at a Large Interactive Public Display. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '15)*. ACM, New York, NY, USA, 1227–1238. DOI:
`http://dx.doi.org/10.1145/2750858.2807532`

2. Thomas Baudel and Michel Beaudouin-Lafon. 1993. Charade: Remote Control of Objects Using Free-hand Gestures. *Commun. ACM* 36, 7 (July 1993), 28–35. DOI:
`http://dx.doi.org/10.1145/159544.159562`

3. Michael Beigl. 1999. Point & Click-Interaction in Smart Environments. In *Handheld and Ubiquitous Computing*, Hans-W. Gellersen (Ed.). Number 1707 in Lecture Notes in Computer Science. Springer Berlin Heidelberg, 311–313. DOI:
`http://dx.doi.org/10.1007/3-540-48157-5_31`

4. Peter Bennett, Stuart Nolan, Ved Uttamchandani, Michael Pages, Kirsten Cater, and Mike Fraser. 2015. Resonant Bits: Harmonic Interaction with Virtual Pendulums. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15)*. ACM, New York, NY, USA, 49–52. DOI:`http://dx.doi.org/10.1145/2677199.2680569`

5. Richard A. Bolt. 1980. 'Put-that-there': Voice and Gesture at the Graphics Interface. In *Proceedings of the 7th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '80)*. ACM, New York, NY, USA, 262–270. DOI:
`http://dx.doi.org/10.1145/800250.807503`

6. John Brooke. 1996. SUS-A quick and dirty usability scale. In *Usability Evaluation in Industry*, Jordan Patrick W, Thomas B, McClelland Ian Lyall, and Weerdmeester Berarnd (Eds.). Taylor & Francis, London, 189–194.

7. A.J. Bernheim Brush, Bongshin Lee, Ratul Mahajan, Sharad Agarwal, Stefan Saroiu, and Colin Dixon. 2011. Home Automation in the Wild: Challenges and Opportunities. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 2115–2124. DOI:
`http://dx.doi.org/10.1145/1978942.1979249`

8. Florian van de Camp, Alexander Schick, and Rainer Stiefelhagen. 2013. How to Click in Mid-Air. In *Distributed, Ambient, and Pervasive Interactions (Lecture Notes in Computer Science)*. Springer, Berlin, Heidelberg, 78–86. DOI:
`http://dx.doi.org/10.1007/978-3-642-39351-8_9`

9. Marcus Carter, Eduardo Velloso, John Downs, Abigail Sellen, Kenton O'Hara, and Frank Vetere. 2016. PathSync: Multi-User Gestural Interaction with Touchless Rhythmic Path Mimicry. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 3415–3427. DOI:
`http://dx.doi.org/10.1145/2858036.2858284`

10. Christopher Clarke, Alessio Bellino, Augusto Esteves, and Hans Gellersen. 2017. Remote Control by Body Movement in Synchrony with Orbiting Widgets: An Evaluation of TraceMatch. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 3, Article 45 (Sept. 2017), 22 pages. DOI:`http://dx.doi.org/10.1145/3130910`

11. Christopher Clarke, Alessio Bellino, Augusto Esteves>, Eduardo Velloso, and Hans Gellersen. 2016. TraceMatch: A Computer Vision Technique for User Input by Tracing of Animated Controls. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '16)*. ACM, New York, NY, USA, 298–303. DOI:
`http://dx.doi.org/10.1145/2971648.2971714`

12. Christopher Clarke and Hans Gellersen. 2017. MatchPoint: Spontaneous Spatial Coupling of Body Movement for Touchless Pointing. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 179–192. DOI:
`http://dx.doi.org/10.1145/3126594.3126626`

13. Travis Cox, Marcus Carter, and Eduardo Velloso. 2016a. Public DisPLAY: Social Games on Interactive Public Screens. In *Proceedings of the 28th Australian Conference on Computer-Human Interaction (OzCHI '16)*. ACM, New York, NY, USA, 371–380. DOI:
`http://dx.doi.org/10.1145/3010915.3010917`

14. Travis Cox, Marcus Carter, and Eduardo Velloso. 2016b. Public DisPLAY: Social Games on Interactive Public Screens. In *Proceedings of the 28th Australian Conference on Computer-Human Interaction (OzCHI '16)*. ACM, New York, NY, USA, 371–380. DOI:
`http://dx.doi.org/10.1145/3010915.3010917`

15. Katie Derthick, James Scott, Nicolas Villar, and Christian Winkler. 2013. Exploring Smartphone-based Web User Interfaces for Appliances. In *Proceedings of the 15th International Conference on Human-computer Interaction with Mobile Devices and Services (MobileHCI '13)*. ACM, New York, NY, USA, 227–236. DOI:`http://dx.doi.org/10.1145/2493190.2493239`

16. Murtaza Dhuliawala, Juyoung Lee, Junichi Shimizu, Andreas Bulling, Kai Kunze, Thad Starner, and Woontack Woo. 2016. Smooth Eye Movement Interaction Using EOG Glasses. In *Proceedings of the 18th ACM International Conference on Multimodal Interaction (ICMI 2016)*. ACM, New York, NY, USA, 307–311. DOI:
`http://dx.doi.org/10.1145/2993148.2993181`

17. Paul Dourish. 2001. *Where the Action is: The Foundations of Embodied Interaction*. MIT Press, Cambridge, MA, USA.

18. Augusto Esteves, Eduardo Velloso, Andreas Bulling, and Hans Gellersen. 2015. Orbits: Gaze Interaction for Smart Watches Using Smooth Pursuit Eye Movements. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 457–466. DOI: http://dx.doi.org/10.1145/2807442.2807499

19. Augusto Esteves, David Verweij, Liza Suraiya, Rasel Islam, Youryang Lee, and Ian Oakley. 2017. SmoothMoves: Smooth Pursuits Head Movements for Augmented Reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 167–178. DOI: http://dx.doi.org/10.1145/3126594.3126616

20. Jean-Daniel Fekete, Niklas Elmqvist, and Yves Guiard. 2009. Motion-pointing: Target Selection Using Elliptical Motions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 289–298. DOI: http://dx.doi.org/10.1145/1518701.1518748

21. Euan Freeman, Stephen Brewster, and Vuokko Lantz. 2016. Do That, There: An Interaction Technique for Addressing In-Air Gesture Systems. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 2319–2331. DOI: http://dx.doi.org/10.1145/2858036.2858308

22. Euan Freeman, Gareth Griffiths, and Stephen A. Brewster. 2017. Rhythmic Micro-gestures: Discreet Interaction On-the-go. In *Proceedings of the 19th ACM International Conference on Multimodal Interaction (ICMI 2017)*. ACM, New York, NY, USA, 115–119. DOI: http://dx.doi.org/10.1145/3136755.3136815

23. Franca Garzotto and Matteo Valoriani. 2013. Touchless Gestural Interaction with Small Displays: A Case Study. In *Proceedings of the Biannual Conference of the Italian Chapter of SIGCHI (CHItaly '13)*. ACM, New York, NY, USA, 26:1–26:10. DOI: http://dx.doi.org/10.1145/2499149.2499154

24. Aakar Gupta, Thomas Pietrzak, Cleon Yau, Nicolas Roussel, and Ravin Balakrishnan. 2017. Summon and Select: Rapid Interaction with Interface Controls in Mid-air. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces (ISS '17)*. ACM, New York, NY, USA, 52–61. DOI: http://dx.doi.org/10.1145/3132272.3134120

25. Jari Kangas, Oleg Špakov, Poika Isokoski, Deepak Akkil, Jussi Rantala, and Roope Raisamo. 2016. Feedback for Smooth Pursuit Gaze Tracking Based Control. In *Proceedings of the 7th Augmented Human International Conference 2016 (AH '16)*. ACM, New York, NY, USA, Article 6, 8 pages. DOI: http://dx.doi.org/10.1145/2875194.2875209

26. Frederic Kerber, Philipp Schardt, and Markus Löchtefeld. 2015. WristRotate: A Personalized Motion Gesture Delimiter for Wrist-worn Devices. In *Proceedings of the 14th International Conference on Mobile and Ubiquitous Multimedia (MUM '15)*. ACM, New York, NY, USA, 218–222. DOI: http://dx.doi.org/10.1145/2836041.2836063

27. Mohamed Khamis, Carl Oechsner, Florian Alt, and Andreas Bulling. 2018. VRpursuits: Interaction in Virtual Reality Using Smooth Pursuit Eye Movements. In *Proceedings of the 2018 International Conference on Advanced Visual Interfaces (AVI '18)*. ACM, New York, NY, USA, 18:1–18:8. DOI: http://dx.doi.org/10.1145/3206505.3206522

28. Mingyu Liu, Mathieu Nancel, and Daniel Vogel. 2015. Gunslinger: Subtle Arms-down Mid-air Interaction. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 63–71. DOI: http://dx.doi.org/10.1145/2807442.2807489

29. Thomas Mattusch, Mahsa Mirzamohammad, Mohamed Khamis, Andreas Bulling, and Florian Alt. 2018. Hidden Pursuits: Evaluating Gaze-selection via Pursuits when the Stimuli's Trajectory is Partially Hidden. In *Proceedings of the 2018 ACM Symposium on Eye Tracking Research & Applications (ETRA '18)*. ACM, New York, NY, USA, 27:1–27:5. DOI: http://dx.doi.org/10.1145/3204493.3204569

30. Tara Mullaney, Björn Yttergren, and Erik Stolterman. 2013. Positional Acts: Using a Kinect™ Sensor to Reconfigure Patient Roles Within Radiotherapy Treatment. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction (TEI '14)*. ACM, New York, NY, USA, 93–96. DOI:http://dx.doi.org/10.1145/2540930.2540943

31. Ville Mäkelä, Tomi Heimonen, and Markku Turunen. 2014. Magnetic Cursor: Improving Target Selection in Freehand Pointing Interfaces. In *Proceedings of The International Symposium on Pervasive Displays (PerDis '14)*. ACM, New York, NY, USA, 112:112–112:117. DOI: http://dx.doi.org/10.1145/2611009.2611025

32. Donald A. Norman and Jakob Nielsen. 2010. Gestural Interfaces: A Step Backward in Usability. *Interactions* 17, 5 (Sept. 2010), 46–49. DOI: http://dx.doi.org/10.1145/1836216.1836228

33. Kenton O'hara, Richard Harper, Helena Mentis, Abigail Sellen, and Alex Taylor. 2013. On the Naturalness of Touchless: Putting the "Interaction" Back into NUI. *ACM Trans. Comput.-Hum. Interact.* 20, 1 (April 2013), 5:1–5:25. DOI: http://dx.doi.org/10.1145/2442106.2442111

34. Derya Ozcelik Buskermolen and Jacques Terken. 2012. Co-constructing Stories: A Participatory Design Technique to Elicit In-depth User Feedback and Suggestions About Design Concepts. In *Proceedings of the 12th Participatory Design Conference: Exploratory Papers, Workshop Descriptions, Industry Cases - Volume 2 (PDC '12)*. ACM, New York, NY, USA, 33–36. DOI: http://dx.doi.org/10.1145/2348144.2348156

35. Ken Pfeuffer, Melodie Vidal, Jayson Turner, Andreas Bulling, and Hans Gellersen. 2013. Pursuit Calibration: Making Gaze Calibration Less Tedious and More Flexible. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 261–270. DOI: http://dx.doi.org/10.1145/2501988.2501998

36. Philips. 2017. Wireless and smart lighting. (2017). Retrieved 2017-09-13 from http://www2.meethue.com/en-us

37. T. Piumsomboon, G. Lee, R. W. Lindeman, and M. Billinghurst. 2017. Exploring natural eye-gaze-based interaction for immersive virtual reality. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*. 36–39. DOI: http://dx.doi.org/10.1109/3DUI.2017.7893315

38. Processing. 2017. Processing.org. (2017). Retrieved 2018-05-17 from https://www.processing.org/

39. Gabriel Reyes, Jason Wu, Nikita Juneja, Maxim Goldshtein, W. Keith Edwards, Gregory D. Abowd, and Thad Starner. 2018. SynchroWatch: One-Handed Synchronous Smartwatch Gestures Using Correlation and Magnetic Sensing. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 4 (Jan. 2018), 158:1–158:26. DOI: http://dx.doi.org/10.1145/3161162

40. Lawrence Sambrooks and Brett Wilkinson. 2013. Comparison of Gestural, Touch, and Mouse Interaction with Fitts' Law. In *Proceedings of the 25th Australian Computer-Human Interaction Conference: Augmentation, Application, Innovation, Collaboration (OzCHI '13)*. ACM, New York, NY, USA, 119–122. DOI: http://dx.doi.org/10.1145/2541016.2541066

41. Jeff Sauro. 2011. *A Practical Guide to the System Usability Scale: Background, Benchmarks & Best Practices*. CreateSpace Independent Publishing Platform.

42. John. V. Seidel. 1998. Qualitative Data Analysis. In *The Ethnograph v5.0: A Users Guide, Appendix E*. Colorado: Qualis Research, Colorado Springs. www.qualisresearch.com

43. Toby Sharp, Cem Keskin, Duncan Robertson, Jonathan Taylor, Jamie Shotton, David Kim, Christoph Rhemann, Ido Leichter, Alon Vinnikov, Yichen Wei, Daniel Freedman, Pushmeet Kohli, Eyal Krupka, Andrew Fitzgibbon, and Shahram Izadi. 2015. Accurate, Robust, and Flexible Real-time Hand Tracking. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3633–3642. DOI: http://dx.doi.org/10.1145/2702123.2702179

44. Jamie Shotton, Toby Sharp, Alex Kipman, Andrew Fitzgibbon, Mark Finocchio, Andrew Blake, Mat Cook, and Richard Moore. 2013. Real-time Human Pose Recognition in Parts from Single Depth Images. *Commun. ACM* 56, 1 (Jan. 2013), 116–124. DOI: http://dx.doi.org/10.1145/2398356.2398381

45. Radu-Daniel Vatavu and Ionut-Alexandru Zaiti. 2014. Leap Gestures for TV: Insights from an Elicitation Study. In *Proceedings of the 2014 ACM International Conference on Interactive Experiences for TV and Online Video (TVX '14)*. ACM, New York, NY, USA, 131–138. DOI:http://dx.doi.org/10.1145/2602299.2602316

46. Eduardo Velloso, Marcus Carter, Joshua Newn, Augusto Esteves, Christopher Clarke, and Hans Gellersen. 2017. Motion Correlation: Selecting Objects by Matching Their Movement. *ACM Trans. Comput.-Hum. Interact.* 24, 3 (April 2017), 22:1–22:35. DOI: http://dx.doi.org/10.1145/3064937

47. Eduardo Velloso, Flavio Luiz Coutinho, Andrew Kurauchi, and Carlos H Morimoto. 2018. Circular Orbits Detection for Gaze Interaction Using 2D Correlation and Profile Matching Algorithms. In *Proceedings of the 2018 ACM Symposium on Eye Tracking Research & Applications (ETRA '18)*. ACM, New York, NY, USA, 25:1–25:9. DOI: http://dx.doi.org/10.1145/3204493.3204524

48. Eduardo Velloso, Markus Wirth, Christian Weichel, Augusto Esteves, and Hans Gellersen. 2016. AmbiGaze: Direct Control of Ambient Devices by Gaze. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16)*. ACM, New York, NY, USA, 812–817. DOI: http://dx.doi.org/10.1145/2901790.2901867

49. David Verweij, Augusto Esteves, Vassilis Javed Khan, and Saskia Bakker. 2017a. WaveTrace: Motion Matching Input using Wrist-Worn Motion Sensors. In *CHI '17 Extended Abstracts on Human Factors in Computing Systems (CHI EA '17)*. ACM, Denver, CO, USA. DOI: http://dx.doi.org/10.1145/3027063.3053161

50. David Verweij, Vassilis-Javed Khan, Augusto Esteves, and Saskia Bakker. 2017b. Multi-User Motion Matching Interaction for Interactive Television Using Smartwatches. In *Adjunct Publication of the 2017 ACM International Conference on Interactive Experiences for TV and Online Video (TVX '17 Adjunct)*. ACM, New York, NY, USA, 67–68. DOI:http://dx.doi.org/10.1145/3084289.3089906

51. Mélodie Vidal, Andreas Bulling, and Hans Gellersen. 2013. Pursuits: Spontaneous Interaction with Displays Based on Smooth Pursuit Eye Movement and Moving Targets. In *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '13)*. ACM, New York, NY, USA, 439–448. DOI:http://dx.doi.org/10.1145/2493432.2493477

52. Daniel Vogel and Ravin Balakrishnan. 2004. Interactive Public Ambient Displays: Transitioning from Implicit to Explicit, Public to Personal, Interaction with Multiple Users. In *Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology (UIST '04)*. ACM, New York, NY, USA, 137–146. DOI: http://dx.doi.org/10.1145/1029632.1029656

53. Daniel Vogel and Ravin Balakrishnan. 2005. Distant Freehand Pointing and Clicking on Very Large, High Resolution Displays. In *Proceedings of the 18th Annual ACM Symposium on User Interface Software and Technology (UIST '05)*. ACM, New York, NY, USA, 33–42. DOI:http://dx.doi.org/10.1145/1095034.1095041

54. John Williamson and Roderick Murray-Smith. 2004. Pointing Without a Pointer. In *CHI '04 Extended Abstracts on Human Factors in Computing Systems (CHI EA '04)*. ACM, New York, NY, USA, 1407–1410. DOI:http://dx.doi.org/10.1145/985921.986076

55. Gottfried Zimmermann, Gregg Vanderheiden, and Al Gilman. 2002. Prototype Implementations for a Universal Remote Console Specification. In *CHI '02 Extended Abstracts on Human Factors in Computing Systems (CHI EA '02)*. ACM, New York, NY, USA, 510–511. DOI:http://dx.doi.org/10.1145/506443.506454