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A New Direct Manipulation Technique for Immersive 3D Virtual Environments

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Abstract

In this paper, we introduce a new 7-Handle manipulation technique for 3D objects in immersive virtual environments and its evaluation. The 7-Handle technique includes a set of seven points which are flexibly attached to an object. There are three different control modes for these points including configuration, manipulation and locking / unlocking modes. We have conducted an experiment to compare the efficiency of this technique with the traditional 6-DOF direct manipulation technique in terms of time, discomfort metrics and subjective estimation for precise manipulations in an immersive virtual environment in two consecutive phases: an approach phase and a refinement phase. The statistical results showed that the completion time in the approach phase of the 7-Handle technique was significantly longer than the completion time of the 6-DOF technique. Nevertheless, we found a significant interaction effect between the two factors (the manipulation technique and the object size) on the completion time of the refinement phase. In addition, even though we did not find any significant differences between the two techniques in terms of intuitiveness, ease of use and global preference in the result of subjective data, we obtained a significantly better satisfaction feedback from the subjects for the efficiency and fatigue criteria.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques. I.3.7 [Computer Graphics]: 3-D Graphics and Realism—Virtual reality.

1. Introduction

Object manipulation is one of the most essential and important interaction in Virtual Reality (VR). Proposing efficient, easy to use and to integrate, flexible and reusable manipulation techniques has been broadly studied over the past few decades. In this paper, we focus on accurate manipulation techniques for large objects in immersive Virtual Environments (VEs). This task is usually difficult because of the obstruction of a user's view caused by the objects' size during his manipulation [BH97] and by other objects (if there are many) in the same scene. It becomes more difficult when the user has to position large objects with a high degree of accuracy. Besides, manipulation in immersive VEs is often difficult and inaccurate because human beings have difficulties in performing accurate manipulation tasks or in keeping the hand motionless in a particular position without the help of external devices or haptic feedback. Due to these difficulties, we propose a new manipulation technique named *7-Handle tool* for 3D objects in VEs. This technique enables a user to adapt the set of seven points of the tool to objects of different sizes and shapes, and to many kinds of manipulation scenarios. We compared this technique with the 6-DOF direct manipulation technique in terms of completion time, discomfort metrics and subjective estimation.

2. Related Work

In the literature, traditional 2D toolkit-based interfaces have been extended in many 3D applications [Bie87, CMS88]. 3D widgets [CSH*92], especially 3D transformation widgets [Bie87], are one of the most widely used manipulation tools in many Virtual Reality (VR) systems. Most 3D trans-

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formation widgets have simple behaviors and few Degrees of Freedom (DOF) to control 3D objects movements. Although these widgets may help the user to manipulate objects more accurately in desktop VEs, so far their efficiency in immersive Virtual Environments (VEs) has not been well justified.

Some other approaches [BH97, PSP99, PBW96, SCP95] have been proposed to manipulate objects at a distance by creating their miniature models or by expanding the user's virtual arm. These propositions have an advantage for large-object manipulation scenarios: when the user has an overall view of objects or of the whole environment, it is easier for him to know how to move these objects to a particular position and orientation without worrying about obstruction issues. However, one main issue of these approaches is that the small movements of the miniature models or of the user's virtual hand from a distance are often magnified in the environment, making accurate positioning difficult. It may be difficult to find a reasonable distance at which the size of objects is not too disturbing and the user can still determine their position. An issue of the HOMER technique [BH97] is that manipulated objects are taken out of their context: sometimes, it becomes less efficient when the user needs to move an object to a particular position relative to its neighbors.

In order to manipulate objects more accurately and efficiently, PRISM [FK05] has proposed a dynamical adjustment method for switching between precise and direct mode occurs during natural interaction according to the current velocity of the user's hand. Nevertheless, sometimes the user may feel a sense of incompatibility caused by the difference between visual feedback and motor control when the precise mode is active. Osawa [Osa08] has proposed a manipulation technique using two hands (one hand is used for positioning and releasing, and the other hand is used for adjustment control). This technique adds a viewpoint adjustment phase to enlarge the scene when the hand grasping the virtual object is moving slowly. However, this adjustment may influence the user's immersion and it may cause fatigue when he manipulates large objects. In brief, these approaches may be suitable for precise manipulation but the obstruction issue caused by large objects remains unsolved.

Several bi-manual 3D interaction techniques have been proposed to manipulate virtual objects with the two hands of a user [HPPK98]. But only a few of them, such as "grab-and-carry", "grab-and-twirl" and "trackball" techniques [CFH97], enable the user to move and rotate virtual objects. The "grab-and-carry" technique [CFH97] is a 5-DOF bi-manual symmetric tool that enables the user to carry and turn an object around its center with both hands. Object roll is not supported in this technique because it is not possible to determine rotation around the axis formed by the user's two hands. The "grab-and-twirl" technique extends the "grab-and-carry" technique, adding the sixth DOF using either the left hand's roll, the right hand's roll, or a combination of both. The "trackball" technique is a bi-manual asymmetric tool that enables the user to use the non-dominant hand to move a virtual object while using the dominant hand to rotate this object around its center.

The 3-hand manipulation technique of [ADL09, ND13] is generic and does not need additional aids. This technique determines the position of virtual objects through the position of three non-aligned manipulation points on a plane. However, this technique is mainly devoted to multi-user collaborative manipulation and it is quite difficult for one user to manipulate objects, unless if it is used with a Reconfigurable Tangible Device [ADL11] called RTD-3. In this last case, the size of the virtual triangle formed by the three manipulation points is limited by the maximal size of the RTD-3 and it could become less suitable for manipulating large objects. This technique has also been improved through the 3-point++ technique in order to be used by a single user [ND13]. It enables the user to manipulate one or two of manipulation points, and to lock the remaining ones.

3. The 7-Handle Technique for Direct Manipulation

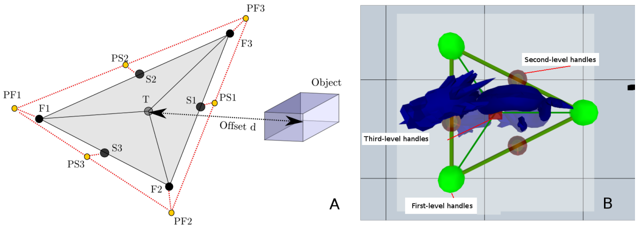

Figure 1: *A (left): Set of seven points of the 7-Handle tool. B (right): Implementation of the 7-Handle tool.*

The 7-Handle technique consists of seven points as illustrated in figure 1.A. The three points F_1, F_2 and F_3, called *first-level* handles, are the three vertices of a triangle. The three points S_1, S_2 and S_3, called *second-level* handles, are initially positioned at the midpoints of the three sides of the triangle. Each second-level handle is used to control its two adjacent first-level handles. The last point, *third-level* handle T, is initially positioned at the centroid of the three first-level handles. The handle T can be used as a direct manipulation tool with 6 DOF. The manipulated object can be positioned from the 7-Handle tool with an offset d, the distance from the barycenter of the object to the centroid of the three first-level handles. This offset will be used to compute the motion of the object according to the motion of the 7-Handle tool. Additionally, we separated the handles (as the parts of an interaction tool) from the controlled object (as an *interactive object*). This separation makes our technique more generic, abstract and flexible to manipulate objects in VEs. We propose three different control modes for the 7-Handle tool, especially for the three first-level handles, including configuration, locking / unlocking, and manipulation modes.

3.1. Configuration Mode

In order to make the 7-Handle tool more flexible in many manipulation scenarios, we have developed a configuration mode for all the seven handles in which their positions can be changed relatively to the position of the object at run-time, which will modify the shape of the tool without moving or rotating the object. The first-level handles are recommended to be put near some parts of interest of the object because later on, the user can easily verify if the part of the object near one of these handles is well placed to the expected position. The second-level handles are initially placed at the midpoints of the sides and the third-level handle at the centroid of the first-level handles. If these handles are somehow placed inside the object and so are difficult to be seen and reached, the user can change their offset with the object. The relative offsets of all the handles to the object are used later in the manipulation mode.

3.2. Locking and Unlocking Mode

Our system provides a possibility of locking or unlocking the three first-level handles. If one first-level handle is locked, the user can rotate the 7-Handle tool (and also its associated object) around the locked handle. If two first-level handles are locked, the manipulation of the remaining first-level handle enables the user to rotate the object around the side formed by the two locked first-level handles. The locking / unlocking mode is only possible for the first-level handles, and useful with only one or two handles locked at the same time otherwise nothing moves anymore.

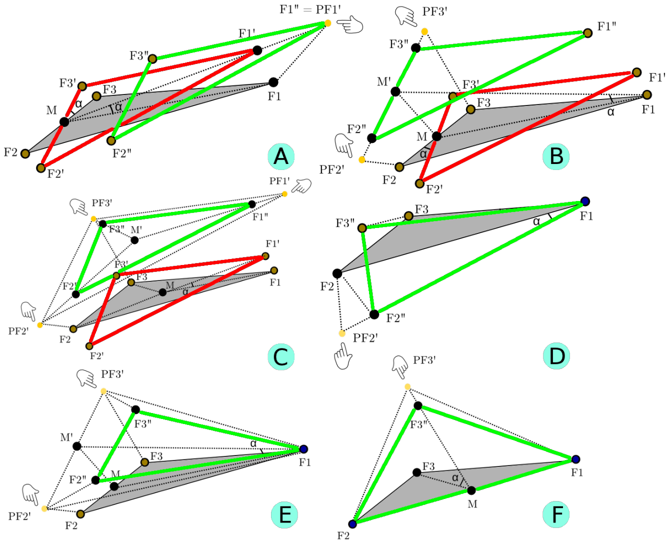

Figure 2: *Six manipulation scenarios using the 7-Handle tool. The triangle with black sides shows its initial position, one with red sides shows its intermediate position, and one with green sides shows its final position.*

3.3. Manipulation Mode

The user can use the tool to modify the position and orientation of the object. Once the tool configuration has been done, the shape of the tool remains unchanged. Due to this constraint, we propose controlling these handles through proxy points PF_1, PF_2, PF_3, PS_1, PS_2 and PS_3 (see figure 1.A). We do not need a proxy point for the third-level handle because the latter can be directly driven in 6 DOF. The proxy points are smaller yellow spheres initially hidden inside their associated handles. The movement of a proxy point reflects the expected position that the user wants its associated handle to go. Therefore, when we talk about controlling a handle, we actually talk about controlling the proxy of this handle. The gap between one handle and its proxy point during the manipulation is made visible by a red elastic link and the deformed triangle shape of the tool is shown in semi-transparent yellow. This proxy point comes back to the position of its associated handle when the user releases it. The way each handle moves depends on the position of its proxy point, its own state (locked or controlled by its neighbor handles), the state of its neighbor handles, and the shape of the triangle. There is no difference between the manipulation of a second-handle and the synchronized manipulation of its two associated handles, this is why we will not talk about second-handle manipulations in the remaining of this section. Using the set of seven handles to manipulate an object, the following manipulation scenarios can occur:

1. No locked handle

   a. *Controlling one first-level handle* (figure 2.A)
   If the proxy point PF_1 is moved to the new position PF_1', the 7-Handle triangle is first rotated $\angle(\overrightarrow{MF_1}, \overrightarrow{MPF_1'})$ degrees around the axis $(M, \overrightarrow{MF_1} \wedge \overrightarrow{MPF_1'})$, and then moved along the vector $\overrightarrow{F_1'PF_1'}$. M is the midpoint of the side F_2F_3. The $\angle(\overrightarrow{MF_1}, \overrightarrow{MPF_1'})$ denotes the angle between the two vectors $\overrightarrow{MF_1}$ and $\overrightarrow{MPF_1'}$. The axis $(M, \overrightarrow{MF_1} \wedge \overrightarrow{MPF_1'})$ denotes the axis which is created by the normal vector of the two vectors $\overrightarrow{MF_1}$ and $\overrightarrow{MPF_1'}$ and passes the midpoint M.

   b. *Controlling two first-level handles* (figure 2.B)
   If the proxy points PF_2 and PF_3 are moved to the new positions PF_2' and PF_3', the triangle is first rotated $\angle(\overrightarrow{F_1M}, \overrightarrow{F_1M'})$ degrees around the axis $(M, \overrightarrow{F_2F_3} \wedge \overrightarrow{PF_2'PF_3'})$, and then moved along the vector $\overrightarrow{MM'}$. M is the midpoint of the side F_2F_3, M' of the side $PF_2'PF_3'$.

   c. *Controlling the three first-level handles* (figure 2.C)
   If all the three first-level handles are grabbed at the same time, the triangle is first rotated α degrees around the axis $(M, \overrightarrow{F_1F_2} \wedge \overrightarrow{F_1F_3})$. M is the centroid of the triangle $F_1F_2F_3$, and M' of the triangle $PF_1'PF_2'PF_3'$. The α is the average of three angles $\angle(\overrightarrow{MF_1}, \overrightarrow{M'PF_1'})$, $\angle(\overrightarrow{MF_2}, \overrightarrow{M'PF_2'})$, and

   $\angle(\overrightarrow{MF_3}, \overrightarrow{M'PF'_3})$. The triangle is then moved along the vector $\overrightarrow{MM'}$.

   d. *Controlling the third-level handle (T)*
   If the third-level handle T is controlled, this technique is equivalent to a 6-DOF manipulation technique.

2. One locked handle (F_1; F_2; or F_3)
   a. *Controlling one first-level handle* (figure 2.D)
   Supposing that the first-level handle F_1 is locked at one place and the proxy point PF_2 is moved to the new position PF'_2, the triangle is rotated $\angle(\overrightarrow{F_1F_2}, \overrightarrow{F_1PF'_2})$ degrees around the axis $(F_1, \overrightarrow{F_1F_2} \wedge \overrightarrow{F_1F_3})$.
   b. *Controlling two first-level handles* (figure 2.E)
   If the first-level handle F_1 is locked and the proxy points PF_2 and PF_3 are moved to the new positions PF'_2 and PF'_3, the triangle is rotated $\angle(\overrightarrow{F_1M}, \overrightarrow{F_1M'})$ degrees around the axis $(F_1, \overrightarrow{F_1F_2} \wedge \overrightarrow{F_1F_3})$. M is the midpoint of the side F_2F_3, M' of the side $PF'_2PF'_3$.
3. Two locked handles (F_1 and F_2; F_1 and F_3; or F_2 and F_3)
   Controlling one first-level handle (figure 2.F)
   If two first-level handles F_1 and F_2 are locked, the only available handle which can be grabbed is F_3. The triangle is rotated $\angle(\overrightarrow{MF_3}, \overrightarrow{MPF'_3})$ degrees around the side F_1F_2. M is the midpoint of the side F_1F_2.

We have implemented the 7-Handle technique in an immersive virtual environment as illustrated in figure 1.B. In order to improve the usability of our technique, we integrated some visual informative feedback about the state of each handle to inform the user about its availability, its behavior and its functionality. Each handle can be in one of three different states. The first one is the active state when the handle is available and can be grabbed by an interaction tool. The handle is green when it is available and turns bright green when it is grabbed. The second is the inactive state when the handle is controlled or manipulated by other handles. Its position and orientation are computed according to its relation with the other handles. When a handle is in the inactive state, it appears in a semi-transparent red color and it cannot be grabbed by an interaction tool. The last one is the locked state: the handle is pinned at one place and it cannot be moved unless the user unlocks it. A locked handle appears in blue.

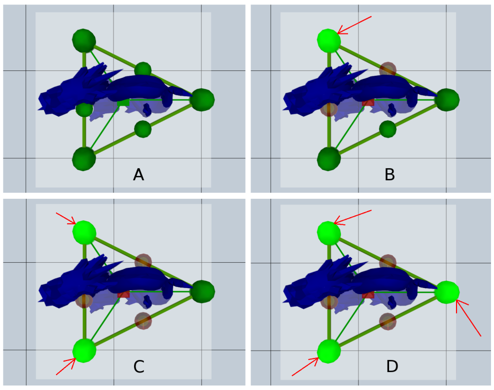

Figure 3: *Color state of the handles in the four following scenarios (the controlled handles indicated by red arrows): A: No handle is controlled - B: One first-level handle is controlled - C: Two first-level handles are controlled - D: Three first-level handles are controlled.*

During the manipulation, there are always constraints between handles at different levels. When a handle is currently controlled, its adjacent handles are indirectly controlled and are not available to be grabbed by interaction tools. Figure 3 shows the color change and the availability of each handle in four different manipulation cases when the user uses only the first-level handles to manipulate an object. If one first-level handle is controlled (in bright green color), the third-level handle and the two adjacent second-level ones associated with this first-level handle are simply made inactive (in semi-transparent red color, see figure 3.B). When two first-level handles are controlled, all the second-level and third-level handles are inactive and the only handle still available is the remaining first-level one (figure 3.C). Last, all the three first-level handles can be controlled by two or more users to get an unconstrained 6-DOF manipulation control over the object (figure 3.D).

4. Experiment

We conducted an experiment to evaluate the performance of the 7-Handle and the 6-DOF techniques for accurate manipulation of objects in an immersive virtual environment.

4.1. Context

In this experiment, we evaluated the interaction between the two factors - the manipulation techniques and the sizes of objects - in terms of efficiency and comfort, using discomfort and efficiency metrics described in section 4.4. We used five 3D models which size varied from small to large (see Table 1). The duplicates of these models, called *targets*, were positioned three meters apart to indicate the final position and orientation of the objects. The target models were semi-transparent and in a different color to differentiate themselves with the object models. The goal of each manipulation task was to superimpose an object with its target.

The 6-DOF manipulation technique was implemented using a 3D cursor driven by a Flystick, enabling the subjects to directly grab and manipulate objects. For the 7-Handle technique, all the three first-level handles were initially positioned near points of interest of each object (points or parts of the object which were remarkable so the subjects can immediately recognize whether or not the object and its target superimposed). We predefined the configuration of the

7-Handle tool because we wanted to measure the completion time of a manipulation task with the same manipulation conditions for all the users. Furthermore, although the 7-Handle technique enables users to manipulate objects with two hands, we only used one input device for both the manipulation techniques to guarantee the consistency of experimental conditions. The subjects therefore used the same Flystick to control a 3D cursor by which they could grab and manipulate the handles. An additional function of this 3D cursor enabled the subjects to lock or unlock the handles.

The hardware setup consisted of a big CAVE-like system of four walls of which the size was 9.60 m long, 3.10 m high and 2.88 m deep. We used 11 trackers (including trackers for two lower arms, two upper arms, two wrists, two legs, neck, trunk, head) to record their postures during the experiment. The tracker positions were recorded at the frequency of 60 Hz during the experiment and this data was analyzed offline to compute discomfort metrics.

Table 1: *Size of the 3D models used for the experiment*

Object	Length (cm)	Width (cm)	Height (cm)
Cat (T1)	77.0	18.6	50.1
Heron (T2)	64.3	36.5	67.2
Horse (T3)	111.9	23.8	80.0
Dragon (T4)	154.0	52.0	142.0
Camel (T5)	161.0	49.0	165.0

4.2. Population

Twelve subjects (one female and eleven males) aged from 21 to 31 (mean: 25.9, std: 3.29) took part in this experiment. They were recruited among our colleagues in our laboratory and our students and they thought the techniques they were comparing were coming both from outside our lab. They were volunteering their time and received no reimbursement beyond light refreshments.

4.3. Procedure

Before beginning the training phase, the goal of the experiment was verbally explained to the participant. In the training session, he was given an example object (a dog model of which the size was 75 cm long, 60 cm high and 20.5 cm wide) that was manipulated to its target object twice by the two manipulation techniques. This session enabled the participant to familiarize himself with the manipulation task, the required precision of the manipulation, and the two techniques. In the evaluation session, the participant was asked to manipulate five objects using the two techniques (ten manipulation trials in total). Each technique was used by the participant to manipulate five successive objects in the order from small to large ones. The order of the techniques changed from one participant to another to reduce the order effect of techniques on results and to get a balanced design of all the experimental sessions.

4.4. Discomfort and efficiency metrics

In order to evaluate the two manipulation techniques, we measured the completion time of each manipulation trial. Each trial consisted in two consecutive phases: an approach phase when the manipulated object was moved over a long distance to near its target object, and a refinement phase for an accurate positioning and orientation. In addition, for each trial, two discomfort metrics (RULA and REBA scores), a subjective discomfort estimation and answers for a questionnaire were also collected.

4.4.1. Completion time

The completion time is a direct measurement of the efficiency of each technique, as we consider that being quick in a virtual environment means being efficient with the manipulation technique. For each manipulation trial, the software recorded the completion time of the approach phase for each participant to manipulate an object from its initial position into an intermediate zone (placing the center of the object closer than 10 cm from the center of its target). The object changed its color from green to blue to inform the participant about the ending of the approach phase. The software recorded the completion time of the refinement phase for the participant to manipulate the object from its position in the intermediate zone into its final zone. The final zone was a sphere of which the radius was 1.5 cm and the center was the target object. In addition, another condition of the final position of the object was that the angle difference between the object and its target was not greater than 0.04 radians. The object changed its color from blue to yellow to inform the participant about the ending of the refinement phase which was also the ending of the manipulation trial.

4.4.2. Discomfort metrics

The Rapid Upper Limb Assessment (RULA) score is an indicator of postural discomfort [MC93] used in relation to assessment of physical risk factors in ergonomics. A minimal score of 1 indicates a relatively comfortable posture, whereas a maximal score of 7 indicates a highly uncomfortable posture. From kinematics outputs obtained from the 11 trackers, we used the processing pipeline described in [PSB*14] to compute the RULA score at each frame. For each phase of each trial, the RULA score was averaged. To compute the final RULA score, adjustments relative to the task properties had to be made. We hypothesized that the “frequency adjustment" was equal to 1 since trials included repetitive motions. Given that the flystick weigh less than 1 kg, the “force adjustment" was set to 0.

The Rapid Entire Body Assessment (REBA) score is also an indicator of postural discomfort [HM00]. The REBA score is quite similar to the RULA score, but takes into account the leg postures and is less constraining than the RULA score for a given task. A minimal score of 1 indicates a relatively comfortable posture, whereas a maximal score of

11+ indicates a highly uncomfortable posture. In this experiment, the REBA score was computed in a very similar way as the RULA score. We hypothesized that the “load score" was equal to 0 as the Flystick weighed less than 1kg. We also hypothesized that the “activity score" was equal to 2 in any situation as the posture was mainly static and the manipulation involved small range repetitive motions.

Rated Perceived Exertion (RPE), using Borg’s CR-10 scale [Bor90] is a reliable subjective indicator of discomfort. It indicates, from 0 (no perceived discomfort) to 10 (nearly painful task), the task painfulness. We collected RPE score varying from 0 to 10 to describe how hard the participant feel his body is working as a subjective measurement after each manipulation trial.

4.4.3. Subjective Questionnaire

At the end of the evaluation session, the participants were asked to fill in a questionnaire with subjective ratings using the 7-point Likert scale for the two manipulation techniques according to the following criteria: intuitiveness, fatigue, ease of use, efficiency and global preference. Some demographic information was also recorded detailing the age, gender and 3D immersion experience of the participants.

4.5. Results

Using the data collected from the experiment, we conducted a statistical analysis to evaluate whether there was an improvement in the manipulation by the 7-Handle technique, compared to the traditional 6-DOF manipulation technique.

4.5.1. Completion Time

We had two different factors (manipulation technique and object size) which could influence the completion time of two consecutive phases of a manipulation trial. Therefore, we used the univariate repeated-measures two-way ANOVA with Greenhouse-Geisser adjustments for balanced design and within-subjects factor to evaluate the interaction of the two factors on the completion time. Interaction plots of the completion time of the approach phase (figure 4.A) and of the completion time of the refinement phase (figure 4.B) were created to display the five size levels on the x-axis and the mean completion time for each technique on the y-axis.

For the approach phase, we found no significant interaction effect between the two factors on the completion time (F(4, 119) = 1.470, p-value = 0.227). The results of the test for the main effect of the two factors, the object size factor (F(4, 119) = 4.485, p-value = 0.004) and the technique factor (F(1, 119) = 14.769, p-value = 0.003), showed a significantly independent effect on the completion time. In other words, the results showed that the completion time in the approach phase of the 7-Hand technique was significantly longer than the completion time of the 6-DOF technique.

For the refinement phase, the result with a Greenhouse-Geisser correction showed that there was a significant interaction effect between the manipulation technique and the object size factor on the completion time of the refinement phase (F(1.23, 95.61) = 3.899, p-value = 0.048).

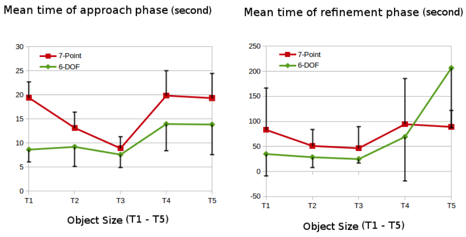

Figure 4: *Two interaction plots of the completion time in the approach phase (A) and in the refinement phase (B) of the two techniques in terms of object size factor.*

4.5.2. Discomfort Metrics

We analyzed the RULA, REBA scores and the RPE values using Wilcoxon’s signed-rank tests with continuity correction for testing differences between groups when there were two manipulation techniques and the same participants have used both (see figure 5). The result showed that there was a significant effect of the manipulation techniques on the RPE score (min = 0, max = 10): the test statistic W = 212, p-value = 0.01, the effect size r = 0.2318. In other words, the participants felt that the 6-DOF technique (median mdn = 2) was less comfortable to use than the 7-Handle technique (mdn = 1). However, we did not find any significant difference on the RULA score of the 7-Handle technique (mdn = 6.237) and the 6-DOF technique (mdn = 6.337): W = 855, p-value = 0.663, r = 0.0403. We did not find any significant difference either on the REBA score of the 7-Handle technique (mdn = 8.473) and the 6-DOF technique (mdn = 8.221): W = 1027, p-value = 0.414, r = 0.0752.

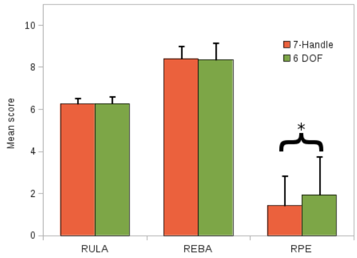

Figure 5: *Means of the RULA, REBA, and RPE scores of two manipulation techniques and their standard deviations on error bars.*

4.5.3. Subjective Questionnaire

A Friedman's test has been performed on the answers of the questionnaire and the p-values are showed in the table 2. The results showed that the participants found that the 7-Handle technique was less tiring and more efficient than the 6-DOF technique. We did not find any other significant differences between the two techniques in terms of intuitiveness, ease of use and global preference.

Table 2: *Mean scores and p-values of the subjective data of the first experiment with significant differences in bold.*

	7-Handle mean	6-DOF mean	p-value
Intuitiveness	5.50	6.50	0.157
Fatigue	**1.66**	**3.33**	**0.019**
Ease of use	5.25	5.08	0.963
Efficiency	**5.92**	**4.58**	**0.034**
Preference	5.66	5.08	0.527

4.6. Discussion

In this experiment, on both the interaction plots of the completion time in the approach phase and in the refinement phase (figure 4), we found a "fall" of the completion time curves for both the 7-Handle and the 6-DOF techniques at the object of average size T_3. This "fall" might be due to the task learning effect. All the participants manipulated the five objects twice using the two different techniques from the smallest object to the largest one. This order did not change for all the experimental sessions. Usually, the participants managed to use each technique efficiently to manipulate objects after two trials. However, it took the participants much longer to complete the manipulation when the objects became larger as it increased the difficulty of the task.

For the approach phase, the statistical results revealed the main effect of the manipulation techniques on the completion time: the completion time of the 7-Handle technique in the approach phase was significantly longer than the 6-DOF technique. This can be explained by the fact that in this phase, the participants usually used the third-level handle to control objects because they would have a 6-DOF manipulation. However, this third-level handle was sometimes difficult to be seen and reached because it was hidden inside the objects. This drawback can be easily solved by adjusting the position of handles relatively to each object so all the handles can be visible and easy to be reached. Besides, the completion time of the approach phase represented a small fraction of the total completion time (the approach phase's mean = 13.36 s, the refinement phase's mean = 72.71 s).

For the refinement phase, the interaction between the manipulation technique and the object size on the completion time was significant, indicating that the effect of the manipulation technique on the completion time differed when the object was small compared to when it was large. The completion time for the object of size T_5 (compared to the object of size T_4) using the 7-Handle technique was significantly shorter than using the 6-DOF technique. Additionally, there was no significant difference between the two techniques for the objects from the smallest to the near largest size. This result showed the advantage of the 7-Handle technique for manipulating large objects in an immersive environment. If the manipulated object was large, the overall view of the participant was obstructed and so he could not observe all the parts of the object at the same time. Another problem for the 6-DOF technique was that when the participant had several DOF simultaneously, a small movement might take the object far from its expected position. Usually, the user had difficulty keeping his hand motionless and it was difficult for him to keep the final position of the object unchanged when he released the control of the object. Due to the hand jitter and Heisenberg effect, the final position of the manipulated object was hard to get, especially when manipulating a large one. The 7-Handle technique enabled the user to locally control the position of each part of the manipulated object without worrying about unexpected movements of his hand.

The statistical analysis of the subjective RPE score showed that the participants felt less comfortable using the 6-DOF technique than using the 7-Handle technique. However, we did not find any significant difference on the RULA score as well as on the REBA score between the two techniques. This result could be explained by the fact that the RULA and REBA scores in the statistical analysis were the mean of the score of a whole manipulation task and therefore the value would be compromised because of the unstable and rapidly changing postures of the participants. In addition, almost all the RULA and REBA scores were considerably high. This significant measured postural discomfort might represent the great difficulty working in an immersive virtual environment in general where users do not have the support from physical tools such as tables, chairs, etc. Moreover, the unfamiliarity of the participants with the environment is a well-known factor of motor control alteration [SBSP03, PSB*14]. The lack of visual and physical references as well as the stereoscopic vision result generally in less controlled postures and kinematics [MBZB12] and this result partially explains the high postural discomfort scores in the current study. The difference observed for the RPE score might be explained by the fact that the participants could control their own body movements more easily with the 7-Handle technique. Using the 7-Handle technique enabled the participants to locally manipulate each part of the manipulated object due to the arrangement of different handles all over the object, contributing to enhance their familiarity with the manipulation task. Moreover, with the 6-DOF technique, the participants needed to keep their hand still longer in space and at the same time to pay attention to the whole object to manipulate it efficiently.

Regarding the result of the subjective data, because when using the 7-Handle technique, the participants did not have to keep their hand motionless in the space in the CAVE-like system for long time, they found it was less tiring and more efficient than the 6-DOF technique. Even though we did not find any other significant differences in terms of intuitiveness, ease of use and global preference, in general, the participants preferred the 6-DOF technique for small objects because it was more natural and intuitive to control them in 6 DOF. However, the 7-Handle technique was more preferred for large objects because this technique enabled the participants to control the objects more accurately, especially when the objects obstructed the participants' view.

5. Conclusion and Future Work

We have introduced the 7-handle technique which is a direct manipulation technique for 3D objects in virtual environments, especially for large objects. We have compared the 7-Handle technique with the 6-DOF technique for 3D object manipulation in an immersive virtual environment. The statistical results from the experiment showed that for manipulating large objects, the 7-Handle technique obtained better results than the 6-DOF technique in terms of completion time, fatigue and efficiency criteria, and RPE score.

In order to completely evaluate the 7-Handle technique, we could study different ways to put the first-level handles of the tool in place and the impact of their position on the efficiency of the manipulation technique. In addition, further experiments of the impact of the shape and size of objects on the manipulation must be also conducted (e.g., evaluating the two manipulation techniques using objects which have the same shape but different sizes, and objects which have the same size but different shapes). Theses experiments would also provide further results about the impact of learning time of the manipulation techniques on completion time.

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