The Role of Haptics in User Input for Simple 3D Interaction Tasks
An Analysis of Interaction Performance and User Experience

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Abstract: Traditionally, input devices allowed for at least a certain degree of haptic experience by involving direct physical contact between user and device. Recently, touchless interaction gained popularity through readily available, cheap devices like the Leap motion controller or Microsoft Kinect. Usually, these devices support more than two degrees of freedom and are thus especially suitable for interaction tasks in a three-dimensional space. However, besides the high potential that lies within touchless input techniques, they also involve new challenges (e.g., lack of borders and natural haptic guidance). In this paper, we aim at the identification of potentials and limitations inherent to three different input techniques that involve a varying amount of haptics (i.e., touchful, touchless and semi-touchless input). We present a study conducted with 25 users that focuses on simple input tasks in a 3D interaction space and analyzes objective interaction performance metrics (e.g., regularity or time) and subjective User Experience aspects (e.g., dependability or efficiency). It reveals parallels as well as contrasts between the users' actual interaction performance and perceived UX (e.g., several metrics suggested haptic input to outperform touchless input while differences regarding UX were not significant). The results are intended to inform other researchers when designing interactive environments.

1 INTRODUCTION

In the past decades, user input seemed to be coupled with at least a certain haptic experience. The most widely used input devices like mice, keyboards, touch screens or game controllers have in common that they involve direct physical contact between the user and the device. Touch-based or haptic input techniques however often suffer from limited interaction options through physical/technological constraints. For instance, most touchscreens only allow for two-dimensional input because the physical device is a flat surface which makes movement along the third axis mostly irrelevant (although this might be up to changes since the advent of 3D touch capabilities with the latest generations of smart phones). Yet, these physical restrictions also provide a certain amount of guidance and haptic input devices mostly offer inherent haptic feedback mechanisms.

During the past few years, touchless input methods and devices, e.g., Microsoft Kinect (further referred to as "Kinect") or the Leap motion controller (further referred to as "Leap") that theoretically allow for nearly unlimited input options (e.g., the human hand theoretically has 27 degrees of freedom (Rehg and Kanade, 1994)) became attractive, e.g., in game-based scenarios that involve physical engagement like sports applications or in therapeutic settings. Touchless input surely offers high potential for a number of selected application fields where other input approaches are difficult to apply (e.g., sports applications that involve whole body interaction). However, touchless input also bears potential shortcomings that should be considered, e.g., connected to haptic perception mentioned before or missing physical constraints that could provide orientation for the user during input. Although there are approaches to overcome these risks (through haptic feedback for touchless input scenarios, e.g., via focused ultrasound (Carter et al., 2013)), most readily-available touchless input devices do not yet support such mechanisms.

In this paper, we aim at investigating the actual relevance of a haptic experience during user input. This relevance might differ with varying complexity of the input tasks. Here, we focus on simple input tasks in a 3D interaction space. It presents a study

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conducted with 25 participants to compare three input techniques: i) touchless input, ii) "touchful" input (relying on application of physical pressure to a surface), and iii) semi-touchless input (combining characteristics of the previous two). We use Leap as touchless input device and two device prototypes (Augstein et al., 2017a) that have been developed specifically to fit the requirements of this and similar studies. The touchful input device can be considered isometric, i.e., connecting the human limb and the device through force (Zhai, 2008) while the other two can be considered isotonic, i.e., connecting the interacting hand and the device through movement (Zhai, 2008).

The study is targeted to analyze i) users' interaction performance and ii) User Experience (UX) with each of the three input techniques. The main aim behind is to study the actual relevance of haptics during user input (and, secondarily, also the potentials of isometric and isotonic input devices) for the selected category of tasks. We believe that the combined findings comprising objective criteria and subjective ones are more conclusive than any of the two in isolation. A good interaction performance does not necessarily have to imply a good UX and vice versa (which is confirmed by the results of our study where we identified contradictions between performance and UX). In our study we introduce so-called interaction tests the users have to take. Based on the raw input data we compute metrics indicative of interaction performance (e.g., time or interaction regularity). To measure UX, the standardized User Experience Questionnaire is used. We expect the results to be interesting for researchers and practitioners conceptualizing and designing interactive environments or input devices.

2 RELATED WORK

This section presents grounding related work on 3D input as well as studies comparing different input techniques for 3D input tasks similar to ours by analyzing interaction performance and UX.

According to (Fröhlich et al., 2006), 3D interaction can be classified into i) navigation and travel, ii) selection, iii) manipulation (e.g., of an object's position) and iv) system control. We categorize the interaction tasks described in this paper (see Section 4) as manipulation tasks (specifically, positioning) and selection tasks. Fröhlich et al. divide devices and sensors into isotonic (measuring movement), isometric (measuring force) and elastic (allowing for movement and providing a counterforce) sensors. (Zhai, 2008) describe elastic input sensors as devices with varying resistance "between the isometric (infinite resistance) and the isotonic (zero or constant resistance)". The devices we use for our study can be considered isometric (see "touchful input" in Section 3.2) and isotonic (see touchless and semi-touchless input in Sections 3.1 and 3.3). (Bowman et al., 2008) argue that many input devices are actually a combination of different types of input sensors which they refer to as "multisensory input". While we agree on the value of multisensory input for practical use we explicitly tried to avoid combinations in our study to be better able to compare.

(Zhai, 2008) presents an exhaustive compilation of studies comparing isometric and isotonic input devices. However, he concludes that the literature on the relative advantages and disadvantages of isometric vs. isotonic devices has not been very conclusive and argues that the definite answer may depend on (among others) the concrete interaction tasks. Thus, we carefully selected tasks for our study and assured that they are identical for all three input devices.

(Bowman et al., 2008) also argue that haptics is "one of the most important types of sensory feedback" and distinguish between "active haptic feedback" and "passive" or "pseudo-haptics". Our touchful input technique can be considered passive haptic input, our touchless input technique intentionally does not involve any haptic experience and our semi-touchless input technique can be classed somewhere in between (see Section 3). The comparison of input techniques involving a differing amount of haptics was our main focus. (Zhai, 2008) further distinguishes between position control, i.e., "control mechanisms by which the human operator controls object positions directly" and rate control, i.e., mapping "human input into the velocity of the object movement". In our study, all three input techniques and interaction tasks are based on position control.

Recently, (Tscharn et al., 2016) have evaluated two isotonic input devices (Leap and the 3D mouse SpaceNavigator) for real world navigation tasks (using Google Earth). Their study participants were asked to solve four different interaction tasks (general movement, targeted movement, specified coordinate movement and specified trajectory movement). They evaluated navigation efficiency (measured based on the time needed for a task) and UX (based on the analysis of facial expressions and the AttrakDiff questionnaire). Their approach is similar to ours regarding the idea of comparing touchless and touch-able input devices along interaction performance metrics and UX. Although it differs regarding domain and UX indicators, some of the interaction tasks and performance metrics are similar. Tscharn et al. found interaction with Leap to be less accurate for complex tasks, compared to SpaceNavigator while it had a good UX for simple tasks (which is in line with our findings).

Another study on interaction performance and UX related to touchless (using a ceiling-mounted gesture recognition device prototype) and touch-able (using SpaceNavigator) input has been conducted earlier by (Stannus et al., 2011). They found that regarding interaction performance and UX indicators as scored by the participants (e.g., naturalness, strain, speed, and accuracy), the touchless device could not keep up with touch-able devices. Interestingly, similar to our findings, for touchless input, UX-related metrics (e.g., naturalness) were scored relatively better than the pure performance indicators. Although study aims were similar, the study design described by Stannus et al. differs from ours drastically as we analyze objective interaction performance metrics automatically while Stannus et al. asked the participants to rate these metrics. We believe these "objective" results reported by users subjectively might be easily biased by users' UX-related impressions and are thus less reliable.

(Dangeti et al., 2016) discuss bare-hand in-air gesture-based interaction vs. object-in-hand tangible interaction for navigation of 3D objects. They present the technological differences between the approaches and announce a user study in which they plan to compare three different interaction methods (traditional mouse/keyboard interaction, bare hand in-air and object-in-hand interaction) along objective criteria like interaction speed and accuracy and UX-related aspects based on interviews. Thus, the planned methodology seems to be similar to ours, unfortunately, they did not publish any results yet.

(Coelho and Verbeek, 2014) conducted a study with a traditional mouse and Leap for pointing tasks similar to ours in a 3D virtual environment. They describe two different tasks their participants had to perform. The first task consisted of simple pointing (start point to target point) while the second task was more complex (start point to first target point to second target point). For the simpler task, Leap outperformed the mouse while for the more complex task, the outcome was contrary. The authors state that the z-axis can be controlled by the "roll of the mouse", which we assume to be the mouse wheel and can therefore be manipulated isolated from the x- and y-axes. Our assumption is that there is a major difference for 3D pointing tasks when using Leap, where all axes are controlled through the same mechanism (i.e., finger or hand tracking). In our study, we tried to avoid such general differences (not related to haptics) among the input techniques. To measure usability (and UX), Coelho and Verbeek used the System Usability Scale (SUS) questionnaire where Leap scored better than the mouse which is partly in line with our results.

(Hürst and Helder, 2011) investigated navigation and selection tasks in a 3D space using mobile devices for moving around virtual objects. However, while we varied the extent of haptics, Hürst and Helder varied the type of visualization. Thus, the results are not directly related to our work but the study setup is similar. They measured objective values from log data and obtained information about UX.

Another similar approach was applied by (Atkins et al., 2009) who compared three different interaction techniques (i.e., mouse wheel, mouse dragging, and a jog wheel) to navigate through a stack of medical 3D images, however the navigation itself was two-dimensional. They also used interaction accuracy, time, and navigation paths as objective measures and qualitatively evaluated participants' preferences.

Although we found several studies with aims similar to ours, we did not find a comparison where input activities with different devices have been aligned in a way that the actual difference between settings is the amount of haptics involved. Most studies compared Leap to a (3D) mouse, however, although both isotonic, interaction with Leap inherently differs from interaction with a mouse e.g., regarding hand movement, interaction space and DoF. We aimed at comparing the input techniques using devices that allow for almost identical input activities (with the amount of haptics involved being the actual difference). We expect the results to be better generalizable and more interesting for designers of interactive environments.

3 INPUT TECHNIQUES

The three input techniques we used for our study have several aspects in common. They all involve small movements of the dominant hand in a 3D space and are based on position control. The 3D manipulation tasks used in the study (see Section 4) only require the input devices to analyze the user's hand position in a predefined 3D space but allow for users to choose the most comfortable hand orientation and posture. The manipulation tasks require movement in the directions left/right, forward/backward and down/up, see Figure 1. The interaction space is identical for all settings and the devices have been calibrated within pretests (see Section 5). Differences (that are subject to our study) can be seen in the amount of haptics involved. Further, our touchless and semi-touchless input techniques and devices can be described as isotonic

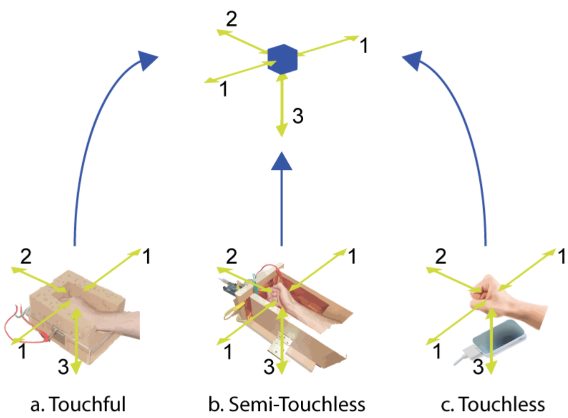


Figure 1: Input devices and techniques and the three DoF as required by the manipulation tasks during the user study.

while touchful input is isometric.

3.1 Touchless Interaction

Touchless interaction is described as interaction that "can take place without mechanical contact between the human and any part of the artificial system" (de la Barré et al., 2009). In many cases, a challenge related to touchless input is the absence of direct haptic guidance during the interaction which can also be the cause of confusion or uncertainty regarding the space sensitive to the user's actions. Further, users are informed about the effects of their actions only via the system's output (e.g., visually). This visual information is present for the other two techniques as well, for touchless input it is, however, the only source of feedback. We implemented our touchless setting with Leap which uses infrared sensors for measurement. It has a size of 8x3x1cm and is usually placed on the table in front of the user. In our study, it was used to track the position of the wrist. Here, the user holds his/her hand above the device (see Figure 1 (c)) and moves it according to the tasks. The provision of a hand rest was not possible as this would have i) interfered with accurate tracking of the user's hand and ii) reduced the "touchless" impression for the users.

3.2 Touchful Interaction

We define touchful interaction as the opposite of touchless interaction, i.e., interaction which involves thorough mechanical contact between human and device. Thus, it generally includes the majority of the most widely used input methods and devices such as mice. Touchful interaction allows for a direct haptic experience and can help the user to orientate and correctly assess the interaction options and limitations (e.g., the physical resistance of a button indicates that applying stronger pressure will make no difference). Yet, these generally helpful boundaries also limit the interaction range. The concrete manifestation of touchful input used in our work can be described as *three-dimensional pressure-based interaction*. The technique aims to combine the advantages of 3D interaction (as also enabled by touchless techniques) and pressure-based interaction while reducing the respective shortcomings. It ties in with previous approaches to one-dimensional pressure-based interaction, see (Augstein et al., 2015) and (Hwang et al., 2013). This technique allows application of different pressure intensities to a specified target area.

The device used for our study, "SpongeBox" (Augstein et al., 2017a), extends this interaction concept by adding several dimensions/directions: left/right, forward/backward and down/up. SpongeBox has been developed specifically for purposes of comparing touchful to touchless input techniques for simple 3D manipulation tasks. It is based on an Arduino microcontroller and several pressure sensors and has the physical appearance of a box with open upper and back walls. The inner walls are covered with sponges. The user puts a hand in the middle (see Figure 1 (a)) and can then press against four sides of the box (bottom, left, right, forward). The material used for the walls provides a haptic experience and physical restriction. Placing the hand inside the box without actively applying pressure does not lead to unintended input, thus a user's arm can rest on the sponge during and between interaction activities. SpongeBox can theoretically distinguish between 1024 pressure intensities in each direction which were however reduced significantly during the pre-tests (see Section 5). The configuration used for the study measured and collected pressure intensities on the percentage level (0-100%) but used only 13 levels to trigger activities (this was the configuration perceived as most predictable and comfortable by the pre-testers). As the interaction space was relatively small, the movement of the digital object remained smooth with this configuration.

3.3 Semi-Touchless Interaction

Semi-touchless interaction can be defined as a combination of the touchless and touchful interaction concepts. It joins the following characteristics: i) physical constraints and ii) touchless position/movement analysis. Again, input is done via small movements of the interacting hand. The directions are equal to those used for the other two techniques and physical borders around the area sensitive to input are provided. The input device used in our study is "SquareSense" (Augstein et al., 2017a). Similar to SpongeBox, it has been developed specifically for purposes of comparing semi-touchless to touchless input techniques for simple 3D manipulation tasks. It consists of a box with highly sensitive capacitive side, bottom and front walls the user can freely move the hand within. The device can recognize touchless movements but also pressure intensities if the walls are touched. Thus the device is isometric-isotonic generally, however, we did not use application of pressure for the study described here as the devices were configured in a way that the physical borders marked the interactive area (which was also aligned to the digital interaction space, see Section 5).

As with the touchful setting, the user's arm can rest on a sponge placed in the rear part of the box which reduces the physical strain often involved with touchless input. SquareSense is based on an Arduino microcontroller and capacitive copper plates fixed to the walls of the box. Similarly to SpongeBox, SquareSense was configured in an iterative process during the pre-tests and used an equal number of 13 distinct proximity levels for each direction.

4 INTERACTION TESTS AND PERFORMANCE METRICS

Our user study considers several objective metrics indicative of interaction performance. These metrics have been selected specifically to fit simple 3D manipulation tasks. To be able to compute values for these metrics, our users perform identical so-called "interaction tests" with each input technique. We consider the metrics to be interesting individually and do not aim at computing an overall index of performance. We thus utilize a user modeling framework (Augstein et al., 2017b) which offers an infrastructure for defining, maintaining and analyzing an arbitrary number of individual metrics. Each test (see the following sections) requires the user to move a red cube (see Figure 2) which acts as a cursor in a 3D space according to a particular task. The devices were used for absolute positioning of the cube in the digital space.

4.1 Reach and Regularity

The first test (and corresponding metric) is called *Reach*. Here, the user has to move the red interactive cube to the personal maximum comfortable position in the directions left, right, forward and down (in all cases starting from the same position in the center of the interaction space). The metric *Reach* has been selected because the mobility and strength of a user's dominant hand (which are decisive for the values achieved for *Reach*) are highly individual and could be significantly reduced for users with (temporary) motor impairments which again can strongly influence interaction performance. The test is similar to the "straight navigation task" used by (Tscharn et al., 2016) in their study on 3D map navigation.

At the touchful (isometric) setting, a user has to apply the highest amount of pressure he/she can (comfortably) achieve in all four directions to move the cube in the respective direction. The maximum values achieved for the four directions are stored as *ReachLeft*, *ReachRight*, *ReachDown*, and *ReachForward*. At the (semi-)touchless (isotonic) settings, the test requires a user to move the cube by moving the hand. The values are stored in percent of the system's global maximum (the red cube cannot be moved out of the interaction space, if it has reached the maximum position, the resulting *Reach* value is 100% and the cube will stop there). The results could also be used to individually adapt the *ContinuousRegularity* test which was done within a similar study with people with impairments where *Reach* was quite diverse.

Additionally, within the same test, the system analyzes deviations from the straight-most path between initial and maximum position and uses it to compute a *Regularity* metric (again, for all interaction directions and measured in percent). A straight path would result in a *Regularity* of 100%. The path (including the respective target and actual positions) is analyzed at every time stamp between initial and end position. The deviation from the straight path is averaged over all time stamps and subtracted from an initial value of 100%. *Regularity* is computed for each direction (*RegularityLeft*, *RegularityRight*, *RegularityDown*, *RegularityForward*).

4.2 Continuous Regularity

The second test *ContinuousRegularity* shares some characteristics with the "rotation navigation task" used by (Tscharn et al., 2016) and requires users to follow a green target cube (see Figure 2) over a path that reaches all relevant areas of the 3D interaction space. The target path starts at the initial position in the center of the interaction space, then moves around.

The computation algorithmically matches the one of *Regularity*, which is, however, tested for each of the four directions individually only while *ContinuousRegularity* requires a user to perform a coordinated, continuous and interruption-free movement that covers all directions. To be able to identify pre-

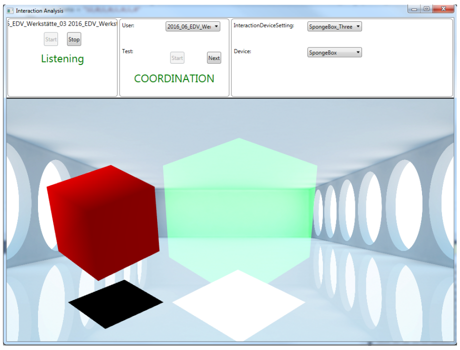


Figure 2: Visualization users see during interaction.

ferred directions (e.g., left or right) or dimensions (e.g., left/right or down/up), we compute individual metrics (*ContinuousRegularityLeftForward*, *ContinuousRegularityLeftDown*, *ContinuousRegularityRightForward* and *ContinuousRegularityRightDown*) in addition to the general *ContinuousRegularity* metric which considers the whole path.

4.3 Time

Finally, the third test called *Time* requires users to reach target cubes that consecutively appear in each of the four directions after a certain delay as quickly as possible. Again, the red interactive cube is positioned in the center of the interactive space initially and is moved back there after a target cube has been reached. The target cubes are big enough to be easily reached as it was not the aim to find out the optimum size of the target area but the interaction speed in case the target is of sufficient size. The metrics are called *TimeLeft*, *TimeRight*, *TimeForward*, and *TimeDown*.

5 USER STUDY

A two-fold user study was conducted in summer of 2016 to compare touchful, touchless and semi-touchless input for pre-specified manipulation tasks in a 3D interaction space. As mentioned earlier, the three devices used have been thoroughly tested and adjusted prior to the actual study. The pre-tests took place with three test users that did not participate in the actual study and aimed at i) ensuring comparability among the three devices related to spatial resolution, reactivity, interaction space and movement range, and ii) identification of device configurations convenient for the user. Thus, we e.g., tested for all devices whether they reacted to user input in the expected way (e.g., without delays and with the physical effort involved being within a comfortable range). As the sensation of physical demand or fatigue is individual it was important to not only test with one pre-test user. Thus we tested with three users (including also a user without previous experience with alternative input methods and devices) and chose a setting that was described as comfortable by all of them. Further, the pre-tests involved an iterative adjustment of the devices' configuration (e.g., regarding interaction space, reactivity and sensitivity to user input) in order to ensure comparability. For instance, we adjusted the minimum pressure intensity required to trigger an input activity for the touchful setting and smoothed the values delivered by the semi-touchless device. Also, we aligned the physical with the digital interaction space and made sure that the physical space was equal also for the touchless setting (which inherently did not involve physical constraints).

5.1 Research Questions

The user study was tailored to evaluate two aspects related to the three input techniques and devices. First, it should identify strengths and weaknesses of the individual devices/techniques, based on the interaction performance indicators *Reach*, *Regularity*, *ContinuousRegularity* and *Time*. In the second part, UX related to each of the input devices/techniques should be evaluated, using the categories *Efficiency*, *Perspicuity*, *Dependability*, *Stimulation* and *Novelty* defined by the standardized User Experience Questionnaire (UEQ)[1] and described later. As i) the interaction tests were identical for all devices, ii) the users' required interaction activities were comparable for all techniques and iii) the users had enough time to get familiar with the input techniques prior to the actual tests, the main difference between the three input techniques is the degree of haptics involved. Additionally, a difference can be seen between touchful and the other two techniques as it relies on force application (isometric) whereas the other two rely on movements (isotonic). Based on our expectations and findings of related studies, we formulated seven hypotheses:

- H1: We expect users to be able to interact fastest with touchless input.
- H2: We expect *Reach* to be about equally high with all three input techniques.
- H3: We expect interaction *Regularity* to be better with input techniques that involve haptics.
- H4: We expect *ContinuousRegularity* to be better with input techniques that involve haptics.
- H5: We expect *UX* to be generally better with input techniques that involve haptics.

[1]http://www.ueq-online.org

- H6: We expect *Stimulation* to be better with input techniques that involve haptics.
- H7: We expect *Dependability* to be better with input techniques that involve haptics.

Regarding H1, we became aware that related studies report divergent results, e.g., (Tscharn et al., 2016) found users to be slower with Leap for navigation tasks, compared to a 3D mouse whereas in the study of (Coelho and Verbeek, 2014) who compared Leap to a common mouse, users were faster with Leap at tasks comparable to ours. Although (Zhai, 2008) concludes that "human response with an isometric device is faster than with a comparable isotonic one since no transport of limb or device is needed" we expected users to be faster with touchless input in our study. First, they did not have to overcome physical resistance to hit the target and second, the distance users had to transport limb (i.e., their hand) over was equal for all three input techniques. Regarding H2, we expected *Reach* to be about equally high with all input techniques as the participants of the study did not have any known impairments (reducing interaction range) and analyzed it just to confirm this assumption. Regarding H3 and H4, we expected *(Continuous)Regularity* to be better with input techniques that provide physical restrictions which constitute some form of guidance. Regarding H5, H6 and H7, we expected general UX, and *Dependability* and *Stimulation* in particular to be better with input techniques that involve a haptic experience because prior research suggests that even simple haptic stimulation can contribute to the communication of emotional information, see, e.g., (Salminen et al., 2008).

5.2 Procedure and Methodology

The within-subjects study took place in a controlled lab setting. Participants were asked to do the three interaction tests with all devices. We used a counterbalanced (latin square) order in which the devices were presented to the them to prevent a bias due to practicing effects and control other position effects like fatigue. Before the tests, users got an introduction by the test supervisor, explaining device and input technique, and could become familiar with it. When they were ready, the tests started. The results were automatically recorded and analyzed. In total, 25 users did 27 interaction tasks each (9 tasks with three devices), resulting in a total number of 675 tasks that were analyzed. The interaction during the phase of getting familiar with a setting was not recorded. After the tests with a device, users answered the standardized UEQ, see e.g., (Laugwitz et al., 2008). The UEQ aims at i) enabling quick assessment, ii) capturing comprehensive impression of UX, and iii) encouraging simple and immediate feedback (Laugwitz et al., 2008). It is available in 15 languages and comprises the following UX aspects ("scales"): attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. Each scale is represented by a number of "items" that have the form of a semantic differential, using a seven-point scale between -3 and 3. For our study we excluded the scale *attractiveness* as we considered the related items less important for our objectives (after making sure that the UEQ allows for reduction of categories). Our users answered 20 items related to the remaining five scales:

- *Perspicuity*: Is it easy to get familiar with the product? Is it easy to learn how to use it? Example items are *not understandable/understandable* or *easy/difficult to learn*.
- *Efficiency*: Can users solve their tasks without unnecessary effort? Example items for this category are *fast/slow* or *impractical/practical*.
- *Dependability*: Does the user feel in control of the interaction? Example items are *unpredictable/predictable* or *meets expectations/does not meet expectations*.
- *Stimulation*: Is it motivating to use the product? Example items for this category are *not interesting/interesting* or *motivating/demotivating*.
- *Novelty*: Is the product innovative and creative? Does the product catch users' interests? Example items are *creative/dull* or *conservative/innovative*.

The procedure was repeated for all input techniques. Afterwards, we collected basic demographic information. The tests took 15 to 30 minutes per person.

5.3 Participants

We could recruit 25 volunteers, aged between 19 and 49 ($AV = 34.12$, $SD = 9.35$), 8 male and 17 female. All participants were right-handed and used the right hand for interaction. Most participants were staff or students of the university. The user group was exceptionally diverse regarding experiences with alternative input techniques (reaching from a UX professor to an office assistant without any previous experiences with alternative input devices). About 24% of the users had previous experience with Leap (only 3 users had used it more thoroughly). Also 24% had used SpongeBox once before (due to an earlier user test). In order not to cause a bias based on previous experiences, we allowed all participants to get familiar with the respective device as long as they needed before the test.

6 RESULTS

This section summarizes the results of the user study.

6.1 Interaction Performance

We will discuss the results based on the metrics described earlier, distinguishing between the categories *Reach*, *Regularity*, *ContinuousRegularity* and *Time* (see details in Table 1 and Table 2). To statistically analyze the differences between the three input techniques, we ran Friedman's tests for these criteria. The test was chosen due to the characteristics of the data which partly violate the normal distribution prerequisite of ANOVA. However, to examine the results' stability, we repeated the analysis with a repeated-measures ANOVA which confirmed all results.

The tests revealed significant[2] differences between the three input techniques regarding *Reach* ($\chi^2(2) = 13.317$, $p = .001^*$), *Regularity* ($\chi^2(2) = 44.163$, $p = .000^{**}$), and *ContinuousRegularity* ($\chi^2(2) = 13.520$, $p = .001^*$) while the differences for *Time* were not significant ($\chi^2(2) = 5.040$, $p = .08$). Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < .017$. More detailed results are reported in the following sections.

6.1.1 Reach

We report the values for the four *Reach* metrics (see Table 1) and their aggregation (see Table 2). Statistically significant differences for *Reach* were found only between the semi-touchless and touchful ($Z = -2.947$, $p = .003$[3]) techniques. Differences between touchful/touchless and semi-touchless/touchless were not significant ($Z = -2.130$, $p = .033$ and $Z = -2.060$, $p = .039$). The results generally suggest that participants could reach the maximum positions well in all directions and with all techniques.

6.1.2 Regularity

Regularity is measured related to four directions (see Table 1). The results for these metrics are then averaged for an overall result for *Regularity* as reported in Table 2. Generally, the semi-touchless technique clearly outperformed the other two. It resulted in a mean value of 93.68% ($SD = 11.04$), while the touchful technique gained 82.13% ($SD = 14.94$) and touchless input resulted in a mean of 43.91% ($SD = 16.9$). 20 of the 25 participants gained their individually best result with the semi-touchless input technique, two with the touchful technique, and the remaining three gained equally good results with the semi-touchless and touchful techniques (none with the touchless one). The differences between the input techniques were significant for touchful and semi-touchless ($Z = -3.072$, $p = .002$), touchful and touchless ($Z = -4.372$, $p = .000$) and semi-touchless and touchless ($Z = -4.372$, $p = .000$) input.

For three directions (left, right, forward), *Regularity* was best with semi-touchless input (with means between 95.15% and 100%, however with high variation in two cases, see Table 1). The touchful technique scored best for *RegularityDown* ($M = 85.87\%$, which is slightly better than the average result with the semi-touchless setting, $M = 84.26\%$, both with high variation). The touchless technique scored worst for all directions (with means between 24.25% and 62.11% for forward and right). This trend is confirmed by the participants' individual results: no user gained any of their individually best results with touchless input.

6.1.3 Continuous Regularity

Continuous regularity is measured for all four directions individually (see Table 1) and further aggregated to *ContinuousRegularity* (see Table 2). For touchful input, the mean values for the different directions were between 76.47% (right forward) and 87.67% (left down). For semi-touchless input, the results were between 72.89% (right forward) and 86.41% (left down). For touchless input, the results ranged from 79.61% (right forward) to 82.50% (left down). Interestingly, even if the differences were in most cases not too high, the coordinated movement was most difficult in the direction right/forward with all devices and least difficult in the direction left/down for all 25 participants. We attribute this to the fact that for right-handed people a movement (or force application) of the right hand to the left (i.e., towards the body) is easier than to the right (away from the body). For the aggregated *ContinuousRegularity* metric, touchful input scored best on average, resulting in a mean of 82.34% ($SD = 3.84$). The touchless technique was slightly worse ($M = 81.41\%$, $SD = 16.49$) and semi-touchless was ranked third ($M = 79.64\%$, $SD = 4.1$). The statistical analysis showed that the differences between touchful and semi-touchless input were significant ($Z = -2.4082$, $p = .016$). The other comparisons revealed no significant differences ($Z = -1.574$, $p = .115$ for touchful/touchless and $Z = -2.301$, $p = .021$ for semi-touchless/touchless).

[2] * denotes a significance level set at $p < .05$, ** a significance level set at $p < .001$

[3] As a significance level of $p < .017$ has been identified, we do not use the standard APA notation ($p < .05$).

Table 1: The computed values for mean, median and standard deviation of all metrics averaged for 25 participants. All metrics except for the ones for Time (which are measured in milliseconds), are measured in percent. LF stands for left forward, LD for left down, RF for right forward and RD for right down respectively.

Metric	Touchful			Semi-Touchless			Touchless		
	M	Mdn	SD	M	Mdn	SD	M	Mdn	SD
ReachDown	100.00	100.00	0.00	100.00	100.00	0.00	98.33	100.00	4.08
ReachLeft	95.33	100.00	19.73	100.00	100.00	0.00	99.00	100.00	4.90
ReachRight	91.33	100.00	12.80	100.00	100.00	0.00	99.67	100.00	1.63
ReachForward	100.00	100.00	0.00	100.00	100.00	0.00	100.00	100.00	0.00
RegularityDown	86.87	100.00	21.70	84.26	100.00	34.28	28.78	28.24	21.97
RegularityLeft	91.85	100.00	22.00	100.00	100.00	0.00	60.48	66.97	26.61
RegularityRight	72.30	93.13	34.31	95.30	100.00	14.81	62.11	72.50	32.21
RegularityForward	77.49	100.00	30.20	95.15	100.00	19.87	24.25	19.89	22.74
Cont.RegularityLF	82.18	83.84	6.12	83.58	84.46	3.40	81.43	85.10	14.02
Cont.RegularityLD	87.67	88.30	3.57	86.41	87.95	4.67	82.50	91.40	23.05
Cont.RegularityRF	76.47	75.92	4.44	72.89	73.38	3.75	79.61	82.20	6.56
Cont.RegularityRD	83.05	82.84	4.61	75.68	80.26	13.02	82.08	91.13	24.36
TimeDown	1272	1002	901	1391	1156	856	1832	1251	1681
TimeLeft	795	653	353	940	801	458	1679	1100	2729
TimeRight	1114	1107	466	978	900	380	1797	950	3862
TimeForward	1356	1014	1032	1451	1151	783	2819	1401	3024

6.1.4 Time

We measure the average time a user took to reach each of the target cubes in the *Time* test. Interestingly and in opposition to our expectation (but consistent with the findings of (Tscharn et al., 2016) or (Stannus et al., 2011)), users were not fastest with touchless input; the statistical analysis did actually not reveal any significant differences. We initially expected users to be faster with touchless input due to the absence of physical resistance. Based on the results we assume that this missing resistance led to an uncertainty regarding whether the goal had already been reached or not (although we visualized this). Due to the high variation we searched for outliers and found a user who had troubles with touchless input in general. Removing this user from the data set reduces the variation considerably but does not affect statistical significance.

6.2 User Experience

UEQ includes a customized data analysis tool and methodology which we primarily used for the analysis of our results reported in this section. Although usually analyzed on the descriptive level (which is sufficient for the evaluation of one condition), we additionally ran a statistical analysis of the UEQ data, in order to be better able to judge the actual differences between the settings on a statistical level. For this analysis we used a repeated-measures ANOVA (as the UEQ data met the ANOVA's prerequisites).

6.2.1 UEQ Summary

The results for the UEQ are summarized in Figure 3 and Table 3. The scale ranges from -3.0 (considered "horribly bad") to 3.0 ("extremely good"). However, the authors of the UEQ consider it "extremely unlikely" to observe answers < -2.0 or > 2.0 in real applications. Values between -0.8 and 0.8 represent a neutral evaluation (visualized yellow in Figure 3), values > 0.8 represent a positive (green) and values < -0.8 a negative one (red). Touchful input was evaluated positively for *Perspicuity*, *Stimulation* and *Novelty* and neutrally for *Efficiency* and *Dependability*. For semi-touchless input, the results were neutral for *Dependability* and positive for all other categories (especially for *Stimulation* and *Novelty*). For touchless input, all categories were evaluated positively.

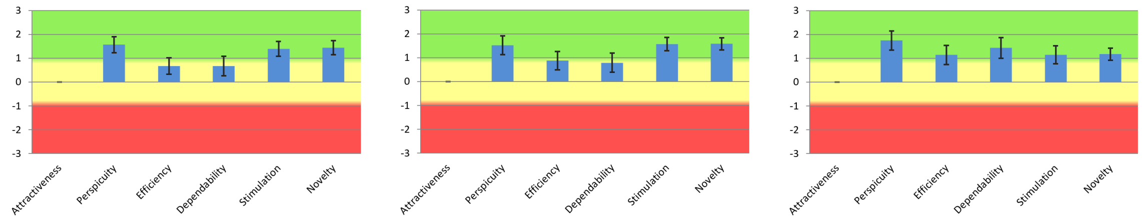
6.2.2 Statistical Analysis

The ANOVA revealed significant differences for *Dependability* ($p = .022^{*4}$) and *Novelty* ($p = .036^{*}$). The pairwise comparison showed significant differences only between the touchful and the touchless input technique ($p = .031^{*}$). The differences for *Novelty* were significant only at the group level (pairwise comparisons did not show significant differences with e.g., $p = .059$ for of semi-touchless vs. touchless input). The statistical results seem to lower the weight

[4]Greenhouse-Geisser correction was applied because *Dependability* data violated the sphericity prerequisite.

Table 2: Aggregated results for mean, median and standard deviation of Reach, Regularity, ContinuousRegularity and Time averaged for the 25 participants, measured in percent (or milliseconds, for Time).

Aggregated Metric	Touchful			Semi-Touchless			Touchless		
	M	Mdn	SD	M	Mdn	SD	M	Mdn	SD
Reach	96.67	100.00	6.36	100.00	100.00	0.00	99.25	100.00	1.85
Regularity	82.13	86.76	14.94	93.68	100.00	11.04	43.91	47.30	16.90
ContinuousRegularity	82.34	82.41	3.84	79.64	80.45	4.10	81.41	86.68	16.49
Time	1134	1026	466	1190	1081	484	2032	1250	2442



(a) Touchful (b) Semi-Touchless (c) Touchless

Figure 3: The UEQ results for all input techniques. The error bars represent the 95% confidence intervals of the scale means.

Table 3: UEQ results averaged for the 25 participants.

UEQ-Category	Touchful	Semi-Touchless	Touchless
Perspicuity	1.560	1.520	1.740
Efficiency	0.670	0.873	1.140
Dependability	0.670	0.790	1.430
Stimulation	1.390	1.570	1.140
Novelty	1.440	1.580	1.170

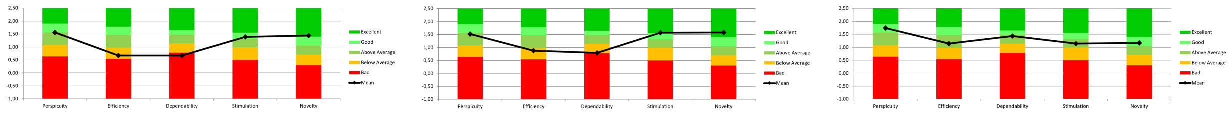
of the UEQ results drastically at first glance. Yet it is surprising that the scores for three of five categories are best for touchless input (even if this effect was not statistically significant for *Perspicuity* and *Efficiency*). We had initially expected a contradictory result with a strong tendency towards haptic scoring better than touchless input. The results could indicate that UX was influenced less than other factors by performance.

6.2.3 Comparison to UEQ Benchmarks

The UEQ data analysis tool also provides a benchmark data set that compares the evaluated system against the responses of 9905 individuals from 246 studies on interactive products. The benchmark data set helps to draw conclusions about the relative (UX) quality of the evaluated product in comparison to others. This was especially interesting to us as the statistical analysis revealed less conclusive insights than expected. The results classify each of the evaluated categories as excellent, good, above average, below average, or bad (e.g., "good" means that 10% of the results are better, 75% are worse). Figure 4 shows that except for *Dependability* for touchful input (which is rated "bad" in comparison), all UX aspects are at least in an "okay" area. All aspects apart from *Dependability* and *Efficiency* for touchful and semi-touchless input range from "good" to "excellent". For touchless input, the results for all categories are at least "above average" ("good" for *Perspicuity* and *Novelty*).

6.3 Findings Related to the Hypotheses

We summarize the results regarding our hypotheses as follows. We had to **reject H1** as we did not find a significant difference in *Time*. **H2** was **partially confirmed**. Although the results showed unexpected significant differences between touchful (isometric) and semi-touchless (isotonic) input, the differences between the techniques that involve a haptic experience and touchless input were not significant. We could **confirm H3** as touchful and semi-touchless were significantly better than touchless input regarding *Regularity*. **H4** had to be **rejected** as we did not find significant differences between touchful and touchless as well as semi-touchless and touchless input regarding *ContinuousRegularity*. **H5** and **H7** also had to **be rejected** as the UX part of the evaluation revealed that while two categories were actually better with touchful and semi-touchless input, the remaining three (including *Dependability*) were better with touchless input. **H6** could **only partially be confirmed**. *Stimulation* actually tended to be better for both input techniques that involve a haptic experience which was however relativized by the statistical analysis. We do not reject H6 because the comparison with the UEQ benchmarks categorized touchful and semi-touchless as "excellent" while touchless input was only "good".



(a) Touchful (b) Semi-Touchless (c) Touchless

Figure 4: Comparison with the benchmark data set.

7 CONCLUSIONS

This section summarizes the work presented in this paper and discusses its impact and limitations.

7.1 Summary

In this paper we have described and compared three input techniques that rely on a different degree of haptics. Aiming at analyzing the impact of a haptic experience on objective and subjective factors related to interaction, we conducted a two-fold user study. The first part focused on objective interaction performance metrics, the second emphasized perceived UX. It was quite surprising that the results for the two parts were relatively contradictory. While the semi-touchless and touchful input techniques both outperformed touchless input regarding selected interaction performance metrics (and touchless input was not significantly better than any of the other two at any metric), three of five UX categories were evaluated better in tendency for touchless input. Some factors that can contribute to the ambivalence between objective and subjective results are discussed as follows. (MacLean, 2008) describes that for humans "precision requires resistance", i.e., absolute position control is difficult and humans need something solid to push against when we want to accomplish fine position control. Touchless input lacks this kind of supporting guidance, which could have led to the inferior performance. However, a lot of research has dealt with the emotional quality of haptics in human-technology interaction (Salminen et al., 2008) and showed that there is an impact on human perception of interaction when haptics is involved. This would support the fact that the more emotion-leaning categories (grouped under "hedonic quality" by UEQ) *Stimulation* and *Novelty* were rated better for the techniques involving a haptic experience, whereas the rather analytic categories ("pragmatic quality") *Perspicuity*, *Efficiency*, and *Dependability* received a contrary result.

Based on our observations we draw the following conclusions related to simple 3D manipulation tasks: i) haptics does play an important role, especially in terms of *Regularity*, ii) it however seems to be more important for interaction performance than for UX, and iii) a lower-performing technique can still retain a good UX. It seems that in our study even the well-known issue of missing physical constraints with touchless input influenced interaction performance more strongly than UX. Although in several cases our participants did actually leave the sensitive area accidentally (which negatively affected interaction performance), they e.g., rated "good" 1.5 for the items *predictable/unpredictable* and "excellent" 1.8 for *understandable/not understandable*. The only UX aspects that might have been affected negatively can be found at *fast/slow* which got a score of 0.8 and *motivating/demotivating* (0.4). Although the UX scores for touchful and semi-touchless input were in most cases below the ones for touchless, most participants verbally expressed that they liked the prototypes a lot. Regarding the comparison of isometric and isotonic devices, our study did not reveal significant insights.

7.2 Impact and Limitations

Regarding the results of our study, these generally allow for conclusions that apply to other input settings as well. The metrics chosen for the user study are relatively general and should be applicable for other input settings, although their significance might differ. *Reach*, *Time*, and *Regularity* are metrics that are e.g., also relevant for interaction based on full-body movement with considerable more DoF or for conventional mouse/keyboard or touch-based input (2DoF). *ContinuousRegularity* is only important for settings that allow for continuous movement-based input.

One limitation related to the interaction tasks is that except for left/right, they focused on one direction per dimension (i.e., forward and down). This was on purpose as for touchful input it would have been impossible to offer an upper wall without depriving users of the visual control of their hand. Regarding the direction back, adding another pressable wall in the back would have been possible but drastically changed the user's interaction activity. In order to ensure comparability of the input techniques and prevent a bias based on the devices rather than the input techniques, we focused on the directions where activities were of sufficient similarity for all devices. Regarding UX, the good results for touchless input suggest that a missing haptic experience does not necessarily have to lead to a bad overall UX. To the contrary, the study has shown that a worse performing device/input technique can still have a good perceived UX. The good UX results for both touchful and semi-touchless input in the category *Perspicuity* have shown that users understood the input technique quickly. Also, the good results for touchful and especially semi-touchless input in the category *Stimulation* are conclusive (e.g., scores of 1.1 and 1.0 for *motivating/demotivating* for semi-touchless and touchful, 0.4 for touchless input). Some results (e.g., the good results for semi-touchless and touchful input for *Novelty*) might be less significant as they might have been biased by the prototypic nature of the devices and the resulting "novel" impression. Yet, this potential bias is only present in a small part of the results. Most semantic differentials suggest a clear focus on the interaction with the device, not its appearance.

7.3 Subsequent Work

We expect our results to generalize to interaction tasks in a similar complexity category while they might differ with varying complexity and DoF, which should be analyzed in consecutive studies. We believe that such studies will reveal interesting findings on the dependence of need for haptics on task complexity and expect that with increasing complexity of the interaction tasks, the importance of haptics increases as well. We already conducted a qualitative study with users with motor and cognitive impairments, see (Augstein et al., 2017a), which revealed a much stronger dependence on haptic guidance, compared to non-impaired users: almost all participants gained their best results for *Regularity*, *ContinuousRegularity* and *Time* with touchful input. Regarding subjective impressions, results were relatively balanced.

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