Tool-based Interaction for Precise Manipulation in VR: an Exploratory Study

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ABSTRACT

Virtual Reality-based interactions are getting more mainstream in several domains, such as gaming, education, and training. While there is extensive literature on new interaction techniques, applying and recombining these for specific tool-based interactions remains challenging. We specifically look at promising VR manipulation techniques using controllers. We implemented these techniques in a proof-of-concept toolchain aimed at spray painters. We extracted and manipulated the relevant parts for a controlled within-subject comparative experiment with 16 participants. We find, among other things, that, as in direct manipulation, tool-based interaction with controllers in VR can benefit from zoom and separation of degrees of freedom to achieve effective and efficient manipulation.

CCS CONCEPTS

• **Human-centered computing** → *Empirical studies in interaction design.*

KEYWORDS

Virtual reality, Tool-based interaction, Accurate manipulation; UX; Zoom; Haptic feedback

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1 INTRODUCTION

Virtual Reality (VR) has found its value in diverse domains, including production, maintenance, and assembly [30], and medical [3], welding [16] , safety [27] and space training [28]. Interaction in VR usually happens through motion-based controllers allowing the user to perform certain actions more naturally [1]. Within the context of tool-based interaction for VR — interaction with objects (at a distance) through virtual tools [36] —, research has shown the benefits of using these controllers [29]. However, adapting and recombining existing interaction techniques to meet the needs and system goals remains challenging. In an industrial context, an appropriate mapping with the real world is crucial to avoid losing context. Also, precise manipulation in VR is challenging given the multiple degrees of freedom (DoF) [32] and the usually limited physical space available [34]. We focus on the former, more specifically on two research questions:

1. Can zooming and haptic feedback improve the accuracy of tool-based interaction in VR?
2. Do these techniques impact (perceived) usability, user experience, and workload?

We performed an exploratory study on the impact of interaction techniques on precise manipulation in VR. We investigate adaptations of existing manipulation techniques (e.g. separating the DoF for direct manipulation in VR) and common interaction techniques (e.g. buttons, zoom, haptic feedback) for tool-based interaction in VR. This paper thus makes the following contributions:

- The impact of common interaction techniques (e.g. seperating the DoF, zoom, haptic feedback) on workload and performance (e.g. accuracy) for precise manipulation in VR
- User experience and preferences for tool-based interaction with controllers for precise manipulation in VR

Finally, we describe the results, present guidelines and discuss what both mean for future research. We believe that the results of this exploratory study can inform future research for precise manipulation of tool-based interaction in VR.

2 RELATED WORK

Manipulation in Virtual Reality. Mendes et al. [23] composed a survey of 3D virtual object manipulation for desktop, touch, and mid-air interaction. Most of the reviewed techniques used 6 DoF tracking for two hands with rotation and translation performed simultaneously. Widgets [24] is a notable exception that separates translation and rotation and thus only needs 3 DoF and one hand at the same time without a performance penalty. They reported increased accuracy of single DoF manipulation at the expense of increased task times. Caputo [7] provided a one-handed variant that had similar performance and was preferred by participants because of its one-handed nature. Our work fits in one of the open challenges Mendes et al. [23] reported; the exploration of adjustable DoF control. Mendes et al. [23, 24] formulated design guidelines for mid-air object manipulation. Lee et al. [20] extended the Widgets approach that uses up to two hands and controllers to manipulate an

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object at a distance. Their approach also allows constraining input to a specific direction or plane. One-handed manipulation showed better performance while two-handed interaction was preferred. Dewez et al. [9] recently reviewed interaction techniques with a focus on avatar-friendliness and the influence of different aspects of manipulation on embodiment sentiment. They derived several guidelines on using input devices, control, and feedback. We strived to apply these guidelines in our application (section 3). Similar to Mendes et al. [23, 24], Dewez et al. see the separation of DoF for manipulation still as a research track.

Hayatpur et al. [15] used bi-manual gesture commands instead of widgets to manipulate objects. They limit degrees of freedom to planes, rays, and points. Participants had to permanently indicate the constraint direction prohibiting them from putting their non-dominant hand in rest-position. We want to avoid this issue in our menu-based approach. Caggianese et al. [5] compared the use of the Vive controller versus the Leap Motion, which allows mid-air hand tracking. They concluded that using the Vive was faster and had a lesser perceived difficulty. They observed difficulties when managing different DoF at the same time. Reski et al. [29] noted a preference for visual indicators of control (hands or controllers) but found no consistent preference between hand-held control or hand tracking in a free exploration task. A more recent study [33] compared the Vive controller, the Leap Motion, and a data glove using a Lego assembly task in VR. In this case, the Vive was faster and had less grabbing errors, albeit less accurate for placement orientation (but within the snapping range). Lao et al. [19] explored the idea of attribute spaces to manipulate objects in VR. While their focus was on a concrete application, some participants noted some things we believe are essential to consider; streamlining the interface (no complex combinations of widgets) and unconstrained mid-air movement might lead to accuracy issues, consistent with Mendes et al. [23, 24].

Tool-based interaction for Virtual Reality. Using appropriate input devices for interaction in VR is essential, given the realistic and immersive characteristics of VR scenes. Also, controllers consist of suitable characteristics for tool-based interaction in VR given its physical and virtual presence, its continuous as well as discrete input possibilities [29]. Ove Beese et al. [1] compared the Vive controllers with Valve Index controllers for three types of tasks: throwing (direct manipulation), archery (tool interaction) and remote character control. While the Valve scored better on usability overall, the Vive controller was higher rated for tool interaction. These findings were similar to those of a study [17] that investigated different interaction techniques for direct manipulation using the Valve Index. It found that using a button (Controller+Trigger condition) on the controller was more accurate than using gesture detection to detect a grab.

Zooming and haptic feedback in Virtual Reality. Several zooming techniques are used for immersive analytics, such as keyboard, controller buttons, 3D menu selection, and hand gestures [11]. Hann et al. [13] used head movement to zoom in during surgery. Another approach mentioned by Fonnet and Prie [11] is to use a magnifying glass activated by a data glove or a lightweight transparent acrylic panel and a stylus. In the latter case [8], a mini system is provided to prevent users from losing orientation. The mini system is a miniature version of the whole visualized data set that can be rotated, resulting in the same rotation of the overall environment. We will use these existing solutions as inspiration for implementing zoom within our context.

Haptic feedback has often been used in VR to improve the level of realism when grabbing or touching objects [26]. It has proven its value for user experience [22], also within virtual environments [18]. We investigate the use of haptic feedback as it remains an open question whether it contributes to more accurate manipulations in VR.

3 SYSTEM

We developed a proof-of-concept tool [1] that mimics the manipulation of a spray painting gun using a VR controller in the dominant hand. The software is a Unity application (developed in v2019.2.6f1 with Open XR, no other external assets) in which a virtual environment is used to perform the different manipulations. We used a HTC Vive Pro 2 VR headset and two Vive controllers given its positive results for tool-based interaction [1]. We generated the mesh of our central game object from a CAD file. The feasible manipulations are a *free form* edit, an *angle* edit, a *distance to object*, and a *scan offset* edit (see Figure 1). The manipulations can be selected through a point-and-click menu (see Figure 2a) and are applied to the world coordinate system of Unity.

Manipulation modes. The *Free form* mode allows users to manipulate the control point's position. The edit is performed by moving the VR controller in 3D space, seeing instantaneous visual feedback about the performed manipulation. The position of the control point in the next frame is computed by applying the VR controller's translation to the control point's current position. The *Angle* mode allows the user to change the orientation with three degrees of freedom. Again, the user can use the handheld controller to manipulate the rotation of the control point. The new direction of the control point is computed by applying the relative rotation of the controller to the point. The *Distance to Object* mode represents the modification of the distance of the paint location toward the object to which the paint has been applied. This edit only allows the user to move the position of the control point along the direction of the paint, keeping its current rotation. This is implemented by projecting the handheld controller's movement vector on the control point's direction vector. The *Scan offset* mode allows the user to move the control point parallel to the surface of the object. The restriction of this tool gives the user better control in case they want to move a point across the object's surface, keeping the same distance from that object. This is implemented by restricting the movement of the point toward the surface. Based on the existing research on manipulation [7, 9, 15, 20, 24], we provided constrained variants of the different manipulation modes. These constrained variants avoid making involuntary manipulations on other axes. Discrete, accurate edits on the x- and y-axis can also be made with the controller's touchpad. Each touch corresponds with a certain translation or rotation to increase or decrease on a specific axis.

Zoom. We provide zooming functionality to support an enlarged view of the manipulations, which can be enabled with the controller

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[1] https://youtu.be/cm66u4xeXgs

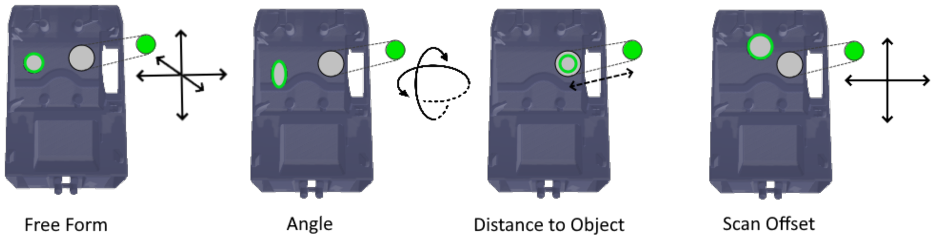
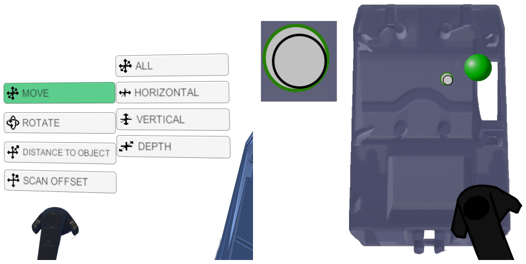

Free Form Angle Distance to Object Scan Offset

Figure 1: Screenshot of our system manipulating a spray-paint area on a 3D object; The manipulation is performed on the green sphere (i.e. control point) and reflected on the 3D object with the black circle, the target is visible with the green border. The different manipulation techniques we implemented: free form, angle, distance to object and scan offset.



(a) **(b)**

Figure 2: Screenshots of our system including (a) Menu: attached to the non-dominant hand, to select the different manipulation techniques with the controller of the dominant hand; (b) The zoom feature on the left shows an enlarged view of the focal area.

(see Figure 2b) [9]. A virtual rectangular surface is shown with an enlarged view of the object's surface surrounding the manipulation area. The surface is positioned on a fixed point relative to the head orientation next to the 3D object. Our virtual zooming tool thus works similarly to the details on-demand feature as discussed in earlier work [11, 31]. The zoom is implemented by positioning a virtual camera at the manipulation point where the user is aiming. In Unity, the zooming effect is achieved by adapting the camera's field of view, allowing a zoom of up to 12 times. The user can zoom in and out with the controller's touchpad of the non-dominant hand.

Haptic feedback. The application provides haptic feedback when a user moves the point/cursor outside the 3D object or is too close to the object with the controller in their dominant hand. Haptic feedback is also given when the user does an unexpected movement with the controller during an interaction where one of the constrained options is activated, e.g. moving vertically with the controller while the horizontal constraint is enabled. The haptic feedback is implemented by activating the haptic pulse of the controller of the dominant hand as long as an *incorrect edit* is being performed.

4 STUDY DESIGN

We conducted an exploratory user study approved by the local ethics committee. We measured and compared the interaction methods using objective and subjective measures. We specifically wanted to investigate the effect of zooming and haptic feedback on performance and user experience. We used a within-subject design with 2x2 factors: no haptic feedback and no zoom, only zoom, only haptic feedback, or both. We used the HTC Vive Pro 2 with Vive controllers for the experiment and provided the participants with a cleared space of 3x3 meters to safely walk around. Since this experiment focuses on how the different interaction techniques can contribute to accurate manipulation (RQ 1) and its impact on perceived workload (cf. NASA-TLX), usability and user experience (RQ 2), we focus only on applying manipulations to one specific point. We recruited 16 participants (1 female, 15 male) [P01-P16] with an opportunistic sampling method among students and staff [6]. The number of participants and the sampling method (i.e. variety in VR experience) were chosen to enable a sound analysis of the results obtained using the chosen study procedure. Table 1 lists the participants' key characteristics. The different options for VR experience relate to: none-'never tried VR solutions before', little bit-'limited experience through occasionally testing out VR solutions', quite a little-'interacting with VR solutions on a regular basis', a lot-'interacting with or/and programming for VR on a frequent basis'. Given that 50% of our participants had none to little experience with VR, we believe our subject group is well qualified to provide user feedback on manipulation techniques that spray painters or operators overall might use in the future. All reported right as their dominant hand to interact in VR, and all have at least some experience with playing 3D games, although being it in their childhood many years ago.

During the experiment, the researcher starts by explaining the study and the data that will be collected. The participant gets a consent form. After completing the form, the participant fills out a short questionnaire with demographic information and experience with VR and 3D games. Lastly, the participant gets a brief explanation of the software and gets some time to get acquainted with the different features of the software in VR. Once the participant indicates to be ready for the experiment, a series of 24 target-matching tasks is presented to them in blocks of 6, each representing one of the four specific conditions (A) no zoom and no haptics, B) only

Table 1: Key characteristics of participants (age group, experience with VR, experience with playing 3D games)

Age group	Percent (count)	VR Exp.	Percent (count)	3D games Exp.	Percent (count)
18-25	31.25% (5)	none	12.5% (2)	none	0% (0)
26-35	50.0% (8)	a little bit	37.5% (6)	a little bit	37.5% (6)
36-45	18.75% (3)	quite a little	31.25% (5)	quite a little	37.5% (6)
46+	00.0% (0)	a lot	18.75% (3)	a lot	25% (4)

zoom, C) only haptics, D) zoom and haptics). Each task includes the positioning of the cursor in the target (circle with green border) that is shown on a realistic 3D object (see Figure 3), similar to the recommendations for object selection and manipulation studies in VR of Bergström et al. [2]. We asked the participant to position (including correct orientation and size) the cursor (circle with black border) as accurately as possible in the target (circle with green border) without any time constraints (= one task). The participant could press a button in the VR environment to go to the next task when he/she was satisfied with the current task's execution and positioning. The order of the blocks of six tasks is counterbalanced and varies across participants to minimize the learning effects that might take place. The order of the six tasks within each block/condition is the same for each participant. For each task, the cursor and target are positioned on the 3D object, each varying in position, size, and rotation. The challenge of the task is to match each parameter (position, size, and rotation) as accurately as possible (see Figure 3).

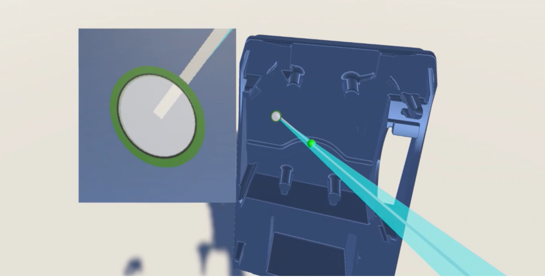


Figure 3: Example of a task in which the cursor and target are being matched with the zoom available

After each block of six tasks (one condition), the participant answers a NASA-TLX [14] questionnaire within the virtual environment [10]. After two blocks, including the questionnaire, the participants can take a short break, after which the study continues with the two remaining blocks. Most participants, except for 4, ignored the offer and continued with the two remaining series of six tasks. Participants spent on average 25 minutes in VR. Afterward, the researcher starts a short semi-structured interview with questions about the participant's experience (i.e., overall user experience, working routine, perceived accuracy, and the usefulness of different features). The used manipulation modes and task duration and performance were logged in the application.

5 RESULTS AND ANALYSIS

In the following subsections, we will describe the findings from the study in terms of usage behavior of the manipulation modes, overall user experience, and the impact of zoom and haptics on o.a. task completion times, accuracy, and perceived workload.

Usage of manipulation modes. For each participant, we logged which manipulation modes were used to get more insights into the usefulness and understandability of these modes. Participants used both the constrained and non-constrained variants, but very few used the scan offset tool except for P04, P08, and P15. This is mainly because scan offset is a sort of constrained variant of the free form (free translation while keeping the distance with the 3D object). Overall, constrained variations were used less than non-constrained tools. However, we observed that these tools were used for final tuning on certain axes, ensuring that other axes would not be altered. Similar behavior was also achieved using the controller's touchpad by making small modifications to the translation or rotation. We analyzed the number of times participants switched between different manipulation modes (RQ 2). Switching between non-constrained and constrained variants was also considered a switch. The average number of switches was low (across all conditions, 4.48 times on average), showing that participants had a good idea of what to expect from each manipulation type and were efficient in selecting the appropriate mode to reach the expected manipulation (see Table 2). We saw that the switches were made to select another manipulation tool they did not use yet, and not to go back and forth between the same tools, which implies that all manipulation modes were clear and intuitive to use.

Everyone, except for P03, used the touchpad generously to fine-tune their edit after first making manipulations more roughly with the controller. The manipulations with the touchpad have similar but more fine-grained behavior compared with their constrained variants with the controller. All participants agreed that using the touchpad increased accuracy (see Figure 4). We also observed that all participants created a working routine throughout the series; e.g. first do a translation with the free form tool, then use the angle tool to achieve the correct orientation, and end with the distance to object tool to achieve the correct size. These routines correspond with the findings of the limited number of switches. One participant also mentioned that he always ended his edit with the free form tool to have it ready for the next task. This fast creation of routines and a limited number of switches contributes to our goal of providing low-learning and efficient solutions for accurate manipulation in tool-based interaction (RQ 2).

Task execution and accuracy. The average completion time per task was 58 seconds (±35.21). Table 2 lists the average completion times per task, per condition and per round of six tasks (=chronological experiment order, independent of condition). The time itself is not relevant to our analysis, but we are interested in the completion times over time (over the four rounds). There is a clear decrease in

Table 2: Average task completion time (in seconds per individual task) and number of switches between the different manipulation modes for the different conditions versus the different rounds (chronological, independent of the condition)

Condition	Zoom	Haptics	Task compl. time	Nr. of switches	Round	Task compl. time	Nr. of switches
A			57 (±27.98)	4.6 (±1.90)	1	66 (±40.06)	4.5 (±1.49)
B	✓		67 (±40.99)	5.6 (±0.54)	2	60 (±31.00)	4.6 (±1.67)
C		✓	52 (±26.93)	4.0 (±1.42)	3	52 (±31.22)	4.8 (±2.17)
D	✓	✓	56 (±40.78)	3.8 (±0.97)	4	51 (±26.53)	4 (±1.18)

Table 3: Overview of the significant findings for task accuracy, i.e. position, size, and rotation

Parameter	Conditions	p-Value	Z	Effect size (r)
Position	A vs B	p<0.001	-3.516	0.62
	A vs C	p<0.001	-3.516	0.62
	A vs D	p<0.001	3.465	0.61
	B vs C	p<0.001	-3.516	0.62
	B vs D	p<0.001	3.516	0.62
	C vs D	p<0.001	3.516	0.62
Size	B vs C	0.006	-2.741	0.48
Rotation	A vs B	0.003	-2.896	0.51
	A vs C	p<0.001	3.516	0.62
	B vs C	p<0.001	3.516	0.62
	B vs D	0.001	3.206	0.57
	C vs D	p<0.001	-3.516	0.62

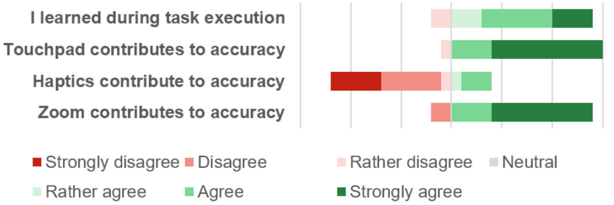


Figure 4: Accuracy and learnability ratings

Table 4: Overview of the significant findings for NASA-TLX related to the conditions (see table 2 for details), based on the Wilcoxon Signed-Rank test.

NASA-TLX	Conditions	p-Value	Z	r
Physical	B vs C	0.006	-2.668	0.47
Successful	B vs C	0.002	2.943	0.52
Successful	A vs D	0.002	-3.063	0.54
Successful	C vs D	0.001	-3.104	0.55
Effort	A vs B	0.004	2.813	0.50
Effort	A vs D	0.001	3.004	0.53

task completion time per round, with the most significant decreases between rounds 2-3 and 1-2, which aligns with the perceived learning effect found in Figure 4 (top line – learnability). Notice that each condition (series of 6 tasks) appeared once for every participant. Per condition, only zoom was the slowest performer, probably because participants took more time to be more accurate given that they could have a more detailed view. Between the other conditions, the differences were smaller. Based on the interview afterward and task completion times for conditions with haptics (C and D), we see that it provided some participants with a form of confirmation that their task was performed well. We found lower task completion times in the two haptic conditions (i.e. 52 and 56 seconds per task). However, no significant difference was found when performing a Friedman test ($\tilde{\chi}^2$(3)=7.725, p=0.05205) (RQ 2).

A Friedman test was also performed for the impact of the four conditions on task accuracy (RQ 1). Task accuracy was measured by taking the position, scale (=size) and rotation of each task (in Unity coordinates) and comparing these with the expected target's coordinates (see Figure 5). Post-hoc analysis with Wilcoxon signed-rank tests (Bonferroni corrections applied) revealed significant findings (see Table 3). Zoom usage correlated with a more accurate location regarding the position. Also, zoom resulted in less accurate rotation (see Figure 5), possibly due to the flat 2D view of the zoom feature (see Figure 2b). We also found a significant difference in condition B (zoom) versus C (haptics) regarding size. Despite the significant findings, it is hard to draw conclusions about the haptic feature. From our qualitative findings (interview and questionnaire), we found that many participants were confused by the behavior of the haptic feedback, given that some participants interpreted this type of feedback as a confirmation of their performance while others related it more to errors. Based on the outcomes of the questionnaire (see Figure 6), we can conclude that zoom is perceived useful and contributes to accuracy. Haptic feedback needs further research on how to apply this well for tool-based interaction.

User experience. We asked participants to rate the core features on usability on a 7-point Likert scale. The results (Figure 6) are overall positive (RQ 2). Only the usage of haptic feedback was rated negatively by the majority since it was not always clear to them when the haptic feedback would appear. The fact that the haptic feedback was not present in two rounds of six tasks played a role in this given its inconsistency throughout the use. Contrary to zoom, haptic feedback has no visual representation. The results for the scan offset were mixed. One in four participants was (slightly) negative about the constrained edit tools as they preferred using the tools without having constraints. Some others mentioned in the interview that they were really happy with the constrained angle tool since the non-constrained angle tool was perceived as too sensitive to movement. Ratings about whether features contributed to accuracy (Figure 4) were largely consistent with the ratings of the usability of these features.

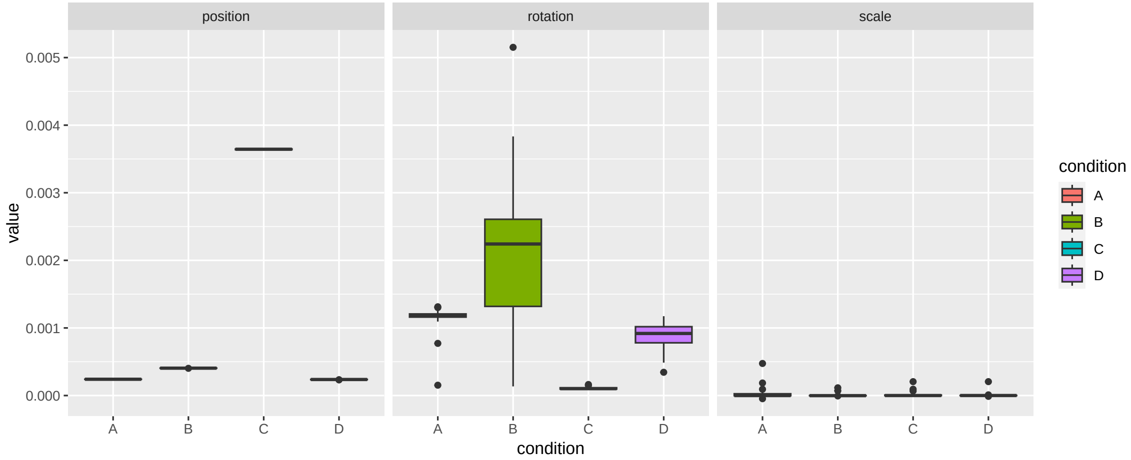


Figure 5: Boxplots of different parameters (position, scale and rotation) for each condition; the parameter values are expressed in Unity coordinates and represent the delta between the target location and the location performed by the user using the proposed manipulation techniques. Higher values relate to less accurate manipulation. (Conditions: A - no zoom, no haptics, B - only zoom, C - only haptics, D - zoom and haptics)

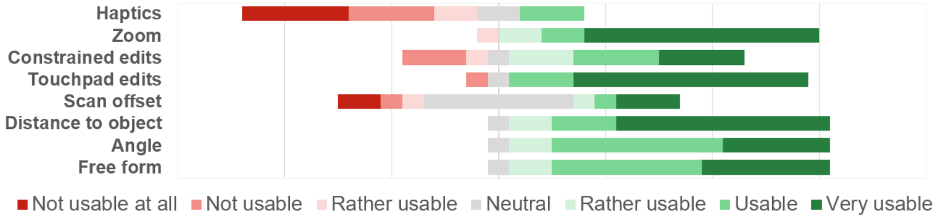
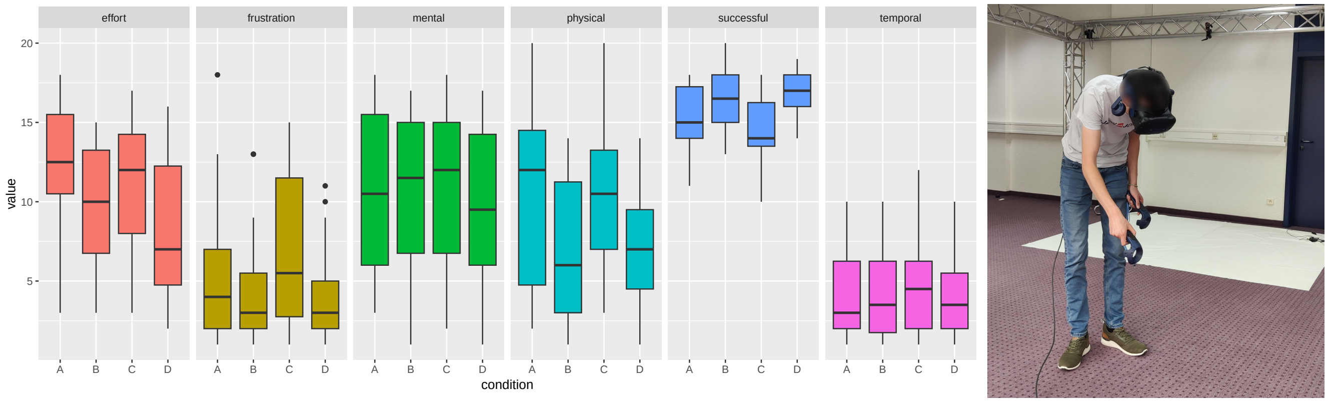


Figure 6: Ratings of the different features of our prototype environment were mostly positive, haptics was an exception



(a) NASA-TLX scores per condition, zoom (B, D), haptics (C, D) (details in Table 4)

(b) Posture without zoom

Figure 7: Disabling zoom affected (a) ratings for effort and physical demand for these conditions (A, C) and (b) posture

Perceived workload. We performed a Friedman test for each factor of the NASA-TLX to investigate the effect of the four conditions. Post-hoc analysis with a Wilcoxon signed-rank test (Bonferroni corrections applied) resulted in significant differences for successfulness, effort to perform, and physical demand (RQ 2) (see Table 4). During the experiments, we also encountered that participants were moving physically (i.e. going closer to the object and bending, see Figure 7b) more when the zoom feature was disabled to be able to see the edit more in detail. The participants experienced low temporal demand and frustration, low to moderate mental and physical demands, and a high feeling of success and accuracy in all conditions (see Figure 7a).

6 DISCUSSION

6.1 Key Findings

Use controls on 3D input devices for more accuracy? We used VR controllers as input device for all our interactions in the VR scene. The study revealed that using these controllers as hand-tracking devices can be rather sensitive to precise changes given that it is impossible to keep hands fully steady, especially when more degrees of freedom are enabled. This is in line with the findings in literature for direct manipulation [19, 23, 24]. P04 mentioned that, especially with rotation, the tool with all directions enabled was too sensitive, so he always used the horizontal or vertical constrained variant combined with further refinement with the touchpad. This strategy was a viable solution for accurate editing for P04 and other participants. We, therefore, suggest always keeping alternatives to mid-air gestures available for precise manipulation. This can be done through buttons, touchpads, or other controls on the VR controller or by using interaction devices that are less susceptible to the accuracy problems of mid-air gestures, such as the 2D mouse [35]. As mentioned earlier in the results, we observed that all participants created some working routine during the first or second round, indicating that they quickly got familiar with the tool and perceived it as intuitive to use.

Visual zoom made manipulations more accurate, also scale physical interaction? The user study showed the potential value of providing a zoomed picture-in-picture when manipulating the position of objects in virtual reality in 6 DoF accurately. This is the opposite of the mini-system provided in [8]. We found that the object's rotation was less accurate with the presence of zoom. Based on the interviews, we encountered that most participants focused only on the 2D zoom view, leading to less focus on the rotation of the cursor which is more visible on the 3D object itself. Further research is needed to investigate better ways of providing (3D) zoom views. In our solution, we provided the 3D object on a 1:1 scale with the real world and provided a view with a modifiable scaling factor next to the 3D object. Given the advantages of virtual reality, it is also possible to work with different scales [34] for the object we want to manipulate in case the physical space does not provide sufficient room. This could make the zoom feature even more beneficial and valuable. A possible future research track could also include investigating scaling manipulations when the zoom is enabled in contrast to the current one-on-one mapping. Currently, we only focused on a one-on-one mapping between the movement of the controller in the real world and the resulting movement in the virtual world.

Use haptic feedback unambiguously. Haptic feedback alone did not have a (significant) positive effect on the overall subjective accuracy and performance in this study. Although we found a significantly more accurate edit for the size of the cursor, the haptic feedback led to less accurate positioning of objects. Contrary to zoom, participants did not encounter haptic feedback in the training/exploration phase. This resulted that this type of feedback was unclear for most participants, as some expected it to act as confirmation. In contrast, others did not know how to interpret the haptic feedback since it did not occur consistently in all similar situations, given that the feature was not present in all tasks (due to the different conditions). Unlike zoom, haptic feedback is not a visually present element, making it harder to be aware of in which conditions it is present. In future studies, we would visualize the availability of haptic feedback to ensure consistency. From the interview, we learned that participants prefer to have haptic feedback in a confirming manner [4]. The results also show that the average number of switches between manipulation modes was lower with the haptic conditions, which aligns with the reasoning for confirmation, making these manipulations more efficient. We believe further research on the use of haptic feedback in terms of performance is needed since haptic feedback in virtual reality still focuses mainly on informing about the presence of something in the VR environment [12].

More focus on ergonomics in future work? The responses to the NASA-TLX questionnaire and the observations during the experiment revealed the lower effort to perform and physical demand of the zoom feature, which is a crucial benefit for operators as they already encounter many ergonomic issues overall [25]. Therefore, we believe our work contributes to the emerging Industry 5.0 paradigm [21] where human factors play a central role. We encourage further investigation of zoom in other use cases of the manufacturing industry, especially for ergonomic purposes.

6.2 Limitations and Future work

One of the limitations of our study is the inclusion of staff and students rather than spray painters. We deliberately made this choice as the goal of our experiment was to investigate how accurately and efficiently the tasks could be performed and the impact of zoom and haptics [6]. We focused on the manipulation task, not on any performance related to painting. Further research on haptic feedback should be performed to investigate how this type of feedback can be implemented unambiguously and support users in performing precise manipulations. Also, further research on the ergonomic impact of such interaction techniques is recommended. Although we developed and investigated the manipulation of objects in the context of spray painting, we believe that our work can be beneficial for other use cases in which manipulating objects accurately through tool-based interaction is relevant since we used an abstract form of editing spray painting in our user study which is more generally applicable. Such use cases include mainly educational or rehabilitation purposes in which precise 6 DoF manipulation is crucial (e.g. assembly training).

7 CONCLUSION

We presented the results of an exploratory study investigating the use of different manipulation and interaction techniques for accurate tool-based interaction in VR. We performed a study with 16 participants performing manipulation tasks in VR as accurately as possible. We found that tool-based interaction with controllers in VR can benefit from zoom and separation of degrees of freedom. Zoom has a lot of potential to increase accuracy in making manipulations (RQ 1) and lower the effort and physical demand to perform (RQ 2). Haptic feedback proved to increase accuracy for the size of the manipulation (RQ 1) but was also evaluated unclear and ambiguously (RQ 2). We found that not only separating the degrees of freedom but also the provision of controls is useful to achieve the aforementioned task. The findings in this paper expand the knowledge on interaction with controllers for accurate manipulation in VR. However, more research on the ergonomic impact and the correct use of haptic feedback in this context is needed.

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