Interaction technique's and task's degrees of freedom manipulation during orientation task in VR environments

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ABSTRACT

In the present paper, we present our study about user's behaviour during orientation tasks. More specifically, in this study we were interested in the influence of interaction modality and task's complexity on user's strategy to achieve orientation tasks. Because common Human - Computer Interaction (HCI) measure aren't sufficient to understand user's behaviour during the task, we introduce a new measure called *IMDOFM, Independency's Measure of Degrees Of Freedom Manipulation*. This measure gives quantitative informations on how the user is orientating an object. Our results suggest that interaction techniques have a strong influence on the user's strategy to rotate an object. It seems that even the interaction technique allows the users to integrate the manipulation of several task's DOF in a single gesture, he tries to decompose the DOF manipulation, thus dividing 3 DOF orientation tasks into successive 1 DOF tasks. On the contrary of what is usually observed, our results show that this decomposition does not introduce any loss in precision or achievement time.

Index Terms: H.5.1 [INFORMATION INTERFACES AND PRESENTATION]: Artificial, augmented, and virtual realities— [H.5.2]: INFORMATION INTERFACES AND PRESENTATION—User Interfaces

1 INTRODUCTION

Virtual Reality (VR) technology and its applications have been considered as a major step towards a more direct and intuitive way of interacting with 3D scenes. By copying real world interactions into virtual applications, researchers were expecting to combine the best of them. However, it seems that interacting with a virtual environment needs to reconsider the way of designing interaction techniques even for the most simple actions like designating or rotating objects.

Indeed, the interaction context of classical desktop stations is very different from what users may experience in VR environments. Such environments provide users with 3D stereoscopic displays immersing them in interactive virtual scenes (see Figure 1). Augmenting interaction dimensionality by the addition of this third dimension was considered as an interesting way of introducing more natural interaction. As a matter of fact in VR environments users can interact with its surrounding scene using everyday commands like grabbing, turning, etc. [2] However while interaction seems more intuitive, VR setup are mainly used for visualisation applications. It seems that providing users with more natural commands is not sufficient to bring them with precise interaction techniques.

Since the emergence of desktop environment in the late 70s, many efforts was made by HCI community to understand user's behaviour when performing critical tasks like pointing or dragging.

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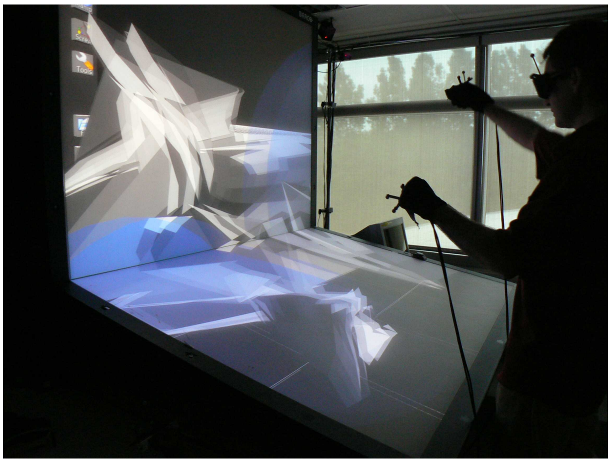

Figure 1: User is grabbing the object with one hand while performing a deformation with the other hand.

Fundamental works like the definition of *Fitt's Law* [4] helps designers to understand the user's behaviour when pointing objects in desktop environments. Understanding user's behaviour is critical to help designers developing efficient interaction techniques. Because of fundamental differences in interaction context, theoretical framework already existing for desktop environments can not be directly applied to 3D VR environments. The difficulties researchers encounters designing a generalisation of Fitt's Law suitable for VR environments [6], illustrate difficulties that arise with such environments.

In this study, we are interested in understanding users' behaviour during orientation task in semi-immersive virtual environments (SIVE). We studied users' behaviour during orientation tasks using two different techniques, one integrating and the other facilitating the manipulation of task's DOF. Even if each technique allow users to rotate virtual objects, their design is fundamentally different. By trying to understand the user's behaviour during orientation tasks, we hope that it will help us design more efficient interaction techniques to rotate objects in SIVE.

2 PREVIOUS WORK

The mental representation and the achievement of a rotation task is very complex [13]. Some studies have tried to investigate which factors, in addition to task's complexity and interaction technique, influences task's difficulty [11, 16]. *LaViola et al.* highlighted the fact that the presence of stereoscopy or head-tracking has a strong influence on performances [11]. Another study conducted by *Prabhat et al.* [16] showed that the environment has a significant influence on user's performance during orientation tasks. It seems that performing the task in a fully immersive environment, like the CAVE, leads to longer achievement times and more important error rates than in a desktop environment.

Even before the emergence of VR, rotation tasks in desktop environment has been widely studied. One of the first difficulty in computer graphics was to design interaction modality using 2 DOF devices – typically the mouse or the pen – for 3 DOF orientation tasks. First interaction techniques that comes out were based on 2D widgets (like sliders) manipulation [3]. Even if sliders manipulation provides users with great precision, this interaction modality forces users to manipulate independently each axis of rotation. It also deports user's attention from orientation task to slider manipulation and vice versa. Switching from one task to the other may explain part of the large increase in time needed to achieve the task. To overcome this limitation, *Shoemake* designed *Arcball* [17], a widely used interaction modality. This technique allows the user, with a single gesture, to perform complex and precise orientation. Another approach is to design specific devices to perform the task. *Sphere Ball* [9] is a specific device aiming at orientating 3D objects by controlling all 3 DOF at the same time. It is a magnetic tracker embodied in a plastic ball that can be rotated to orientate virtual objects. The shape of the device and the mapping between interaction device rotation and object rotation makes it easy to use. But introducing a specific device to achieve the orientation task can be cumbersome especially in a highly interactive application involving many different tasks. Forcing the user to grab the device and switch from one device to the other when necessary can break interaction flow. The emergence of virtual reality environments provide users with 3D virtual environment in which users can have more direct and more natural interactions through 6 DOF devices, more specifically using data gloves.

Users can interact with their surrounding environment through everyday commands. However even if rotation tasks seem more natural to achieve using 6 DOF interaction devices, users aren't provided with efficient and precise interaction modalities. For example because of evident anatomical constraints, when grasping an object (real or virtual) we can't turn it from 360 degrees around any axis of rotation using a single gesture. *Poupyrev et al.* implemented a direct rotation technique with which, by amplifying rotations amplitude using a transfer function, the user can perform large rotations using single actions [15]. Many of those works were about trying to provide users with an efficient and precise modality to rotate objects in 3D environments. Nevertheless in order to understand differences between interaction techniques we may consider more fundamental characteristics.

Usability properties like *nulling or directional compliance* [14] may highlight differences between interaction techniques providing similar performances in terms of common HCI indicators like precisions, achievement time or error rates. In the present study we designed new measures to understand the user's behaviour during orientation tasks and thus try to understand more fundamentals differences between interaction techniques. These new measures aims at understanding DOF manipulation when the user rotates objects in SIVE. In fact, finding a way of rotating an object to have a specific orientation can be done with various strategy. One would be to rotate the object randomly to get to an orientation close to the target, and make some final adjustments to match as precisely as possible the target orientation. Another one would be to rotate the object around one axis at a time to get to the final orientation. The strategy used to achieve the task may depend on how the interaction technique integrates the task's DOF. Previous works recommend to integrate task's DOF to provide the users with efficient interaction techniques [9]. Using these measures we hope that it will help us understand user's behaviour during orientation tasks regarding DOF manipulation and highlight fundamental differences between interaction techniques.

3 EXPERIMENTAL CONDITIONS AND APPARATUS

In this study, we compared the user strategy during orientation tasks using two interaction techniques. After describing the two interaction techniques used in this study, we explain measures and experimental conditions.

3.1 Interaction techniques

For this experiment, we studied the user's behaviour when using two rotation techniques. One of them is a commonly used rotation technique and the other is a bi-manual interaction technique we propose. For both rotation technique we use in this study, we introduce a constant mapping between users gestures and rotations applied to the manipulated object. We now describe the interaction techniques.

3.1.1 Indirect manipulation

We wanted to use a condition where the user would realise rotations directly by grabbing and rotating the object with his/her hands, as it is the more immediate and intuitive way to interact in virtual reality applications. However, such technique have a limited range of action since the object manipulated must be presented within arms reach. In situations were the users have to reach for the objects, performances would probably be affected.

To overcome this difficulty, we implemented a technique were the user would grab an object positioned immediately at arms reach, without having to bend to grab the house. The user grabs the object with his dominant hand, and can then orientate it just by rotating the hand. By rotating this object, the user affects the targeted house by the same rotation (see Figure 2).

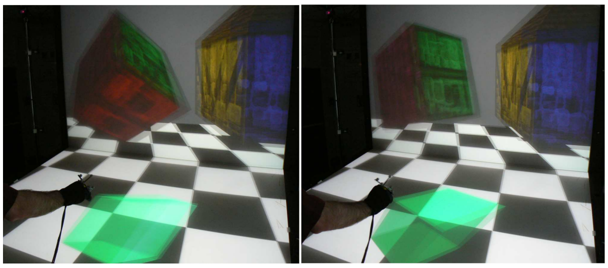

Figure 2: Indirect manipulation technique. User's grasping and turning the cube at arms reach.

3.1.2 Bi-manual plane constrained rotation (BPCR)

This technique is inspired from a recent trend in the field of 3D interaction. Recently, new approaches have been explored that aim at restraining the DOF simultaneously manipulated by the users in order to reduce the downward drift of the performances observed for common interaction tasks in SIVE. For example, these approaches try to simplify 3D interactions by adding some real life constraints inspired from the semantics and behaviour of the object manipulated in the real world. Studies from *Smith et al.* and *Kiyokawa et al.* [10, 18] show that these approaches can lead to significant improvements.

3D interaction based on 2D inputs has lately also been explored as a possibility of providing more intuitive and efficient interaction for 3D virtual environment. In this approach, efforts tend to propose new interaction techniques that combine 2D and 3D environments [8]. Such techniques could supply us with solutions that may improve simultaneously users performances and users satisfaction at least regarding VR environments [7]. The BPCR modality tries to implement these ideas in SIVE in a way that does not require the use of ad hoc controllers.

This modality takes advantage of our specific application environment. We wanted to propose to the users a technique that would not necessitate a drift in the realisation of the task by switching users attention between the object manipulated and a manipulation widget. Since the bottom screen of a workbench is at arms reach, we thought it could be a first step towards this purpose to exploit it by asking the users to touch this screen with is forefinger to enter in rotation mode. By moving his finger along the screen axis, the user commands a rotation around the corresponding axis of the objects coordinate system. The user can use both hands simultaneously or successively to realise rotations by touching the screen. Each hand gives him access to 2 specific axis of rotation of the object, as shown in figure 3. This modality allows to realise a 3 degrees of freedom interaction for rotations while looking at the object manipulated.

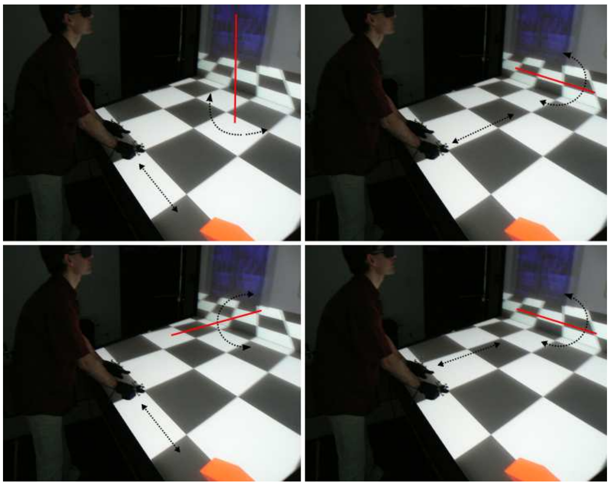

Figure 3: Bi-manual plane constrained rotation : the two images on the top illustrate the mapping between dominant hand (DH) movements and rotations, on the bottom, the mapping between non dominant hand (NDH) movements and rotations

3.2 Experimental conditions

We asked 13 subjects to participate in the comparison of two interaction techniques : the bi-manual plane constrained interaction (BPCR) and the indirect rotation technique (IM). Subjects have different levels of experience with SIVE. The task consisted of rotating an object to orientate it in the same position has a given target (orientation of the target do not change across conditions and can be represented as a unit quaternion). Since the task used in similar researches consists of orientating a house [3, 15, 16], we used the same object for our experiments (see Figure 4).

The experiments spread out as follow. We explain the task they are requested to achieve and describe the rotation technique before the rotation techniques switching. They were asked to match as closely as possible the manipulated object's and the target's orientations. During the experiment, between each tasks subjects could rest as long as they desired. To start a task, subjects were asked to put their dominant hand into a red cube. The cube then turned yellow and after a second it turned green, starting the task (see Figure 5). When subjects thought that the actual manipulated object's orientation is the most accurate results they can produce, they validate their realisation by activating the cube.

Each subject was asked to realise 24 rotations using each technique. To avoid learning trade-off, we used a latin-square distribution of the rotation techniques order of presentation. Subjects were asked to perform two types of orientations : *simple* and *complex* orientations. Considering rotation difference between manipulated object and the target for every axis of the world coordinate system, an orientation was considered as simple when there was a rotation difference around one axis. When subjects were asked to manipulate at least two world coordinate system axis, it was considered as complex. For each condition, there was 12 simple and 12 complex orientations.

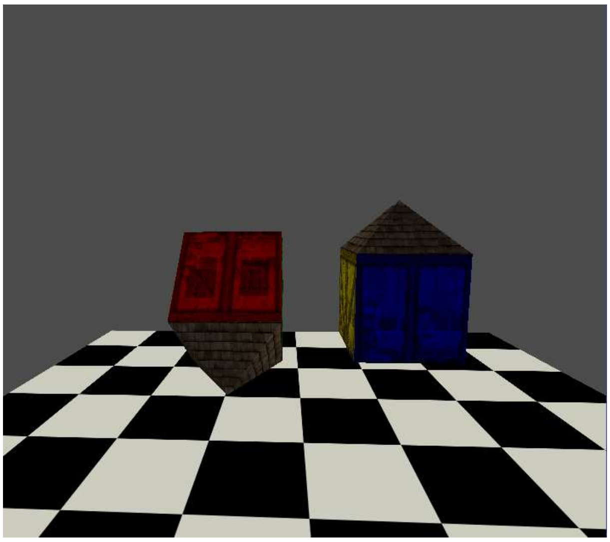

Figure 4: Rotation task orientate the house on the left in the same position as the target on the right.

3.3 Apparatus

Each experiments was conducted on a Barco Consul, a semi-immersive Virtual Reality environment using stereoscopic display – resolution 1400x1050, refreshed at 100Hz – and CrystalEyes CE-2 glasses. Images were generated using two HP Workstation XW8000 – one for each screen – fit out with a 3Ghz Quad Xeon and a NVIDIA Quadro FX 3000. Head and hands tracking was ensure by the ART tracking system and magnetic trackers. Users used XIST Data Gloves to interact with the virtual reality environment.

3.4 Measures

During each session we record different quantitative datas.

- Orientation precision
- Interaction device position (Magnetic Trackers)
- Interaction device state (Data Gloves)
- Validation button state

Datas were collected every 0.5 second. Using this data sample we computed several measures. The most relevant ones for the present study are :

- Global angular velocity
- Angular velocity along each axis of the world coordinate system (see Figure 6)
- Number of rotations
- Time to achieve the task
- Orientation's precision

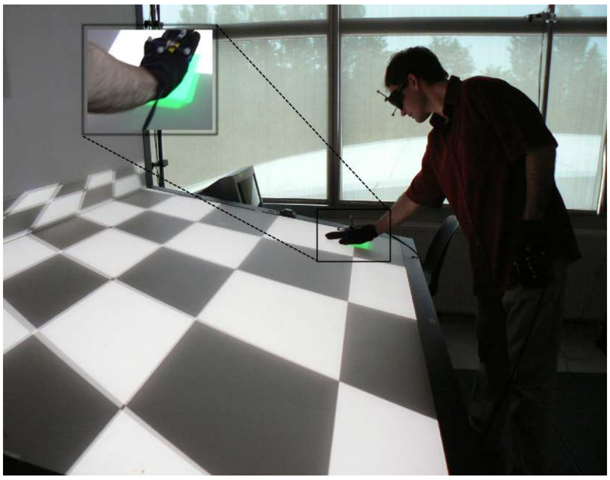

Figure 5: Subjects start or end a task by activating the cube using dominant hand.

Global angular velocity is defined as the angular velocity in degrees per second the user rotates the object. The angular velocity along each axis of the world coordinate system is the angular velocity (in degrees per second) along each axis, *x*, *y* and *z*. The number of rotations represents how many rotations subjects used to achieve the task. A rotation begins when the appropriate command is activated and depends on the interaction technique (grasping the cube for indirect technique, touching bottom screen for BPCR, etc.) and ends when the command is released.

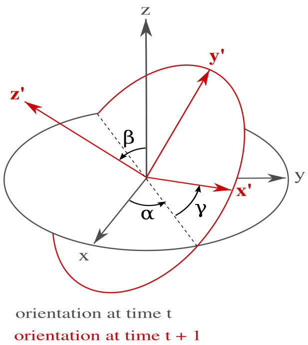

Figure 6: Angular velocities illustration. α, β and γ represent the angular distance along each world coordinate system axis between object at time t and $t+1$. Using these angular distances we compute angular velocities along each axis.

Measures presented above are widely used for experimental studies in the field of HCI. But these measures aren't always sufficient to understand differences between interaction techniques. Some new measures need to be designed to understand more fundamental specificity of interaction devices [12] or interaction techniques. Indeed, we observed in an other study that results in terms of angular precision are similar for each interaction technique. Moreover, using IM and BPCR interaction techniques users performed similar completion times (see Table 1). More fundamental differences regarding the strategy subjects used to achieve the task may appear even if these results do not highlight differences between IM and BPCR. To observe these differences, we had to design specific measures to understand and study the user's behaviour during orientation task.

	IM	BPCR
Time	14.29	14.53
Angular precision	4.38	4.12

Table 1: Task completion times and angular precisions for all 4 modalities. Execution times are given in seconds, angular precisions are given in degrees.

3.4.1 IMDOFM : Independency's Measure of DOF Manipulation

In this study we want to know if the user is performing a rotation around an axis of the world coordinates system (called *simple rotation*) or performing a more complex rotation for example by combining simple rotations (called *complex rotations*). We define *IMDOFM*, a new measure aiming at evaluating rotations' degree of complexity. We will now define and explain our measure.

We expect this measure to be high when the subject is manipulating one DOF independently from the others, while when the user is manipulating several DOF at the same time and similarly the measure must be low. Considering that IMDOF value is between 0 and 1, we illustrate the expected behaviour of IMDOFM measure on three examples of particulars rotations (α, β and γ are angular velocities illustrated in Figure 6).

1. $\alpha = 0$, $\beta = 70$, $\gamma = 0$: user rotates the object around one axis so we expect IMDOFM value to be equal to 1

2. $\alpha = 25$, $\beta = 25$, $\gamma = 25$: user rotates the object around all axis at the same time with equal velocity so we expect IMDOFM value to be equal to 0

3. $\alpha = 25$, $\beta = 25$, $\gamma = 150$: user rotates the object around all axis at the same time but the rotation is much more important around z axis so we expect IMDOFM value to be between O.5 and 1

We consider three curves representing the angular velocity along each of the three axis of the world coordinate system (see Figure 7). Those curves noted f_x, f_y and f_z represent respectively angular velocity profile's along *x*, *y* and *z* world coordinate system axis during the task. Considering a period of time, for example between t_n and t_{n+1}, we want to know how the user is performing a rotation. The integral of these curves between t_n and t_{n+1} gives a quantitative measure of the amplitude of the rotation along each axis. These integrals are noted I_x, I_y and I_z and defined as follow :

$$I_x = \int_{t_n}^{t_{n+1}} f_x(x)dx,$$

$$I_y = \int_{t_n}^{t_{n+1}} f_y(x)dx,$$

$$I_z = \int_{t_n}^{t_{n+1}} f_z(x)dx$$

To have the relative importance of each angular velocity during a period of time we can compute P_x, P_y and P_z.

$$P_x = \frac{I_x}{I_{tot}}, P_y = \frac{I_y}{I_{tot}}, P_z = \frac{I_z}{I_{tot}}$$

With $I_{tot} = I_x + I_y + I_z$. This first normalisation gives us a measure which is independent of the angular velocity. Finally, the measure of dependency is defined as :

$$IMDOFM_{t_n} = \frac{|P_x - P_y| + |P_x - P_z| + |P_y - P_z|}{2}$$

Each part of the sum gives the absolute difference between each rotation and the sum gives us a quantitative value of the amount of difference between each rotation. Finally, to have a value ranging from 0 to 1, we divide the sum by 2.

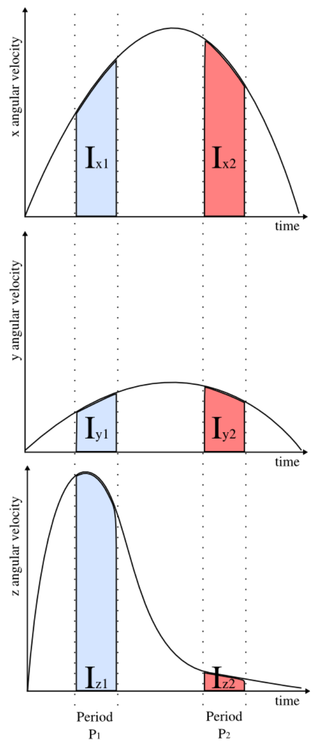

Figure 7: An example illustrating the independence measure. The three curves represent the angular velocity along each axis. The more the I_x, I_y and I_z values differs, the more the independence value is high.

This measure was designed to characterise and understand user's behaviour during orientation task. In a more general way, this measure can characterise the DOF manipulation during other tasks. For example to understand DOF manipulation during designation task, we could use IMDOFM measure and just substitute angular velocities by linear velocities along each axis of the world coordinate system.

To help us understand user's behaviour during the task, we also wanted to have a quantitative measure characterising the evolution of the object orientation state. That's why we define an extension of IMDOFM, the *OOS* measure.

3.4.2 OOS measure : Object Orientation State measure

To understand how subjects rotate the object during the task we designed the IMDOFM measure. But in order to have a better understanding of subjects' DOF manipulation it could be interesting to have a quantitative measure describing the manipulated object orientation state. Applying the IMDOFM measure to world coordinates system's axis, angular velocities profiles gives us informations about how users are rotating objects. By applying this measure to angular distances for each axis of the world coordinate system, the measure gives us informations about how object is currently rotated. More precisely, we compute this measure by replacing the definition of I_x, I_y and I_z. I_x is equal to the angular difference along x axis between the manipulated object's and the target's orientation. I_y, I_z are defined by the angular difference along the appropriate axis.

A value of OOS measure close to 1 means that the object has a orientation close to the target around two axis, but not around the third axis. A value close to 0.5 means that the angular distance between the manipulated object and the target is low around one axis and significantly higher for the two other. Finally the value is close to 0 when the orientation distance is high around the three axis.

In addition to common measures used in HCI, we designed and use these two new measures to help us understand subject's behaviour and strategy used during orientation task for several rotation techniques. Using these two measures we hope that we can highlight differences between interaction techniques regarding DOF manipulation.

4 RESULTS

We present results we obtained regarding angular velocities, IMDOFM measure, OOS measure and number of rotations. To perform the statistical analysis of our results, we used multiples ANOVA and T-Tests.

4.1 Angular velocity

Considering angular velocities during orientation tasks, mean rotations speed is different for each interaction technique (see Table 2). Regarding global angular velocity or angular velocity along x axis, subjects rotate the object quicker with BPCR (Bimanual Plane Constrained Rotation) than other techniques. This result is statistically significant ($p < 0.0001$). But regarding angular velocity along y or z axis, subjects performed rotations quicker using IM. This result is also statistically significant. Regarding these first results, we can notice that each rotation technique offers different level of control of each task's DOF.

Modality	Vel_{tot}	Vel_x	Vel_y	Vel_z
BPCR	*24.614*	*10.832*	7.356	5.251
IM	19.221	8.710	*9.224*	*9.950*

Table 2: For each interaction technique, mean angular velocities in $^o/s$ during orientation task.

The first results we obtained don't give us precise informations about user's behaviour during the task. With a finer analysis using angular velocity peak as a descriptor of user's intention, we wanted to see if user's behaviour is different before and after angular velocity peak. We call phase 1 (P1) the phase before the velocity peak, and phase 2 (P2) the phase after velocity peak. Considering results in Table 3, mean angular velocity, mean number of rotations and mean IMDOFM measure across the two interaction techniques, the differences between value obtained for P1 and P2 are all statistically significant ($p < 0.0001$). According to these results, the subjects' behaviour is different during the two phases of the task.

Measure	**P1**	**P2**	**T-Test**
Angular velocity ($^o/s$)	40.065	18.407	$p < 0.0001$
Number of rotations	3.808	4.952	$p < 0.0001$
IMDOFM	0.807	0.766	$p < 0.0001$

Table 3: For each measure, the value's difference between first phase and second phase is statistically significant.

The angular velocity is different regarding interaction technique, task complexity or orientation amplitude (see Table 4). Subjects reach higher velocity using BPCR than IM technique. BPCR velocity peak is 52.08% higher than the other technique's velocity peak. This difference is statistically significant (see Table 5). Velocity peak also differs with various orientations complexity and amplitude velocity. When orientation complexity or orientation amplitude increase, velocity peak also increases significantly (see Table 4).

Pair	P-value	Modality	Vel. Peak
BPCR vs IM	0.034	BPCR	297,734
		IM	195,764

Table 5: Statistical difference between of angular velocity peak for each interaction techniques. p value limit is 0.05.

4.2 IMDOFM and OOS measures

To try to understand user's task's DOF manipulation, we computed IMDOFM value during all the experiments. Table 6 gives mean IMDOFM value for each interaction techniques. We can notice that IMDOFM value is much higher for BPCR than for the IM technique. These results is statistically significant with $p < 0.0001$. We can also notice the global high IMDOFM value with a mean of 0.76775. These results suggest that subjects manipulated task's DOF differently in relation to the interaction techniques used. Using BPCR, subjects tend to manipulate each task's DOF independently. This phenomenon isn't so important for the IM interaction technique. This may show that interaction technique has a strong influence on how subjects are combining DOF when achieving the task. However, the global high value of Independence measure suggests that subjects are trying to decompose task's DOF.

Pair	P-value	Mod.	IMDOFM
BPCR vs IM	$p < 0.0001$	BPCR	0.959
		IM	0.696

Table 6: There's a significant interaction between interaction technique and independence measure.

We also computed OOS measure on manipulated object's orientation to understand if subjects get through specific steps during orientation. Table 7 reports mean maximum OOS measure during the tasks. This maximum is identified before subjects are to close to the target's orientation to avoid bias in the measure. Indeed, our OOS measure is independent of orientation distance. When orientation distance to the target is small, a little difference between angular distances along each axis could lead to an unwanted increase in OOS measure. For each interaction technique, maximum OOS measure is very high, meaning that during the task and when subjects are not close to the target's orientation, the orientation distance between the manipulated object and the target is close along two axis and more important along the third one.

Modality	OOS measure
BPCR	0.865
IM	0.864

Table 7: Orientation evaluation thanks to *OOS* measure applied to angular precisions along each axis.

To understand user's behaviour we also look at the OOS measure when peak velocity appears to understand what is the object's orientation state when user is switching from P1 to P2. We only consider OOS measure in the context of complex orientations and ignore OOS value when subjects were asked to achieve simple orientations, because in the context of simple orientations, OOS measure could be biased. There's no statistical difference between interaction techniques' OOS measure. Whatever was the interaction technique used to achieve the task, when velocity peak appears OOS measure is very close to 0.5 (see Table 8), meaning that the angular difference between the manipulated object and the target is low around one axis but high (and similar) around the two other axis.

Modality	Mean
BPCR	0.490
IM	0.411

Table 8: For each interaction technique, mean *OOS* measure when angular velocity peak appeared.

5 Discussions

Using results we obtained in this study, we will highlight task's achievement similarities between rotation and designation task. We will also try to understand DOF manipulation during rotation task.

5.1 Coarse and fine rotations during orientation task

Our intuition was that users' behaviour during orientation task is divided in two phases similar to the two phases often observed during designation task [1]. During the first phase users' try to get closer to the target using large rotations. During this phase users' don't need precision. When they are close enough to the target, they entered in the second phase. During this phase, users need precision to make adjustments to get as precisely as possible close to the target. During this phase, users may perform smaller and slower rotations providing users with more precisions. As for designation task, we identify the time when switching for first to second phase as the time when angular velocity peak occurs. During P1 subjects rotate the object quicker than P2. This phenomenon is similar to the one observed for designation task, linear velocity is more important during coarse approach than during final approach.

IMDOFM measure shows that subjects use more simple rotations during the first phase than during the second phase. We think that the main reason of this phenomenon is that during first phase users try to align the object along one axis to simplify the task complexity. They also perform more rotations during second phase, maybe to perform little and precise adjustments to get as precisely as possible close to the target, whereas during first phase subjects make fewer rotations to get quickly and coarsely closed to the final orientation.

Velocity peak characteristic during rotation and designation task also presents some similarities. Regarding designation task, when distance between the manipulated object and the target increases, because users needs to cover larger distance velocity peak also increases [1]. During orientation task, when initial rotation distance increases the angular velocity peak also increases. Moreover velocity peak increase also appears when the task is more complex. We think that subjects may perceive orientation complexity and orientation amplitude as two factors characterising orientation task difficulty. When task's difficulty perceived by the user increases, by performing large rotations users may try to coarsely match the target's orientation thus reducing task complexity and simplifying task's planification.

We study more precisely how users are manipulating interaction techniques' DOF and task's DOF using results obtained regarding IMDOFM and OOS measures.

Modality	Mean	Complexity	Mean	Amplitude	Mean
BPCR	297.734	CO	234.365	LR	280.553
IM	195.764	SO	188.920	SR	142.732

Table 4: Pick of angular velocities in degrees per second regarding interaction technique and orientations types. Orientations types are CO (Complex Orientation), SO (Simple Orientation), LR (Large Rotations) and SR (Small Rotations).

5.2 Degrees of freedom manipulation

Using IMDOFM measure, we study DOF manipulation during orientation task. First, we can notice that for each interaction technique, mean IMDOFM is high. It may suggests that even if the interaction technique does not provide any specific cues helping the manipulation of one axis at a time, subjects may prefer to perform simple rotations rather than complex rotations (see Table 6). But we can notice significant differences between interaction techniques regarding mean IMDOFM value. The mean difference between mean IMDOFM value for BPCR and the IM interaction technique is more than 50%. These results may identify a specific behaviour of manipulating DOF of interaction techniques. Using BPCR the users try to decompose the global orientation tasks into several simple rotations.

IMDOFM value is close to 1 when using BPCR, suggesting users are manipulating one axis at a time, like for sliders manipulation. But time to achieve the task using BPCR is similar to IM, an interaction technique allowing user to manipulate all DOF at the same time. Regarding this result we may reconsider the reasons why sliders manipulation isn't suitable for efficient object's orientation. As a matter of fact, sliders manipulation is often presented as a cumbersome rotation technique because users are required to decompose 3 DOF orientation into successive 1 DOF orientations. But it also requires users to select sliders very often. This can lead to a large increase in achievement time especially when performing little orientation's adjustments, requiring user to go and select each slider. That may explain sliders poor performances by the add of selection time and not by the decomposition of rotations.

Orientation tasks has 3 DOF, which are the orientation distances along each world coordinate system axis between the manipulated object and the target. Thanks to OOS measure we identified specific behaviours when achieving the task. One interesting result is that when subjects switch from P1 to P2, the mean OOS value is 0.4495. As it is described in Section 3, an OOS value close to 0.5 means that the angular distance between the manipulated object and the target is low around one axis and significantly higher for the two others one. So subjects are switching from P1 to P2 when the orientation between the objects matched around one axis. When aligning the objects along one axis, the subjects may think that they are closer to the target and reduce their angular velocity to have a better control. It suggests that the task's difficulty perceived by the user is defined by the orientation distances between the objects and the orientation complexity. Orientation complexity may be high when objects are not aligned along any axis and may decrease when they are aligned along one or two axis. Orientation distance and axis alignment may play different roles in the perception of task difficulty. By aligning the objects along one axis, subjects may try to simplify task complexity.

We also found out that mean of maximum OOS measure considering every rotation technique is more than 0.8 and the values are similar for each interaction technique. This similarity suggests that at a moment during the orientation tasks, subjects closely aligned the manipulated object and the target around two axis but not along the third one. This may confirm what was suggested in previous paragraph. In a first step, subjects simplify the orientation task by orientating the object correctly along one axis, and than they align it around two axis, thus reducing the task to a 1 DOF task. To match the target subjects need only to rotate the object around the last axis. By using this strategy users may reduce task's DOF to simplify mental rotations and task's planning. This is only an hypothesis since we do not make any verification about temporal precedence of one axis alignment and two axis alignment.

6 Conclusions

Orientation task is complex and widely used in lots of applications whether in VR environments or desktop setup. Experimental studies are needed to understand users' behaviour in order to provide them with precise interaction technique. In this study we compare subjects' behaviour during orientation task using two different rotation techniques. Using common HCI indicators and measures, we highlighted the fact that the users decompose the orientation task two separate, a *coarse orientation phase* followed by a *precise orientation phase*.

We also designed two new measures, *IMDOFM* and *OOS*, which was designed to characterise and understand DOF manipulation during orientation task. Indeed, during each of those phases, we noticed that subjects try to perform successive simple rotations to achieve the task thus dividing a 3 DOF task in three 1 DOF tasks. When appropriate cues were provided to the subjects throughout interaction modality, subjects take advantage of it to help him decompose the global orientation using simple rotations. This results are in opposition to previous studies asserting that interaction techniques in VR environment should integrate the manipulation orientation task's DOF. In this study, we observed that using BPCR subjects decompose the orientation tasks by manipulating one axis of rotation at a time. However, using this technique we did not observed any significant decrease regarding users performances in relation to an interaction technique integrating task's DOF. Moreover, it seems that the users try to successively reduce task complexity by aligning the manipulated object and the target first around one axis then around two axis. But to confirm that we need to conduct another study in order to verify the temporal precedence between the alignment around one axis and the alignment around two axis.

Considering our results, we do not say that users always want to perform simple rotations. The present study highlight the fact that interaction technique has a strong influence on rotation strategy. But we need to conduct another study to more deeply understand the influence of interaction technique. For example it would be interesting to study the influence of the mapping between hand gesture and rotations applied to the object using BPCR. Indeed, we observe that using BPCR subjects achieve the task using almost only simple rotations. But this decomposition may be due to the fact that the mapping between hand gesture and rotation is not understandable enough to allow subjects to combine simple rotations to produce complex rotations.

We observed that orientation is divided in two phases that can be identified using angular velocity peak detection. A study about nonlinear mapping, like PRISM [5], might be interesting to conduct. Subjects are rotating the object with high velocity when there's no need of precision whereas low velocity indicate the need of precise rotations. This idea of using velocity has a descriptor of user's intention is well known in HCI and has lead to efficient interaction techniques [5]. We could apply this idea to our BPCR interaction technique, and study the influence of such a mapping on user's performances and behaviour. This example of non-linear mapping could provide user with a faster rotation technique during the coarse phase of orientation allowing him to perform rotations of larger amplitude. But this mapping could also provide users with a more precise technique by helping them to perform smaller adjustments during the final phase.

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