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Article

Controller-free Hand Tracking for Grab-and-place Tasks in Immersive Virtual Reality: Design Elements and their Empirical Study

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Abstract: Hand tracking enables controller-free interaction with virtual environments, which can, compared to traditional handheld controllers, make virtual reality (VR) experiences more natural and immersive. As naturalness hinges on both technological and user-based features, fine-tuning the former while assessing the latter can be used to increase usability. For a grab-and-place use case in immersive VR, we compared a prototype of a camera-based hand tracking interface (Leap Motion) with customized design elements to the standard Leap Motion application programming interface (API) and a traditional controller solution (Oculus Touch). Usability was tested in 32 young healthy participants, whose performance was analyzed in terms of accuracy, speed and errors as well as subjective experience. We found higher performance and overall usability as well as overall preference for the handheld controller compared to both controller-free solutions. While most measures did not differ between the two controller-free solutions, the modifications made to the Leap API to form our prototype led to a significant decrease in accidental drops. Our results do not support the assumption of higher naturalness for hand tracking but suggest design elements to improve the robustness of controller-free object interaction in a grab-and-place scenario.

Keywords: hand tracking; virtual reality; leap motion; oculus; user experience; interaction; immersion

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1. Introduction

Immersive Virtual Reality (VR) enables the user to "dive into" a computer-generated 3D environment. Scenarios in immersive VR are typically presented on a head-mounted display (HMD) that blocks out vision of the outside world and adapts the virtual environment based on the user's head movements, thereby enabling a sense of presence (i.e., a feeling of actually being in the virtual world despite knowing it to be an illusion [1,2]). The popularity of immersive VR has been increasing for a wide range of applications, for example for entertainment, education and industry but also research and clinical purposes [3]. Commercial VR systems (e.g., Oculus Rift, HTC Vive) enable interaction with virtual environments and objects (beyond head movements) typically by way of handheld controllers (e.g., the Oculus Touch). Such setups have been used, for example, for safety and equipment training in mining (e.g.,[4]) or manufacturing scenarios (e.g., [5]). In basic research, VR enables naturalistic (i.e., dynamic, multisensory, interactive) experiments while maintaining full experimental control and allowing precise measurements of the participant's behavior [6–9]. Effects found in such naturalistic experiments promise to generalize to real-world scenarios. The same features make VR a promising tool for clinical applications, where it could improve diagnostic precision and increase a therapy's transfer effects – the degree to which it improves the patient's life outside the clinic [10–12].

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1.1. Controller-free Object Interaction

Controllers, while necessary for interaction in gaming, can be cumbersome: they are extra equipment to carry and maintain, and they may require a learning period for those unaccustomed to this mode of interaction. Controller-free hand-tracking technology offers an alternative: it allows users to interact with virtual objects using their bare hands, and it decreases the amount of equipment as well as time to get acquainted with the interface. It can be assumed that interacting with objects in VR as one would in real life increases the intuitiveness and naturalness of interaction - and with it the efficacy and outcome of VR-based applications (e.g., the user's gain, safety and comfort). Camera-based interaction is also central to other immersive technologies like augmented reality (AR) or mixed reality (MR), which often do not provide controllers. In addition, controller-free interaction can increase the accessibility of VR technology for user groups that are unable or uncomfortable to use controllers (e.g., older adults, children or patients).

1.2. Controller-free Interaction with the Leap Motion

The Leap Motion is a small, lightweight optical sensor that uses infrared signals to detect hand and finger motions for camera-based, controller-free (i.e., contact- / touch-less) human-computer interaction [13]. It can be attached to the front of a VR HMD to detect the user's hands in immersive VR, and it provides a modifiable application program interface (API) and software development kit (SDK). Its feasibility and usability has been tested in various contexts (e.g., [5,10,14–16]).

Other sensors that allow hand tracking, like the Microsoft Kinect, take an "outside in" approach [17] by positioning the camera to face the user, thus requiring additional setup in the room. Data gloves (e.g., by Manus VR: https://www.manus-vr.com/) can be used for gesture recognition and may include haptic feedback, but, like controllers, they come with the disadvantages of additional equipment.

1.3. Design Challenges to Hand Tracking

Challenges when using a hand-tracking interface in VR (e.g., the Leap Motion) include that detection errors can occur when the user's hands are occluded, which typically happens more often with camera-based than with controller-based position tracking. In contrast to, for example, the Oculus Touch controller, the Leap Motion (being attached to the VR HMD) also requires the user to direct the head towards the hands, so that they are within the field of view. In addition, without additional haptic (e.g., vibro-tactile) feedback, the sense of touch provides no information about virtual objects [2,16]. Through this absence of feedback and the type of gestures, camera-based interaction does not fully resemble hand-based object interaction in the real world, which may require some time to get acquainted with it. While one cannot control a user's prior experience with a technology, a well-designed interface can make an unfamiliar technological experience more intuitive [18].

1.4. Our Prototype

For the use case of grabbing and placing objects in an immersive VR scenario (i.e., with the Leap Motion attached to the VR HMD), we modified the basic Leap API. The following design elements were introduced, based on our own experiences and previous studies:

- Smart object colouring (a green "spotlight" emitted from the virtual hand) to indicate when an object is in grabbing distance. Color indicators on the virtual hand, the virtual object or both have been shown to improve time on task, accuracy of placement and subjective user experience [5,14,15].
- The user can only grab the object after first making an open-hand gesture within grabbing distance of the object, in order to prevent accidental grabs
- Semi-transparent hand representation as long as no object is grabbed, to allow the user to see the object even if it is occluded by the hand

- The grabbing area is extended so that near misses (following an open hand gesture, see above) are still able to grab the object
- If the hand is moving above a certain velocity, grabbing cannot take place, in order to prevent uncontrolled grabs and accidental drops)
- Once the object is released from the hand, rogue finger placement cannot alter the trajectory of the falling object
- Audio feedback occurs when an object is grabbed and when an object touches the table surface after release (pre-installed sounds available in the Unity library)

1.5. Present Study and Hypotheses

In this study, we assessed the usability of camera-based object interaction for a grab-and-place use case in immersive VR, which is common in VR-based rehabilitation and industry applications. We modified the basic implementation of Leap Motion-based hand tracking and created the HHI_Leap prototype (described above). We then compared it to the basic Leap Motion (B_Leap) and the Oculus Touch controller. Performance was evaluated along measures of accuracy, speed and errors (accidental drops) as well as subjective experience (self-report questionnaires).

1.5.1. Hypotheses

Based on the literature and our own experiences, we had the following hypotheses:
HHI_Leap vs. Oculus

1. Performance measures: The HHI_Leap shows lower accuracy (greater distance from target), higher times (total time, grab time and release time) and more errors (accidental drops) than the Oculus controller.
2. Subjective measures: The HHI_Leap is rated higher than the Oculus controller for naturalness and intuitiveness. For all other subjective measures (other individual ratings, SUS, overall preference), we did not have hypotheses (exploratory analyses).

HHI_Leap vs. B_Leap

1. Performance measures: The HHI_Leap shows higher accuracy (greater distance from target), lower times (total time, grab time and release time) and fewer errors (accidental drops) than the B_Leap.
2. Subjective measures: The HHI_Leap is rated higher than the B_Leap on all subjective measures (individual rating questions, SUS, overall preference).

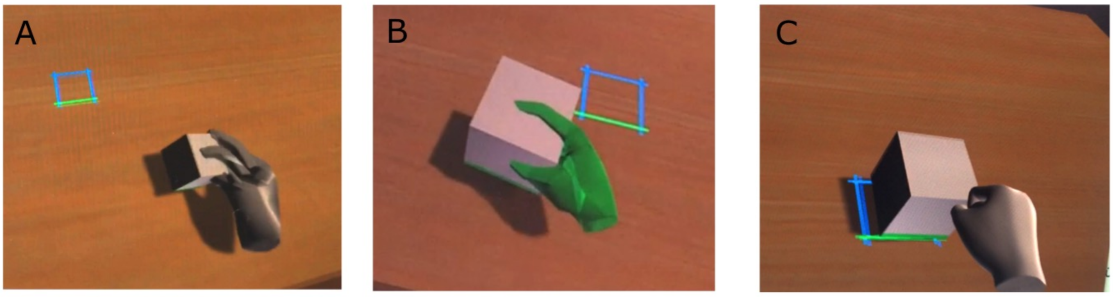
2. Methods

2.1. Study design

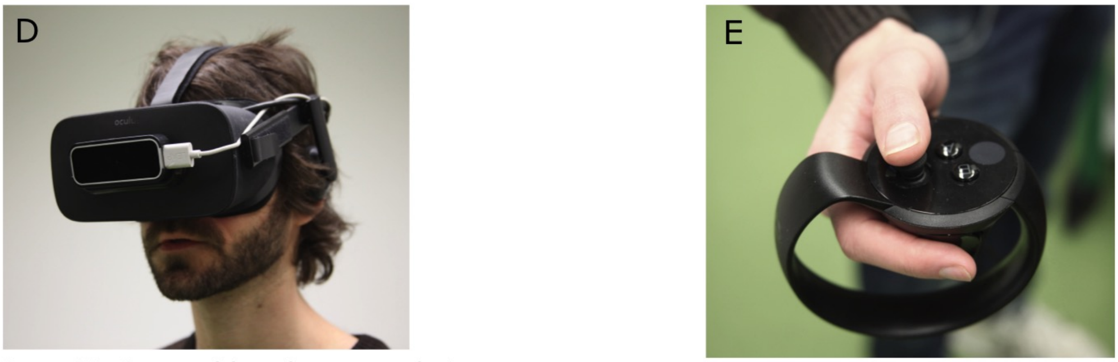
In a repeated-measures design with interface (B_Leap, HHI_Leap, Oculus controller) as the independent variable (Figure 1), all participants completed the task with all interfaces in randomized order. Performance was measured during the task, and participants answered questions about their experience after each interface (Figure 2).

2.2. Sample

Participants were recruited from staff at the Fraunhofer Heinrich Hertz Institute who were not involved in this research project. Exclusion criteria were injuries or vision impairments that would prevent them from completing the task. The sample comprised 32 participants (23 males, 8 females, 1 undisclosed) between 22 and 36 years of age ($M = 27.8$, $SD = 3.34$). The majority of participants ($n = 20$) reported "no" ($n = 10$) or "some" ($n = 10$) prior experience with VR. All participants ($n = 32$) reported at least "some" prior experience with video game controllers and half of the participants ($n = 16$) reported "frequent" current use of electronic games (including mobile phone games).



B_Leap HHI_Leap Oculus



Leap Motion and head-mounted visor Oculus Touch controller

Figure 1. Virtual representations of the hands for (A) basic Leap Motion (B_Leap), (B) modified Leap Motion (HHI_Leap), and (C) Oculus Touch handheld controller (Oculus); (D) mounted Leap Motion sensor; (E) Oculus Touch handheld controller

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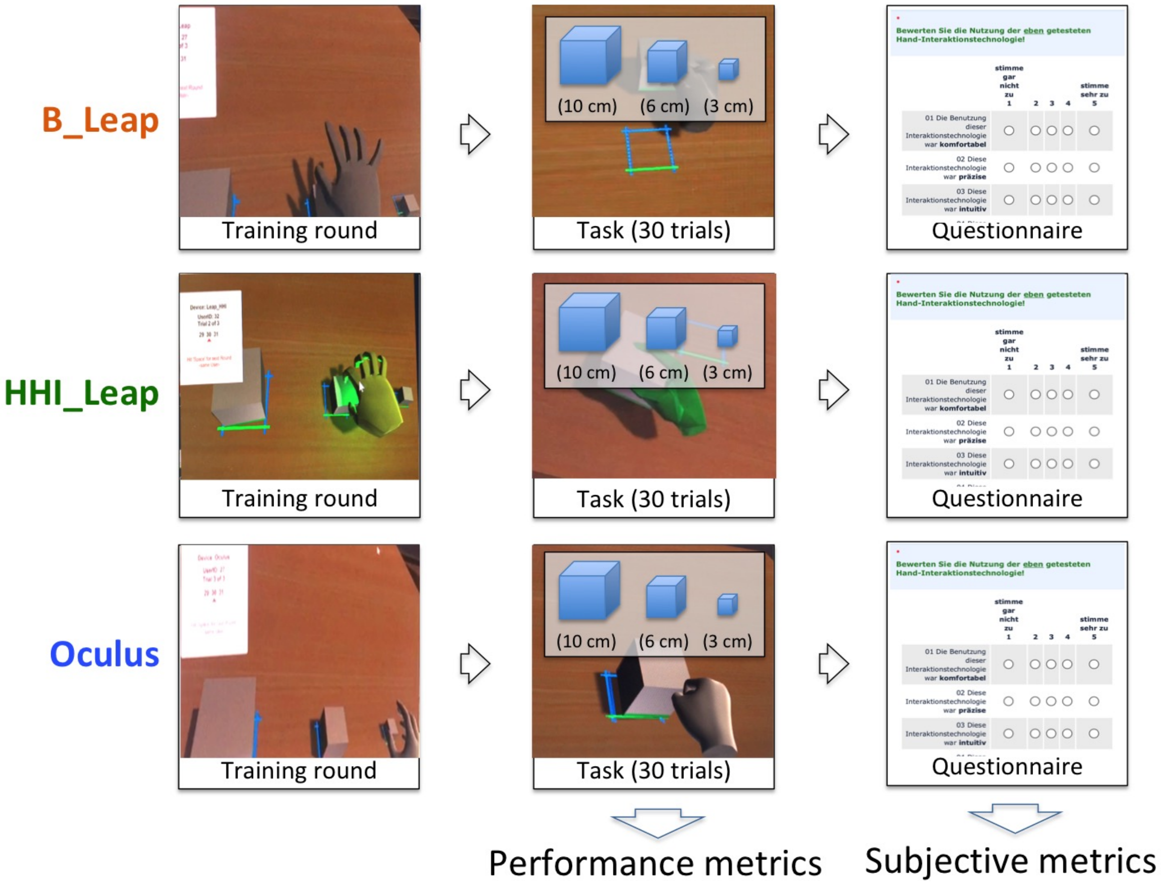

Figure 2. Study design: after a training / practice round (left column), the task (middle column) and questionnaires were completed (right panel). Interfaces (order randomized across participants): B_Leap = basic Leap Motion, HHI_Leap = modified Leap Motion, Oculus = Oculus Touch handheld controller.

Figure 3. Participant engaging in task (front view of one of the Leap Motion trials)

2.3. Task

Participants completed a virtual grab-and-place task, in which they had to place virtual cubes, one at a time, onto a target area on a virtual table (Figure 2). In 30 trials per interface (B_Leap, HHI_Leap, Oculus), 10 cubes of 3 different sizes (small: 3 cm; medium: 6 cm; large: 10 cm) were presented in random order. In each trial, the cube appeared randomly at one of 10 positions at 30 cm from the target (Figure 4). Participants used their dominant hand to place each cube as quickly and accurately as possible onto a target, which consisted of a 2D square the size and shape of one face of the cube (Figure 1). After grabbing the cube, the participant had one chance to place it on the target; they could not adjust the cube once it made contact with the table.

2.4. Measures

2.4.1. Performance measures

- Accuracy: Euclidean distance, in meters, from the 2D center of the bottom face of the cube to the center of the target square.
- Total time per trial: Time from cube spawn (appearance on the table) until the time the cube made contact with the table after having been picked up; equal to the sum of the following two time measures (grab and release time).
- Grab time (time from spawn to grab): Time from when the cube appeared on the table to the time it was grabbed.
- Release time (time from grab to placement): Time from when the cube was grabbed to the time the cube made contact with the table after being released.

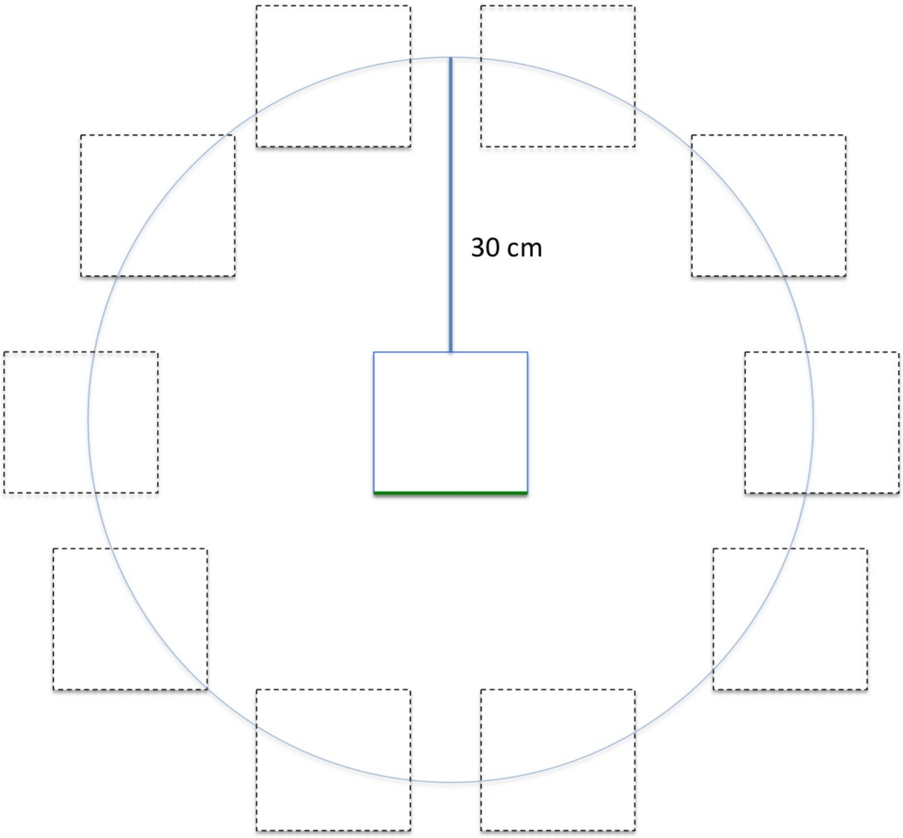

Figure 4. Diagram of target and cube spawn positions: cubes spawned (appeared) at one of 10 positions located 30 cm from the target

- Accidental drops: Prematurely terminated trials due to mistakenly dropping the cube (for details see below); used for both cleaning the data and as additional outcome measure to quantify interface performance.

2.4.2. Subjective experience measures

- System Usability Scale (SUS): A "quick and dirty" (Brooke, 1996) questionnaire to assess the usability (primarily "ease of use") of any product (e.g., websites, cell phones, kitchen appliances). It contains 10 items with 5-point Likert-scale response options from 1 (strongly disagree) to 5 (strongly agree). Responses are transformed by a scoring rubric, resulting in a score out of 100.
- Single subjective questions: 8 questions assessing user experience (i.e., comfort, ease of gripping, likelihood to recommend to friends) with Likert-scale response options ranging from 1 (strongly disagree) to 5 (strongly agree).
- Agency: The feeling of control over and connectedness to (a part of) one's own body or a representation thereof [19] was measured with the question "I felt like I controlled the virtual representation of the hand as if it was part of my own body" [15]. Response options ranged from 1 (strongly disagree) to 7 (strongly agree).
- Overall satisfaction on a Kunin-scale: Response options ranged from 1 (least satisfied) to 7 (most satisfied) with smiley faces representing degree of overall satisfaction [20]).
- Overall preference: After the participants completed all 3 interfaces, they answered the question "Of the three interfaces you used, which did you like best?"

2.5. Data cleaning / pre-processing

Accidental drop trials were removed before calculation of other performance metrics, using the following method:

A trial was considered an accidental drop if it fulfilled at least one of three criteria:

1. the experimenter noted that the participant accidentally dropped the cube before getting a chance to place it on the target,
2. release time below 0.5 seconds *and* accuracy above 10 cm
3. accuracy above 20 cm

Trials with accidental drops (8 %: 233 of 2880 trials in total) were removed from the analysis (199 according to criterion 1, of which 168 also fulfilled criterion 2 or 3; 34 fulfilled criterion 2 or 3 but not criterion 1). Hence, 2647 trials entered the analyses of performance.

2.6. Analysis

For each metric, a one-way repeated-measures analysis of variance (ANOVA) with the three-level factor "interface" (B_Leap, HHI_Leap, Oculus) was conducted. For all statistical tests, a two-sided alpha of .05 was used to determine significance. In case of significance in the ANOVAs, paired t-tests were conducted between the HHI_Leap and the other two interfaces (we were not interested in the comparison between the B_Leap and Oculus). Multiple-comparison correction (for the two comparisons), was performed using the Holm-Bonferoni method [21]. For measures of central tendency, we used means and 95% confidence intervals.

The analysis was conducted in R (v. 1.2.5) using the following packages: readr v. 1.3.1, readxl v. 1.3.1, tidyverse v. 1.3.0, dplyr v. 0.8.3, ggplot2 v. 3.2.1, see v. 0.3.0, cowplot v. 1.0.0, lsr v. 0.5, ggpubr v. 0.2.4, car v. 3.0-84 and rstatix v. 0.3.0. The R code can be found at https://github.com/alexmasurovsky/leap-vr-ux-study/blob/new_analysis/data_analysis.Rmd.

In the plots, asterisks indicate (Holm-adjusted) p-values: * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

3. Results

3.1. Performance measures

Table 1. Results of one-way repeated-measures ANOVAs comparing performance measures between interfaces (B_Leap, HHI_Leap, Oculus). For post-hoc comparisons, see Table 2.

Performance Measures Measure	df_n	df_d	F	p	η_p^2
Accuracy	2	62	41.711	p <.001	0.574
Total Time	2	62	36.619	p <.001	0.542
Grab Time	2	62	29.057	p <.001	0.484
Release Time	2	62	30.342	p <.001	0.495
Accidental Drops	2	62	44.383	p <.001	0.589
Subjective Measures Measure	df_n	df_d	F	p	η_p^2
SUS	2	62	7.132	0.002	0.187
Comfortable	2	62	7.911	p <.001	0.203
Precise	2	62	27.921	p <.001	0.474
Intuitive	2	62	0.198	0.821	0.006
Tiring	2	62	0.012	0.989	0.0004
Gripping	2	62	23.420	p <.001	0.430
Releasing	2	62	25.571	p <.001	0.452
Natural	2	62	1.608	0.209	0.049
Recommend	2	62	6.556	0.003	0.175
Agency	2	62	1.602	0.21	0.049
Satisfaction	2	62	5.901	0.005	0.160

There were significant main effects of interface for all performance measures (Table 1), which were driven by the Oculus controller performing significantly better than the HHI_Leap on all performance metrics (Table 2). No significant differences were found between the HHI_Leap and B_Leap for accuracy or total time per trial. The grab time with the HHI_Leap was significantly longer than with the B_Leap by 0.22 seconds on average (Figure 5). Release time with the HHI_Leap was significantly shorter than with the B_Leap by 0.27 seconds on average (Figure 6). With the HHI_Leap, significantly fewer accidental drop errors occurred than with the B_Leap, with a difference of 2.34 drops on average (Figure 7).

3.2. Subjective measures

3.2.1. System Usability Scale (SUS)

There was a significant main effect of interface for SUS scores (Table 1). This effect was driven by the Oculus controller as the paired-samples t-test comparing the HHI_Leap showed that their SUS scores were not significantly different (Table 2, Figure 8). Scoring guidelines for the SUS [22] put both Leap interfaces at the border (score = 70) of "acceptable" and "marginal." SUS scores for the HHI_Leap were significantly lower than for the Oculus controller (Table 2).

3.2.2. 5-point Likert Scale Questionnaire Items

ANOVA found significant main effects for Interface on ratings of comfort, precision, gripping, releasing and likelihood to recommend (Table 1). These effects were driven by differences between the HHI_Leap and Oculus, as post-hoc paired-samples t-tests showed no significant difference between the HHI_Leap and the B_Leap (Table 2, Figure 9). All 5-point Likert question ratings were lower for the HHI_Leap than for the Oculus controller, and paired-samples t-tests showed that ratings were

Table 2. Results of post-hoc paired t-tests, comparing performance and subjective measures for HHI_Leap and Oculus (top) as well as HHI_Leap and B_Leap (bottom).

Performance Measures	HHI_Leap		Oculus				
Measure	*M*	*SD*	*M*	*SD*	*t*	*df*	*p*(Holm)
Accuracy (m)	0.0158	0.0081	0.0071	0.0038	7.1268	31	p <.001
Total Time (s)	3.5145	1.3465	2.2705	0.753	7.8842	31	p <.001
Grab Time (s)	1.573	0.6522	0.9462	0.2479	6.9393	31	p <.001
Release Time (s)	1.9416	0.8561	1.3243	0.5745	6.7013	31	p <.001
Accidental Drops (#)	2.4062	2.0924	0.125	0.336	6.2427	31	p <.001
Subjective Measures	HHI_Leap		Oculus				
Measure	*M*	*SD*	*M*	*SD*	*t*	*df*	*p*(Holm)
SUS	70.4688	18.8418	82.3438	14.7416	-2.6887	31	0.022
Comfortable	3.375	1.1	4.156	0.92	-3.0886	31	0.008
Precise	2.594	0.875	4.156	0.92	-6.4689	31	p <.001
Gripping	3.094	1.174	4.406	1.073	-5.2133	31	p <.001
Releasing	2.781	1.099	4.406	1.073	-6.1393	31	p <.001
Recommend	3.375	1.238	4.094	0.928	-2.6592	31	0.025
Satisfaction	5	1.047	5.594	0.875	-2.4615	31	0.039
Performance Measures	HHI_Leap		B_Leap				
Measure	*M*	*SD*	*M*	*SD*	*t*	*df*	*p*(Holm)
Accuracy (m)	0.0158	0.0081	0.0154	0.0052	0.2934	31	0.771
Total Time (s)	3.5145	1.3465	3.5661	1.5687	-0.2926	31	0.772
Grab Time (s)	1.573	0.6522	1.3543	0.4097	2.2529	31	0.032
Release Time (s)	1.9416	0.8561	2.2118	1.2365	-2.3171	31	0.027
Accidental Drops (#)	2.4062	2.0924	4.75	2.6761	-3.8627	31	p <.001
Subjective Measures	HHI_Leap		B_Leap				
Measure	*M*	*SD*	*M*	*SD*	*t*	*df*	*p*(Holm)
SUS	70.4688	18.8418	69.9219	18.8418	-0.1871	31	0.853
Comfortable	3.375	1.1	3.438	0.982	-0.3117	31	0.757
Precise	2.594	0.875	2.438	1.076	0.5958	31	0.556
Gripping	3.094	1.174	2.875	1.129	0.9088	31	0.37
Releasing	2.781	1.099	2.594	1.214	0.641	31	0.526
Recommend	3.375	1.238	3.344	1.096	0.1664	31	0.869
Satisfaction	5	1.047	4.844	1.081	0.776	31	0.444

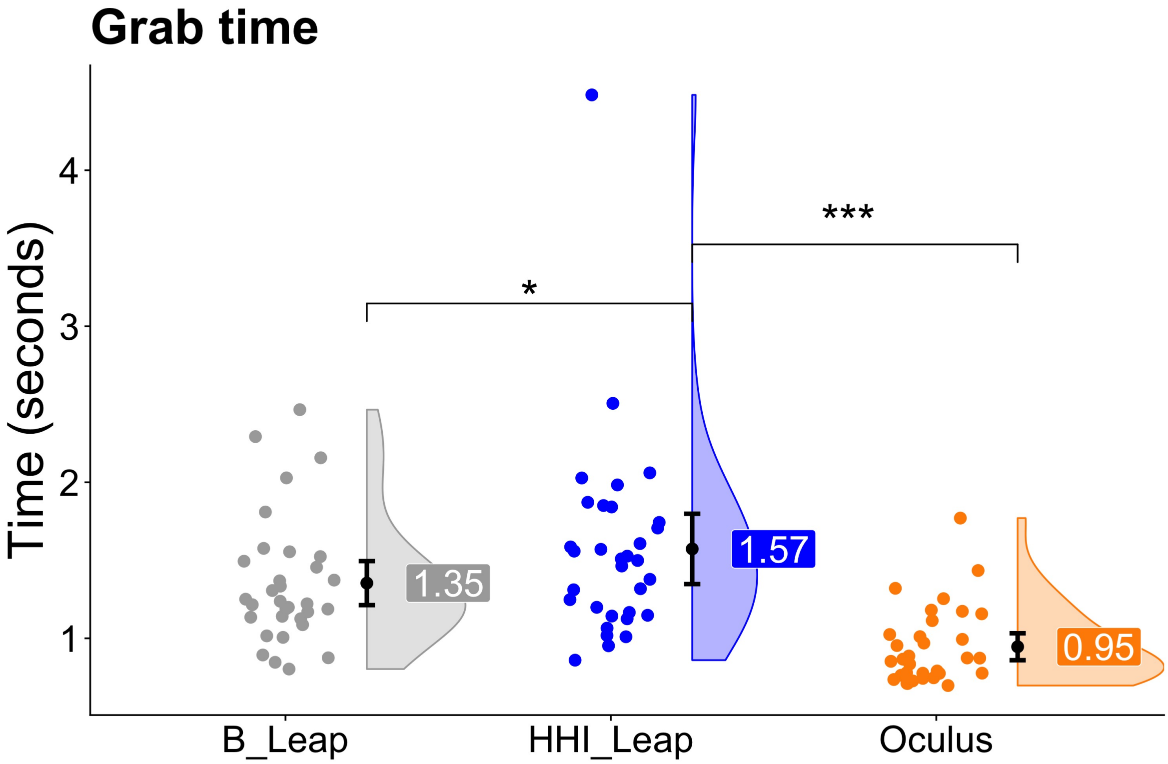

Figure 5. Grab time by interface, with means and 95% confidence intervals, individual participant times (colored dots), smoothed density distributions and results of paired-samples t-tests

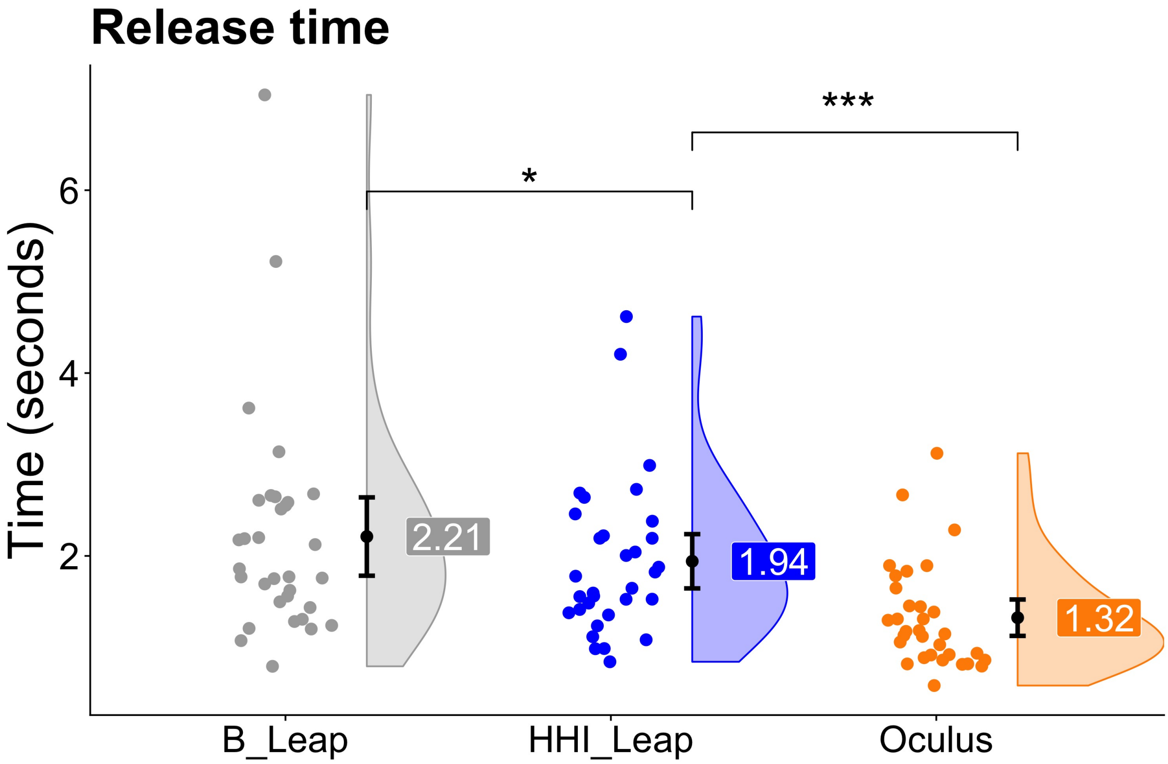

Figure 6. Release time by interface, with means and 95% confidence intervals, individual participant times (colored dots), smoothed density distributions and results of paired-samples t-tests

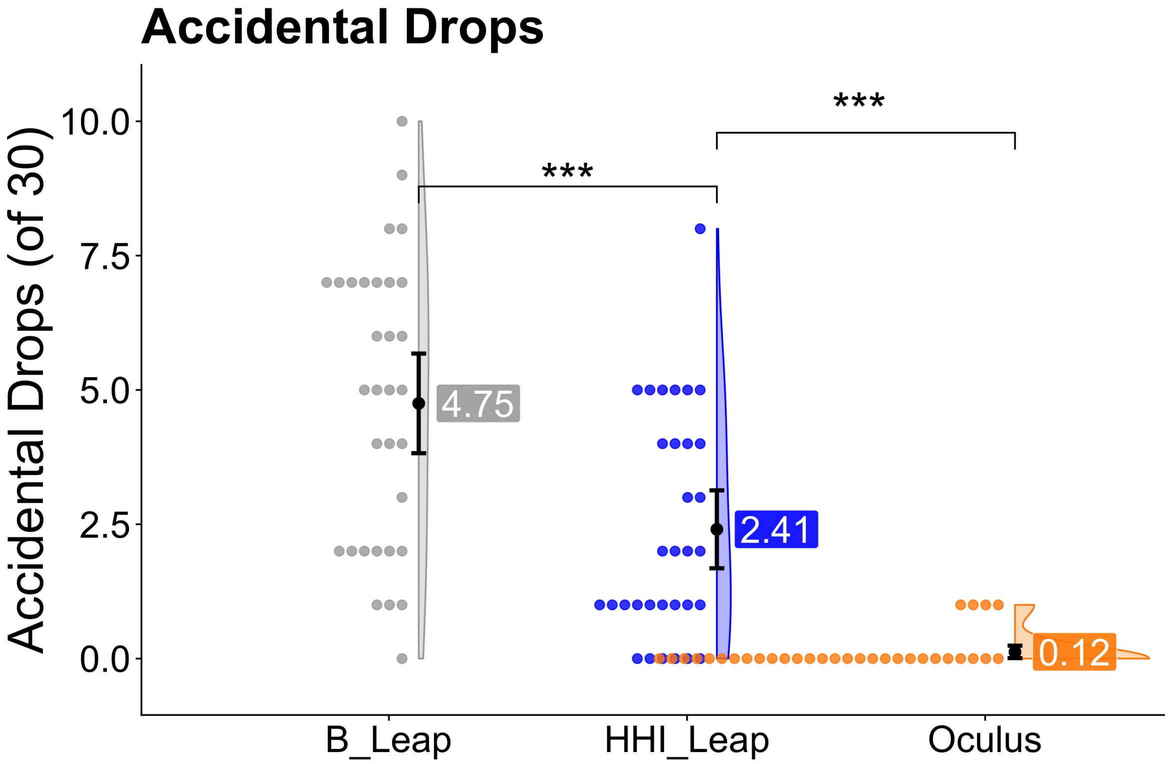

Figure 7. Accidental drops by interface, with means and 95% confidence intervals, individual participant counts (colored dots), smoothed density distributions and results of paired-samples t-tests

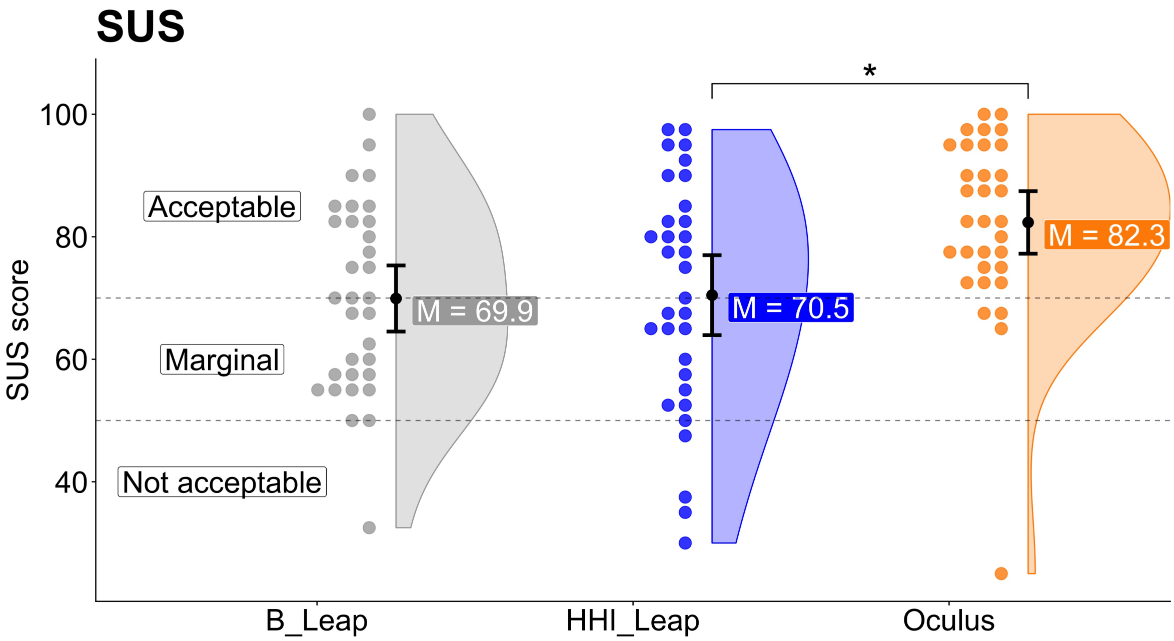

Figure 8. Usability scores (System Usability Scale, SUS) by interface, with means and 95% confidence intervals, individual participant scores (colored dots), smoothed density distributions, results of paired-samples t-tests and scoring categories [22]

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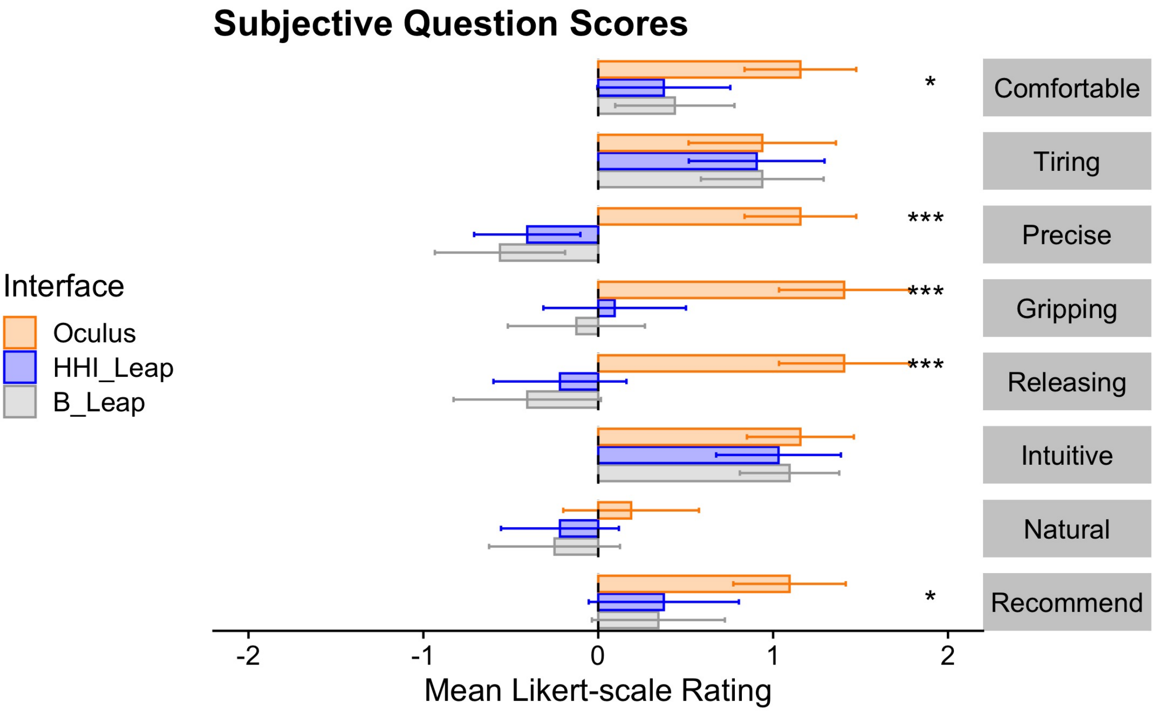

Figure 9. Mean scores for subjective questions, converted to a scale of -2 to 2, with 95% CI. * = p < .05, *** = p < .001. All significant differences are between Oculus and HHI_Leap.

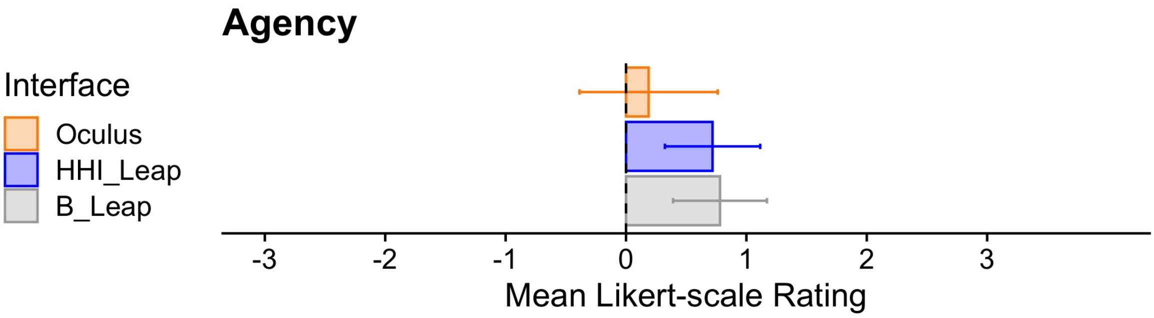

Figure 10. Mean scores for Agency, converted to a scale of -3 to 3, with 95% CI.

significantly lower for the HHI_Leap than the Oculus on comfort, gripping, releasing, precision and likelihood to recommend (Table 2, Figure 9).

3.2.3. Agency

ANOVA found no significant effect of interface on ratings of Agency (Table 1, Figure 10).

3.2.4. Overall Satisfaction

ANOVA found a significant main effect of interface on ratings of Overall Satisfaction (Table 1). Post-hoc paired-samples t-tests showed a significant difference between the Oculus and HHI_Leap (Table 2, Figure 11).

3.2.5. Overall Preference

Out of the 32 participants, 18 selected the Oculus controller as their overall preferred interface, 7 selected the HHI_Leap and 7 selected the B_Leap.

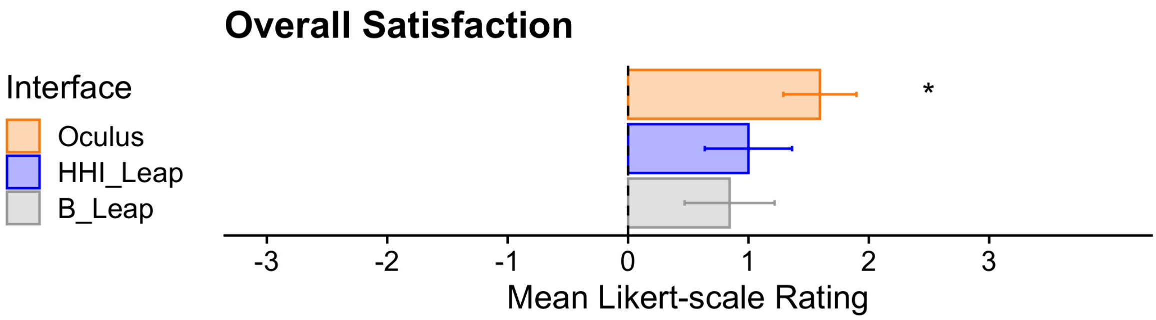

Figure 11. Mean scores for Overall Satisfaction, converted to a scale of -3 to 3, with 95% CI. * = p < .05. Significant difference is between Oculus and HHI_Leap (see Table 2)

4. Discussion

4.1. Comparing Hand Tracking to the Traditional Controller

For a grab-and-place task in immersive VR, we empirically compared a prototype of a camera-based (Leap Motion) hand tracking interface with customized design elements (HHI_Leap) to the standard Leap Motion API (B_Leap) and the Oculus Touch controller (Oculus). Usability was tested in terms of performance (accuracy, speed, errors) and subjective experience (e.g., comfort, naturalness, precision). The traditional controller (Oculus) outperformed both the HHI_Leap and the B_Leap on all performance metrics. Subjective ratings were significantly higher for the Oculus for ease of use (as measured by the SUS) as well as gripping, releasing, precision, comfort, likelihood to recommend, and overall satisfaction. For the remaining subjective dimensions, there were no significant differences between the Oculus and HHI_Leap. Because the HHI_Leap enabled bare-hand interaction, we hypothesized participants would rate the HHI_Leap higher on naturalness and intuitiveness. The absence of significant differences on these ratings between the HHI_Leap and Oculus controller could be because of unfulfilled user expectations about the capabilities of hand tracking (see [23] and [24] for voice interfaces). Technological limitations with mapping the virtual to the real hand and the responsiveness of the Leap Motion system may have lowered feelings of naturalness [16] as well as the related dimension of agency: even small differences between the user’s intended hand gesture and how the virtual hand actually behaves can lower the sense of agency [19,25,26]. For some users, the HHI_Leap and the B_Leap may also have created an uncanny valley effect [27,28], in which the similarity to reality results in the VR experience feeling highly unsettling. Argelaguet et al.[15] found that less realistic virtual hand avatars created higher feelings of agency. Another factor may be that *any* haptic feedback may support perceived naturalness: Users may have found it unnatural to manipulate objects with their hands without the sense of touch. Combining the Leap Motion with a haptic feedback device can create stronger feelings of presence and immersion than the Leap Motion on its own [1]. Though the Oculus controller did not map haptic feedback to interaction with virtual objects, it was itself a physical object, with buttons to press to engage in interaction. Participants may have responded positively to this minimal amount of tactile sensation when interacting with virtual objects.

4.2. Comparing Our Hand Tracking Prototype (HHI_Leap) to the Basic API (B_Leap)

Performance metrics showed that the HHI_Leap improved upon the B_Leap by reducing errors (accidental drops), while being slightly slower for grabbing (grab time), slightly faster for placing (release time), and not significantly different in accuracy or total time per trial. Increased grab time can be explained by the modification of the HHI_Leap, which required users to hover with the hand over the object before grabbing was possible (see section 1.4 for a list of specifications to our prototype). Although the measure to prevent unintentional gripping led to an increase in grab time, the total time for the task remained the same, as the release time was correspondingly shorter. The additional features of HHI_Leap (compared to B_Leap) against unintentional gripping and unintentional dropping during fast movements may explain the reduced errors. Specifically, these features were the prevention of grab recognition when the hand was moving too fast and the prevention of rogue fingers from altering the trajectory of the cube after release. While subjective scores were slightly higher overall for the HHI_Leap on ease of use (as measured by the SUS, Figure 8) and individual questions (Figure 9), we found no significant differences between the HHI_Leap or the B_Leap on any subjective experience measure.

4.3. Limitations and Recommendations for Future Research

As our sample was relatively homogeneous, the results may not generalize - for example to particular populations that might use VR in clinical settings, such as older adults or patients. While previous VR experience among our sample was low, video game experience was high, which might have increased familiarity with video game controllers and prepared our participants for use of the Oculus controller. Familiarity generally increases affinity [29] and has been shown to increase user satisfaction and performance for interfaces [24].

In addition, users may have had expectations for hand tracking based on cultural phenomena, such as science-fiction films (e.g., Minority Report (2002)) [23], which may have been their only source of their mental models ([18,30] for such an interface. If expecting a highly fluid experience like in the movies, participants would be disappointed by the performance of the Leap Motion, which may have led to lower ratings. We recommend future research efforts to assess expectations and prior experience that may be a factor in observed usability.

5. Conclusions

Our study forms a basis for determining the state of the art of a flexible, common implementation of a hand tracking VR interface by comparing it to a traditional VR controller, on a task representative of the types of motions found in VR applications. The traditional controller provided better overall usability than the hand tracking interface, as evidenced by performance and subjective metrics. On individual questions, however, the only significant differences were on questions related to performance, and the hand tracking interface was rated as acceptable (within 1.1 standard deviations from the middle rating; see Table 2, Figure 9) on all subjective items except for those assessing performance. For tasks that involve grabbing and placing, where high accuracy and quick grabbing are not the main focus, hand tracking can be a viable alternative, especially given the flexibility of the Leap API. Our customization improved the performance of the Leap Motion on the dimension of release time and accidental drops. Our results do not support the hypothesis of higher naturalness for hand tracking in its current state over traditional controllers.However, as familiarity with hand tracking in the general population increases and technical issues are progressively overcome, this may change.

Supplementary Materials: Data and analysis files are available at https://github.com/alexmasurovsky/leap-vr-ux-study/tree/new_analysis.

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Abbreviations

The following abbreviations are used in this manuscript:

AR	Augmented reality
HMD	Head mounted display
MDPI	Multidisciplinary Digital Publishing Institute
MR	Mixed reality
VR	Virtual reality

Appendix A

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