Tangible Interaction for Simple 3D Interaction Tasks: Comparing Device-In-Hand and Hand-In-Device Scenarios

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Abstract: Although recently, touch-based input with a reduced amount of haptic guidance gained popularity, traditional tangible input devices like mice or joysticks are still indispensable of everyday human-computer interaction. Most traditional tangible devices are implemented in so-called device-in-hand settings. There, the user's hand grabs the device and the device-hand system is then moved to trigger an input activity. Thus, the user's hand posture usually stays relatively stable. Hand-in-device approaches are an alternative form of tangible interaction settings where the user's hand moves within a tangible device. Such a setting differs considerably as i) the user's hand posture is more flexible, and ii) the device itself is stable while the interacting hand moves. This paper describes a comparative study on users' interaction performance with device-in-hand and hand-in-device settings for simple 3D interaction tasks. Further, it contributes to the body of knowledge on favourable interaction directions (left or right).

1 INTRODUCTION

Most traditional input devices like mice or joysticks strongly rely on a haptic experience during the interaction process. Throughout the past years, the advent of current smart phone and tablet technology brought about a sharp increase in the usage of touch screen interfaces that resulted in ever less haptics involved in the interaction process. Most such devices do not (any more) provide physical buttons or other tangible hardware elements (other than the touch screen itself).

A lot of effort was recently taken to re-introduce a haptic experience for touch screen interfaces (see, e.g., (Ciesla et al., 2013; Kincaid, 2012; Bau et al., 2010) for work on tactile touch screens and haptic guidance for touch screens). Guidance through haptics is especially important when interactive systems should be well controllable without permanent visual observation. This is most relevant in automotive or industrial sectors but also for traditional, physically split interactive settings (such as a mouse-monitor combination) where the user's eyes usually rest on the screen most of the time and the mouse handling is controlled via the visual output (e.g., the mouse cursor's movement on the screen) only. For everyday human-computer interaction settings, particularly those aside from embedded input/visualization systems like most touch screens that generally allow for a more direct way of interaction, tangible input devices are still indispensable.

The focus of this paper lies on tangible interaction for simple 3D interaction tasks. By *tangible interaction* we understand interaction that relies on a permanent physical contact between the user's interacting hand and the input device. This kind of scenario is most common, e.g., in the gaming sector or for the operation of control panels in the industrial area. For both, precision and thus also guidance is decisive.

The most popular form of tangible input devices is the one of a device held in the user's interacting hand (e.g., mice or joysticks). In this paper we will refer to such settings as *Device-In-Hand (DIH)* scenarios, whereas in so-called *Hand-In-Device (HID)* settings, the user's interacting hand is moved within the device (which also defines physical boundaries) while the hand posture itself is flexible.

Both types of settings involve advantages. In DIH settings, we expect the user to be better able to control the input process as most related devices offer a high hand-device *stability*. In HID settings, the user is provided with a higher *flexibility* and can choose the own hand posture according to individual prere-

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quisites. This paper reports a study on users' interaction performance with representative DIH and HID input devices. Further, it analyzes differences in performance related to the interaction direction (left or right, towards or away from the body respectively).

2 RELATED WORK

This section describes related work on DIH and HID approaches and preferred interaction directions.

2.1 Interaction Approaches

(Shen et al., 2011) distinguish between two forms of interaction that are possible with hands: i) device-assisted hand interaction and ii) bare-hand interaction. In some aspects, this distinction is similar to ours. For HID and bare-hand interaction the user's interacting hand does not grab and hold on to a physical device and the hand posture is flexible. Regarding device-assisted and DIH interaction, both involve permanent physical contact between the user's hand and a device. However, the definitions differ in other aspects, the most important being that we focus on *tangible HID interaction* which involves permanent physical contact between user and device and thus also haptic guidance. The latter is an aspect that is usually missing with touchless input (although there have already been endeavours to re-introduce haptic feedback for touchless settings, see e.g., (Pfeiffer et al., 2014; Carter et al., 2013)).

In general, lots of work can be found related to DIH interaction for 3D navigation tasks. In most cases these approaches use 3D mice. We picked out a few we consider most relevant within the scope of this paper and describe them as follows. (Stannus et al., 2011) compared touchless gestural interaction to two DIH interaction techniques for navigation tasks in Google Earth. For DIH interaction they used a 3D mouse[1] and a conventional mouse. More recently, a similar study was conducted by (Tscharn et al., 2016), who also analyzed users' performance at 3D navigation tasks with SpaceNavigator (a DIH input device) and the Leap motion controller (for bare-hand input). In both cases the task-based study design, the interaction tasks (of varying complexity) and the metrics analyzed (e.g., their *accuracy* closely matches our *regularity*) are similar to ours.

In addition to the parallels between HID and touchless interaction with the Leap motion controller, there are many similarities between the DIH device used by our study and the ones of (Stannus et al., 2011; Tscharn et al., 2016). SpaceNavigator as well as the joystick we use (a Thrustmaster T.Flight X) are devices that are held in hand (i.e., grabbed once and then held on to during the further process). Additionally, the physical appearance of SpaceNavigator reminds of a small joystick and both e.g., use push/pull activities for forwards/backwards movement. They differ in some other aspects like movement range of the physical device or number of supported DoF.

A different comparison of DIH to bare-hand in-air interaction is described by (Dangeti et al., 2016) who focus on navigation of 3D objects in modeling environments. They propose a prototype utilizing Microsoft Kinect for gesture recognition and an iPhone or Playdoh/Lego augmented with an accelerometer as a tangible solution. While their work is still preliminary, the scope of interest is similar to ours.

Tangible HID is less popular than tangible DIH interaction as most common HID approaches use touchless input. Yet, (Sato et al., 2012) discuss novel application areas for capacitive sensing capabilities, amongst them a fish tank filled with water. Although the research aims of (Sato et al., 2012) are not directly related to ours, their approach is highly interesting for us as their interactive water tank constitutes a HID approach according to our definition. There is a permanent physical contact between user and “device” and resistance provided by the water. Further, the tank borders physically limit the interaction space.

A related study of (Augstein et al., 2018) compared a tangible HID approach to touchless input (without provision of physical borders, thus not a HID setting according to our definition) and an input technique that can be classified as somewhere in between tangible HID and fully touchless input without physical constraints: it uses physical boundaries in form of a box and touchless input (however also allowing for the walls of the box to be touched, interpreting also the amount of pressure). The study used SpongeBox, the device that is also used for the study described in this paper as an example for HID (see Section 3.2), the Leap motion controller for touchless input and another device prototype called SquareSense for the third kind of interaction just explained.

Although the methods for gathering data related to users' interaction performance are similar compared to what is described in this paper (see Section 4), the study of (Augstein et al., 2018) differed drastically regarding its research questions. It was intended to compare interaction with three devices involving a different amount of haptics along several interaction performance but also User Experience criteria.

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[1] The concrete model is not named in their paper.

2.2 Favorable Hand-Arm Movements

Prior work in the field of ergonomics and work place safety dealt with the question which movements of the hand-arm system are favorable for humans. (Strasser et al., 1989) and (Strasser and Müller, 1999) conducted experiments throughout a decade using electromyography to detect strain for different arm movements on a horizontal plane and found out that angles (to the body plane) of about 30° were optimal whereas 150° where most suboptimal, i.e., the areas towards or closer to the body were preferred.

(McDonald et al., 2012) investigated shoulder muscle demands in horizontal pulling and pushing activities and found that there is “a potential increase in intramuscular pressure (IMP) that occurs in abducted postures”, which is relevant for the interaction direction right (if the right hand is used).

Further, according to (Rinck and Becker, 2007), humans consider a movement of the arm away from the body an action of avoidance (i.e., unpleasant) and a movement towards the body an action of approach (i.e., pleasant). These findings are also backed by our results. Especially for complex tasks, the interaction in the direction left worked significantly better than right for right-handed users.

3 INPUT TECHNIQUES

This section describes the input techniques and devices used for the study reported in this paper. The 3D interaction tasks users had to perform during the study (see Section 4), the interaction space, user interface and reactivity of the digital object moved in this space were almost[2] identical for both settings in order to allow for comparison. Also, we configured the two input devices we used to both function as isometric input devices (i.e., input devices that connect the human limb and the device through force (Zhai, 2008)). The input methods however are fundamentally different regarding the interplay of the user’s hand and the device. The most important difference can be seen in *stability (DIH)* vs. *flexibility (HID)* regarding the hand-device system.

During *DIH* interaction, the user’s hand grabs the device and holds on to it during interaction. This can lead to better controllability and the hand-device posture usually remains unchanged (if an input activity requires movement, e.g., for a navigation task, the hand-device system is moved altogether). During *HID* interaction, the device is steady while the user’s hand moves. Thus, the hand-device posture constantly changes (but without losing physical contact). This can decrease controllability but it allows for more freedom regarding the hand posture itself, which is especially beneficial when the hand’s mobility is limited. The participants of our study had no known motor impairments, however we plan a second study with people with motor impairments (as discussed later) and expect substantial differences between the two groups.

3.1 DIH Interaction with a Joystick

A typical example for a DIH setting is interaction using a joystick. A joystick is usually grabbed once and then held in the hand during the interaction without major changes of hand-device posture. Many joysticks directly support this stability by their physical appearance. For instance, the Thrustmaster T.Flight Stick X USB we used for our study is designed according to the physiology of the human hand and provides a wide hand rest which prevents slipping.

Figure 1 shows a pre-test user while getting familiar with the device. In general, most commercially available joysticks enable two or three Degrees of Freedom (DoF). The joystick we used in the study supports movement along three axes. Two axes are operable by pressing the stick forward, back, to the left and to the right while movement along the the z-axis can be done by stick rotation. For reasons of better comparability regarding the input process, we used a slightly different configuration during the study (relying on movement forwards, back, left and right), as explained in Section 4. Further, the joystick was configured to require force application instead of just movement (thus constituting an isometric device).

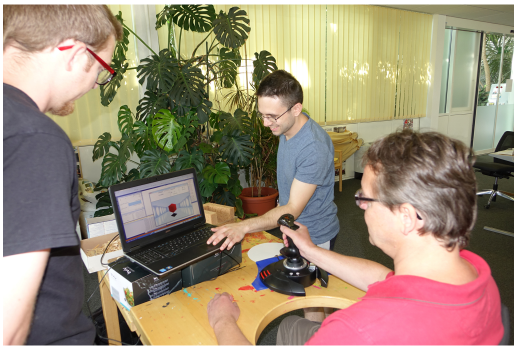

Figure 1: User interacting *DIH*, using a joystick.

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[2] There is one exception we could not avoid due to the nature of the devices which is explained in Section 4.

3.2 HID Interaction with SpongeBox

While DIH interaction is widely used, HID input is less popular, at least for a larger target group and for tangible settings. As described earlier, there are some parallels between HID and touchless interaction (e.g., flexible hand movement while the device remains stable) but also differences, the most important being that tangible HID settings provide permanent physical contact and borders during the interaction process.

Thus, a user is not able to leave the device's physical interaction space (i.e., the space sensitive to user input). Further, a user receives direct or indirect haptic feedback and guidance (e.g., via the physical resistance of the device that needs to be overcome to trigger an action). While HID settings might cause users to feel less in control of the process, compared to DIH interaction, they offer other potentials like e.g., reaching additional target groups due to the hand-device posture which can be individualized easier (e.g., for users who have difficulties grabbing a device but also for users who prefer an alternative hand posture for other reasons).

For our study, we used the SpongeBox device prototype (Augstein et al., 2017a), which has been developed specifically for comparative studies on tangible interaction. As mentioned earlier, it has e.g., been used for a comparative study on input devices that provide a different amount of haptics.

SpongeBox is a box with open upper and back walls while the left, right, front and bottom walls are covered with sponges. The user interacts by placing the hand inside the box (see Figure 2) and pressing it slightly against the sponges. The hand posture is thus flexible, a user can freely choose to, e.g., make a fist or keep the hand open.

Technologically, SpongeBox consists of an Arduino Uno and several pressure sensors placed under the sponges. It supports the interaction directions left, right, forward, back, down and up, and three DoF (the directions back and up are restricted to moving back to the initial position after having moved forward or down, due to missing upper and back walls, which was intended, however. A back wall would make it impossible to place the hand comfortably inside the box and an upper wall would inhibit occasional visual control of the interacting hand.

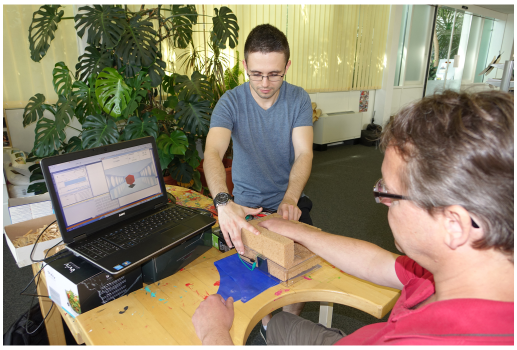
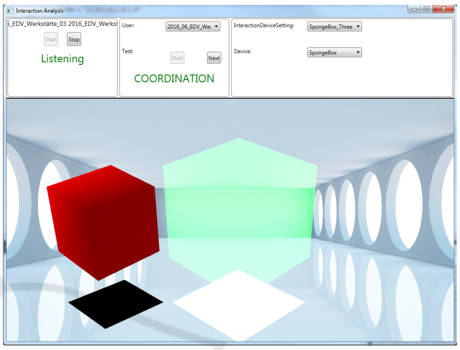


Figure 2: User interacting *HID*, using SpongeBox.



Interaction Analysis

_EDV_Werkstätte_03 2016_EDV_Werks

Listening

User: 2016_06_EDV_We

Test:

COORDINATION

InteractionDeviceSetting: SpongeBox_Three

Device: SpongeBox

Figure 3: Visualization users see during the tests (Augstein et al., 2018) (the red cube is the user's "cursor" in the interaction space, the green cube is used to indicate target areas).

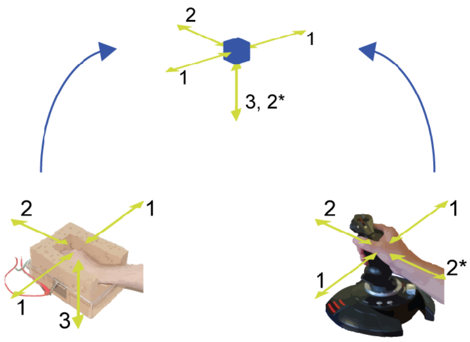
4 TASKS AND METRICS

Our study focuses on simple 3D interaction tasks and considers three basic metrics indicative of performance at these tasks. We rely on tasks and metrics that have been tested earlier in a similar-procedure but different-purpose study on the effect of haptics on interaction performance and user experience (see a more detailed general description of the metrics in (Augstein et al., 2018)).

To be able to compute concrete values for the metrics, the participants of our study performed identical so-called "interaction tests" with both settings. First, users see a UI with a predefined 3D interaction space and an interactive digital object acting as their "cursor" visualized as the red cube depicted in Figure 3. The interactive object can be moved along two dimensions and in several directions, starting from the initial position in the center of the space.

The setting in our study allows for movement of the interactive object in the directions left (and back to the initial position), right (and back to the initial position), forward (and back to the initial position) and down (and back up to the initial position). Some tasks require a user to perform simple, one-directional movements while others require a user to perform more complex movements involving several directions and dimensions.

Figure 4 shows the two input settings HID (a.) and DIH (b.) and the DoF as relevant for the study.



a. Hand in Device b. Device in Hand

Figure 4: Input devices and methods and the two to three DoF used by the interaction tasks during the study.

Further, the figure shows the effects of input activities with the two settings on the interactive object (upper part of the figure). E.g., the horizontal movement between left and right is denoted as the first DoF in the figure and both, moving the hand within the SpongeBox device to the left or right, and moving the joystick to the left or right will result in a position change of the digital object (moving it to the left or right).

Regarding the second DoF, moving the hand/joystick forward and back to the start position will cause the digital object to move forward in the interaction space and back to the start position. These movements are well comparable among the settings and cause identical effects regarding the change in the digital space.

The down-movement of the interactive digital object is however triggered differently with the two settings due to the nature of the devices. The related results are thus not as well comparable as the rest and will only be reported for purposes of completeness in Section 5.4. With the HID setting, the user's physical activity (pressing down) results in the matching reaction in the digital environment (the cube moves down). With the DIH setting this was not possible as the z-axis is addressed by rotation of the stick. This is a common solution with joysticks, however it differs significantly from the input activity that addresses the z-axis with the HID setting.

In order not to introduce a completely different input activity (rotation) to trigger the down-movement, we decided to implement it by moving the joystick backwards (from the default position) and then forwards to reach the start position again.

The following sections describe in more detail the concrete 3D interaction tasks the study participants were asked to do and the related metrics indicative of interaction performance.

4.1 Reach

The first task requires a user to move the interactive cube to the personal maximum comfortable position in the directions left, right, forward and down.

Thus, the related *Reach* metric describes the *maximum distance to the starting point that can be comfortably reached by a user*. The directions are tested separately, each starting from the initial position in the center of the interaction space. The related metrics are stored as *ReachLeft*, *ReachRight*, *ReachForward* and *ReachDown*. In addition to the individual values for the relevant directions we compute an aggregated *Reach* result which averages over all directions.

The metric was chosen because the mobility as well as strength of a user's dominant hand and comfort during movement are highly individual. They could be significantly reduced for people with motor impairments but also differ due to personal preferences. We however expect the results to be similarly good for all participants here (all without known impairments).

At the HID setting, users are required to press the hand against the sponges in all directions to move the cube in the respective direction. At the DIH setting, the joystick has to be moved forwards, left, right and back (for the down movement of the interactive object), to the respective personal maximum comfortable position. The joystick we used for the study can be configured regarding its physical resistance which is why we did a thorough pre-test before the actual user study to find a configuration where resistance is neither perceived as too high (i.e., physically demanding) nor as too low (i.e., prone to unintended interaction). Likewise we also calibrated SpongeBox regarding the amount of physical pressure needed to trigger an input activity and device reactivity. Thus for the study, the amount of physical effort demanded by the tasks was about equal for both settings.

The values for *Reach* are stored in percent of the system's global maximum (the interactive cube cannot be moved out of the interaction space, if it has reached the maximum position, the related *Reach* is 100% and the object stops there). The task is similar to others used for related studies (e.g., the one described in (Tscharn et al., 2016)) comparing different interaction settings.

4.2 Regularity

The logs of the *Reach* tasks are used to compute an additional metric called *Regularity*. *Regularity* describes *how straight and direct a user's path is between start and end point*. *Regularity* is again stored for all interaction directions: *RegularityLeft*, *RegularityRight*, *RegularityForward*, *RegularityDown* and *Regularity* (i.e., an aggregated value averaging over these directions).

To compute the results, the system analyzes deviations from the straight-most path between initial position and the user's maximum position in each direction. The metric is again measured in percent; a straight path would result in a *Regularity* of 100%. The path is analyzed at every time stamp between initial and end position, the deviation from the straight path is then averaged over all time stamps and subtracted from an initial value of 100%.

4.3 ContinuousRegularity

The *ContinuousRegularity* task, which shares some similarities with the "rotation navigation task" of (Tscharn et al., 2016), requires the user to follow a green target cube (as depicted in Figure 3) over a path that reaches all relevant areas of the 3D interaction space and that includes movement in all directions described earlier. The path starts at the initial position in the center of the interaction space.

ContinuousRegularity measures how straight and interruption-free a complex path (covering several dimensions and directions) is. The computation matches the one of *Regularity* algorithmically. However here, the user is required to perform a continuous movement that covers all relevant directions whereas *Regularity* is tested for every direction individually (with a break between the tests for the individual directions).

Based on the *ContinuousRegularity* task, we compute the following metrics: *ContinuousRegularity* which is an aggregated result for the related task, *ContinuousRegularityLeftDown*, *ContinuousRegularityLeftForward*, *ContinuousRegularityRightDown*, *ContinuousRegularityRightForward*, *ContinuousRegularityLeft* (which aggregates the metrics that involve the direction *left*) and *ContinuousRegularityRight* (which aggregates the metrics involving *right*). The latter two metrics are stored individually to be better able to analyze preferred interaction directions (as also targeted by our hypothesis H5, see Section 5.1). We did not compare the directions *forward* and *down* as these are not fully comparable due to differing input activities, as explained earlier and depicted in Figure 4.

All metrics just described focus on the "quality" of a user's interaction related to simple 3D interaction tasks. To gain additional information we however also measured an average time needed for each task with the HID and DIH settings but did not find any notable differences which is why we do not report it in detail in Section 5.4.

5 USER STUDY

This section describes research questions, methodology, participants and results of our comparative user study on HID and DIH settings. As described above, we conducted a pre-test before the actual study in order to configure the devices and ensure comparability.

5.1 Research Questions

The user study aimed at analyzing two aspects related to i) the users' interaction performance with DIH vs. HID interaction settings and ii) the user's better-performing interaction direction (left or right). The first aspect contributes to better understanding tangible interaction and related supporting and inhibiting factors, the second aspect contributes to better understanding users' non-individual interaction prerequisites and preferences.

Accordingly, we formulated hypotheses in order to investigate the aforementioned aspects of our research questions. They are listed below, followed by a discussion of how we arrived at them.

- H1: We expect users' *Reach* to be about equal with DIH and HID interaction.
- H2: We expect users' *Reach* to be high ($\geq 95\%$) for both settings and for all directions.
- H3: We expect users' *Regularity* to be better with the DIH interaction as we believe controllability to be higher being able to grab the device, holding on to it.
- H4: We expect users' *ContinuousRegularity* to be better with DIH interaction, again for reasons of better controllability holding on to the device.
- H5: We expect users to be better able to control their movement in the direction towards the body than away from the body (in our study, all participants were right-handed and used their dominant hand, thus the direction *left* is *towards the body* while *right* is *away from the body* for all users).

Regarding H1 and H2, we believe that for users without motor impairments (such as the participants of our study), the interaction space used for the study is well coverable. We did include the related metrics even if we do not expect significant insights here as we plan to do a subsequent analysis with people with motor impairments and aim at comparing the results.

Regarding H3 and H4 we believe that the stable hand-device posture and related better controllability leads to better regularity performance for both, single-direction tasks (*Regularity*) and continuous movement tasks (*ContinuousRegularity*).

Regarding H5, we found two interesting aspects in related literature that led to this hypothesis. First, (Rinck and Becker, 2007), e.g., describe a movement of an arm away from oneself as an action of "avoidance" (pushing unpleasant objects away) and a movement towards the body as an action of "approach" (pulling pleasant objects closer). Second, (Strasser and Müller, 1999) analyzed favorable movements of the hand-arm system (physiologically assessed by electromyographic investigation and subjectively rated by the participants in addition). They found out that the participants (who had to handle light weights) could perform a movement towards the body best while it was more uncomfortable the further it got away from the body. These findings are also confirmed by (McDonald et al., 2012) who analyzed muscle demands in horizontal pushing (away from the body) and pulling (towards the body).

5.2 Procedure and Methodology

The study followed a within-subjects design and took place in a controlled lab setting. The participants did all tasks described earlier with both settings. We used a counterbalanced order in which the settings were presented to the participants to prevent a bias related to practicing effects. Further, participants could try the devices and their handling as long as they wished so that the actual tests did not start before users felt ready. Also, all participants received a short introduction by a test supervisor who explained to them the input devices and techniques. The test supervisor was present during the full duration of the tests to be able to help in case of technical problems, to switch between the tasks and set up the input devices for the users. The results of the tests were automatically recorded and analyzed using the framework described in (Augstein et al., 2017b).

5.3 Participants

We recruited 24 volunteers aged between 20 and 49 (M=26.75, SD=8.38), 14 female. None of the participants had previous experiences with the interaction tasks or the concrete devices used (although some had generally used a joystick before). They were recruited via email as well as direct invitations. All were university students or staff and generally had high media skills related to input techniques and devices.

5.4 Results

This section discusses the results of the study based on the metrics related to *Reach*, *Regularity*, and *ContinuousRegularity*. The results for the metrics for all directions are listed in Table 1; Table 2 shows the aggregated results. To statistically analyze the respective difference between the HID and DIH settings, we conducted a T-Test on related samples (see Tables 1 and 2). The T-Test assumes data to be normally distributed which is violated by a small subset of our metrics. Thus we additionally conducted a Wilcoxon test for two related samples which does not presume normal distribution. It confirmed the results of the T-Test in all cases and suggested statistical significance for the same comparisons. As the T-Test is generally more reliable in the identification of statistical significance, we report the results of the T-Test here and used the Wilcoxon results for confirmation.

Additionally, we conducted a comparison of users' results with the same setting related to the directions left or right. This comparison was mainly aimed at the confirmation of hypothesis H5. The results of this direction-related comparison are reported in Table 3 where we list the outcome of a T-Test. We again subsequently conducted a Wilcoxon test which confirmed all occurrences of statistical significance.

5.5 Reach

As expected, the results show little variance for all *Reach*-related metrics and were about equally high (i.e., close to 100%) with HID and DIH interaction. As described earlier, we believe *Reach* to be of high relevance especially in cases where users' hand mobility is limited. The results confirm that there is no general barrier limiting the user's personal interaction space with any of the settings (which would lower the quality of user's interaction with the system and negatively affect also the results for other metrics).

5.6 Regularity

For *Regularity* we found significantly different results in two cases (see Table 1). Users gained significantly better results for *RegularityDown* with the DIH (i.e., joystick) setting. This finding is of limited reliability however, as the direction *down* is not fully comparable for the two settings as described earlier).

Further, users gained significantly better results for *RegularityLeft* with the HID (i.e., SpongeBox) setting. For the other comparisons (i.e., *RegularityForward* and *RegularityRight*), the differences were not statistically significant.

Table 1: Metrics and the computed values (all in percent) averaged for the 23 participants. The results are compared for the hand-in-device and device-in-hand settings. Bold values in the *sig* column denote statistical significance on the 0.05 (*) or 0.001 level (**).

Metric	**Result**		**T-Test**		
	mean	**stdev**	**t**	**df**	**sig**
ReachDown HID	100.0	0.00	1.282	22	.213
ReachDown DIH	98.55	5.42			
ReachForward HID	100.0	0.00	.	.	.
ReachForward DIH	100.0	0.00			
ReachLeft HID	100.0	0.00	1.367	22	.186
ReachLeft DIH	97.83	7.63			
ReachRight HID	98.19	4.99	-.463	22	.648
ReachRight DIH	98.19	5.21			
RegularityDown HID	53.22	43.21	-2.770	22	**.011***
RegularityDown DIH	75.32	20.88			
RegularityForward HID	82.11	33.65	1.848	22	.078
RegularityForward DIH	68.33	25.90			
RegularityLeft HID	93.64	14.83	3.328	22	**.003***
RegularityLeft DIH	73.56	24.51			
RegularityRight HID	70.93	35.32	-.167	22	.869
RegularityRight DIH	72.30	26.83			
ContinuousRegularityLeftForward HID	81.96	7.56	-2.969	22	**.007***
ContinuousRegularityLeftForward DIH	87.14	3.21			
ContinuousRegularityLeftDown HID	87.23	5.38	-1.105	22	.281
ContinuousRegularityLeftDown DIH	89.00	5.50			
ContinuousRegularityRightForward HID	74.72	5.01	-4.955	22	**.000****
ContinuousRegularityRightForward DIH	81.05	4.25			
ContinuousRegularityRightDown HID	83.05	12.17	-1.635	22	.116
ContinuousRegularityRightDown DIH	87.69	5.63			

Table 2: Aggregated metrics and the computed values (all in percent) averaged for the 23 participants. The results are compared for the hand-in-device and device-in-hand settings. Bold values in the *sig* column denote statistical significance on the 0.05 level (*).

Metric	**Result**		**T-Test**		
	mean	**stdev**	**t**	**df**	**sig**
Reach HID	99.55	.26	.914	22	.370
Reach DIH	98.82	.72			
Regularity HID	74.97	21.57	.566	22	.577
Regularity DIH	72.38	18.50			
ContinuousRegularityLeft HID	84.59	6.33	-2.309	22	**.031***
ContinuousRegularityLeft DIH	88.07	3.49			
ContinuousRegularityRight HID	78.88	7.36	-3.203	22	**.004***
ContinuousRegularityRight DIH	84.37	3.95			
ContinuousRegularity HID	81.74	6.66	-2.897	22	**.008***
ContinuousRegularity DIH	86.22	3.39			

Table 3: Comparison between the interaction directions left and right including all relevant metrics (all values in percent). The results are listed for the hand-in-device and device-in-hand settings. Bold values in the *sig* column denote statistical significance on the 0.05 (*) or 0.001 level (**).

Metric	**Result**		**T-Test**		
	mean	**stdev**	**t**	**df**	**sig**
ReachLeft HID ReachRight HID	100.0 98.19	.00 5.00	1.738	22	.096
ReachLeft DIH ReachRight DIH	97.83 98.91	7.63 5.21	-1.367	22	.186
RegularityLeft HID RegularityRight HID	93.64 70.93	14.83 35.32	3.101	22	**.005***
RegularityLeft DIH RegularityRight DIH	73.56 72.30	24.51 26.83	.200	22	.844
ContinuousRegularityLeftForward HID ContinuousRegularityRightForward HID	81.96 74.72	7.56 5.01	5.626	22	**.000****
ContinuousRegularityLeftForward DIH ContinuousRegularityRightForward DIH	87.14 81.05	3.21 4.25	6.069	22	**.000****
ContinuousRegularityLeftDown HID ContinuousRegularityRightDown HID	87.23 83.05	5.38 12.17	2.516	22	**.02***
ContinuousRegularityLeftDown DIH ContinuousRegularityRightDown DIH	89.00 87.69	5.50 5.63	2.580	22	**.017***
ContinuousRegularityLeft HID ContinuousRegularityRight HID	84.59 78.88	6.33 7.36	8.241	22	**.000****
ContinuousRegularityLeft DIH ContinuousRegularityRight DIH	88.07 84.37	3.49 3.95	5.760	22	**.000****

Regarding the aggregated *Regularity* metric as reported in Table 2 the differences were not statistically significant which generally was a bit surprising for us as we had expected users to be better able to control their movement with the DIH (i.e., joystick) setting. Regarding the comparison of the interaction directions *left* and *right*, the tests however did reveal significantly better results for the direction *left* with the HID setting (for the DIH setting the difference was not significant), compared to *right*.

5.7 ContinuousRegularity

Regarding *ContinuousRegularity*, the results were generally more conclusive (see Table 1). We found significant differences in the results for the metrics *ContinuousRegularityLeftForward* and *ContinuousRegularityRightForward* (for the latter, the differences were statistically highly significant). In both cases the users performed better with the DIH setting (joystick) which confirmed our expectations.

The results for *ContinuousRegularityLeftDown* and *ContinuousRegularityRightDown* were not significantly different as shown in Table 2 (however, in this case the comparability is generally limited anyway due to the strong influence of the *down* direction). Regarding the aggregated results, users gained significantly better results with the DIH setting (joystick).

Regarding the interaction directions *left* and *right*, we found statistically different results for all comparisons (see Table 3). For *ContinuousRegularityLeftForward* and *ContinuousRegularityRightForward* we found the direction *left* to be statistically highly significantly better than *right* for both settings. Also for the comparison of *ContinuousRegularityLeftDown* and *ContinuousRegularityRightDown left* was significantly better than *right* for both settings.

Here, the results are reliable although the direction *down* is involved as the device (and thus also input activity) remained equal within a comparison. The comparison of the aggregated *ContinuousRegularityLeft* and *ContinuousRegularityRight* results show a statistically highly significant difference for the HID as well as the DIH settings (with *left* outperforming *right* in all cases).

5.8 Findings Related to the Hypotheses

We summarize the results regarding our hypotheses as follows. The study **confirmed H1** and **H2** related to users' *Reach* as the results were not notably different for HID and DIH and about equally high ($\geq 95\%$) for all interaction directions with both settings. Inspecting the raw data, we found out that for the total of the users and for all settings and directions, only 8 of 184 (23*2*4) reported values were slightly lower.

H3 had to be **rejected** as we did not find significant differences between HID and DIH for *Regularity*. In fact, we found significantly better results for DIH interaction only for *RegularityDown* which is however of limited reliability. Unexpectedly, we found significantly better results with HID interaction for *RegularityLeft*, compared to DIH. For the rest of the comparisons there were no significant differences.

We could **confirm H4** as all highly reliable results (i.e., for the comparison of *ContinuousRegularityLeftForward* and *ContinuousRegularityRightForward*), as well as those for the aggregated metrics *ContinuousRegularityLeft*, *ContinuousRegularityRight* and *ContinuousRegularity* indicated a significantly better performance of users with the DIH setting, compared to the HID setting. The results for *ContinuousRegularityLeftDown* and *ContinuousRegularityRightDown* (which might be biased due to the involvement of the direction *down*) were better with the DIH setting as well for the majority of the users, however the difference was not statistically significant.

H5 was **confirmed** as all comparisons except for the aggregated *RegularityLeft* metric in the DIH setting, revealed statistically significantly or even highly significantly better results for the direction *left*.

6 DISCUSSION

In this paper we have compared users' interaction performance with isometric HID and DIH settings for simple 3D interaction tasks. Besides analyzing differences in interaction performance, we aimed at investigating differences between the interaction directions *left* and *right* for both settings, HID and DIH.

The study revealed that there are no significant differences between HID and DIH settings regarding users' *Reach*. This might lead to the assumption that the *Reach* metric is of limited relevance generally which we however want to argue against.

As shortly mentioned earlier, we believe that information about users' *Reach* is of utmost importance as a limited *Reach* can lead to a barrier that might inhibit users to be able to interact with predefined settings at all. We thus believe that especially when designing accessible UIs (including input devices and methods), a user's *Reach* should be analyzed and used to individually configure the UI in case it is considerably reduced for whatever reason. This was confirmed also by a user test with a small number of people with motor impairments we conducted earlier (Augstein et al., 2017a). Except for SpongeBox, this test used different devices and it was purposed to reveal insights regarding the importance of haptics for the target group. Thus the results are not comparable to those presented in this paper but they generally suggest that *Reach* differs more considerably among people with impairments.

Our study further revealed that regarding *Regularity*, the differences between HID and DIH settings were less conclusive than expected. For most related metrics, the differences between the results with the two settings were either not statistically significant or even significantly better with the HID setting (*RegularityLeft*). From these findings we derive that for simple one-directional interaction tasks users' *Regularity* is less dependent on a stable hand-device posture than expected.

Regarding *ContinuousRegularity* where users had to perform a more complex interaction task covering several interaction dimensions and directions, the study has shown that a stable hand-device posture actually had a positive impact on the users' performance. This was confirmed by the statistically significantly better results for all reliable and all aggregated *ContinuousRegularity* metrics with the DIH setting. We thus conclude that the positive influence of a certain hand-device stability is strongly dependent on the complexity of the interaction task (increasing with increasing task complexity).

Regarding the comparison of performance in the interaction directions *left* and *right* we derived our expectations from related research on favorable movements due to positive and negative associations as well as physiological prerequisites.

Literature research led to the assumption that for right-handed users, *left* is the better-performing interaction direction. The results of our study confirm this assumption, especially with increasing task complexity. Similarly, we assume that *right* is the better-performing direction for left-hand interaction, which we however could not confirm as all of our participants were right-handed and used their dominant hand for interaction.

Our study did not reveal cases where the HID setting seemed to be generally preferable over the DIH setting. We found little evidence for actual benefit people without known impairment might gain from HID interaction. Thus we believe that most users without impairments will prefer DIH over HID.

Limitations of our work reported in this paper are discussed as follows. First, our findings are restricted to relatively simple 3D interaction tasks and to isometric input devices. Our results have shown that task complexity influences several relevant aspects of interaction performance, thus for even more complex tasks (especially involving more DoF), they might be less reliable. We hence recommend analyzing interaction performance anew in case the findings should be generalized to more than three DoF.

Further, as explained earlier, the results related to the interaction direction *down* are less reliable due to the limited comparability of the related input activities. We reported these results for reasons of completeness in spite of this limitation but recommend relying only on those we suggested as conclusive.

Another limitation is that the interaction directions *up* and *back* were restricted to moving back to the initial position after having moved forwards or down in our user study.

Future work could include repeating the study with a different target group. We believe that the HID setting bears higher potential for people with limited hand mobility than for users without motor impairments affecting the interacting hand. Further, we believe that a similar study with devices offering more DoF will lead to interesting insights and expect it to confirm the trend regarding task complexity.

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