Influence of Degrees of Freedom's Manipulation on Performances During Orientation Tasks in Virtual Reality Environments

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Abstract

In this paper we investigate the influence of the integration and separation of the Degrees Of Freedom (DOF) on the users' performances during 3-D orientation tasks. For this purpose, we compare the performances and the level of DOF's coordination users reached using two interaction techniques, one integrating and the other separating the task's DOF. To evaluate the degree of coordination, we propose a new behavioural measurement (called *Magnitude of Degrees of Freedom's Separation*), which provides the number of DOF simultaneously manipulated during an orientation task. The results of our study suggest that users are not able to integrate the manipulation of all the DOF during the whole task even using a direct manipulation technique. Moreover, if the interaction eases the task's decomposition, its use can lead to significant improvements regarding the achievement times. This result suggests that the simultaneous manipulation of all the DOF does not necessary lead to the best performances.

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

Keywords: Human - Computer Interaction, Virtual Reality, Degrees of Freedom, Measurements, Rotation, Interaction Technique

1 Introduction

Virtual Reality (VR) technology has been considered a major step toward a more direct and intuitive way to interact with 3-D worlds. In addition to be immersed in 3-D scenes, in a semi-immersive VR environment (SIVE) users are able to interact directly with virtual objects (an example of a SIVE is given in Figure 1). The use of six degrees of freedom (DOF) devices –such as data gloves and optical tracking systems– allows users to interact with 3-D objects using natural gestures such as grabbing, moving or turning.

At first, many works focused on the design of new interaction techniques –such as the *over-the-shoulder-deletion* technique [Mine et al. 1997]– strongly inspired from our everyday life. By exploiting the users' natural skills, they expected to provide users with a more intuitive and more efficient interaction. However, the use of such a direct interaction introduces new difficulties. The troubles researchers encounter to design a generalization of the Fitt's Law suitable for 3-D [Grossman and Balakrishnan 2004] illustrate the issues that arise in such environments.

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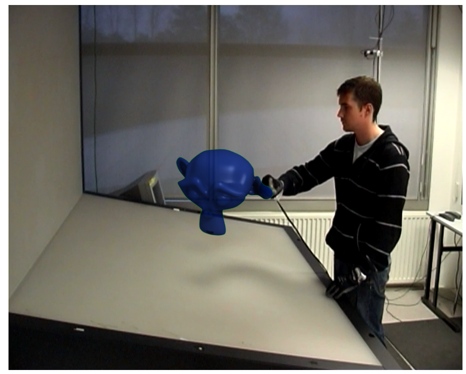

Figure 1: *Example of a user warping a 3-D object using his hand.*

We think that the increasing number of DOF simultaneously manipulated in VE may account for certain difficulties users encounter when interacting in such environments. In fact, when using direct interaction techniques users are required to manipulate up to six DOF at the same time just to position an object. This is not the case using a mouse where users manipulate only up to two DOF simultaneously. This is also not the case in the physical world where all the physical constraints –such as gravity– reduce the interaction dimensionality. We think that in certain situations of interaction, reducing the number of DOF simultaneously manipulated may lead to better performances. This necessitates to understand how DOF are manipulated during interaction tasks.

In this work, our objective is to observe the influence of the DOF's integration and decomposition on the users' performances during a fundamental task: the orientation of a 3-D object. This paper is organized as follow. In Section 2, we introduce previous works related to our purpose. Than, in Section 3 we introduce the *Magnitude of DOF's Separation* measurement. We use this measurement to quantify the level of the DOF's coordination during the orientation task. In Section 4 we describe the design of the experimental study we conducted to examine the influence the DOF's manipulation on the users' performances. Than, in Section 5 we present the results we obtained in order to analyze it in Section 6. Finally, in Section 7 we make some conclusions and propose some perspectives for this work.

2 Related works

Previous works have been interested in investigating how users manipulate the DOF associated to a task and its influence on the users' performances.

2.1 Degrees of freedom

Jacob et al. [Jacob et al. 1994] introduced the principle of *integrality* and *separability* of the perceptual structure of an input device. Each device has its own perceptual structure that gathers all the attributes that can be modified. On the other hand, each task involves the manipulation of several attributes and also has its own perceptual structure. The perceptual structure is integral when the semantic distance between the attributes is low. On the opposite, if the semantic distance is important the perceptual structure is separable. *Jacob et al.* studied the influence of the perceptual structures on the users' performances. They showed that to obtain the best performances, the perceptual structure of the interaction device should match the perceptual structure of the task.

Assuming that the orientation task has an integral structure, we should use an interaction device with an integral perceptual structure to obtain the best performances. In practice, the results provided by many studies suggest that the use of six DOF devices reduces the achievement times without no significant loss regarding the precision [Poupyrev et al. 2000] [Hinckley et al. 1997] [Chen et al. 1988]. For instance, in the study conducted by *Chen et al.*, the users were asked to achieve the orientation task using sliders and a six DOF device. Whilst providing a similar precision, the six DOF device has proved to be faster than the sliders. The possibility to integrate the manipulation of all the DOF in a single gesture is often presented as the key feature explaining such performances' differences [Chen et al. 1988]. However, in almost every study there is no quantification of the proportion of time users were able to manipulate all the task's DOF simultaneously.

The theoretical framework proposed by *Jacob et al.* ignores the users' aptitude to manipulate several DOF simultaneously. Even if the interaction device has an integral perceptual structure, it is not obvious that users are always able to combine all the DOF at the same time. Some previous works seem to corroborate this idea. For instance, *Kiyokawa et al.* focused on the design of new tools to introduce constraints, reducing the number of DOF simultaneously manipulated during an assembly task to improve the users' efficiency [Kiyokawa et al. 1997b]. In a more formal study, *Wang et al.* showed that for a six DOF manipulation task, users are not able to manipulate simultaneously the position and the orientation of the object during the whole task [Wang et al. 1998].

These examples suggest that users may not be able to always completely integrate the manipulation of all the DOF at the same time during the whole task. In order to understand how users manipulate the DOF associated to a task, we need to design new measurements which could yield a quantitative information about the level of the DOF's separation.

2.2 Degrees of freedom's manipulation and measurements

Usually, in experimental studies the measurements used are precision, error rate or achievement time [Bowman and Hodges 1997]. They are used to highlight the possible differences about performances between two or more interaction techniques or interaction devices. However, they do not explain where the differences come from. To understand the reasons behind these differences the design of new measurements is necessary. New ones are proposed by *MacKenzie et al.* to characterize the users behaviour during a pointing task [MacKenzie et al. 2001]. When comparing several interaction devices, they proved to be helpful to supplement classical measurements to understand why an interaction device is more efficient than another.

In the context of the DOF's manipulation, the two main measurements proposed are the *inefficiency* [Zhai and Milgram 1998] and the $\mathscr{M}-metric$ [Masliah and Milgram 2000]. The main issue is that both measurements depends on the optimal path between the manipulated object and the target. Because many studies have shown that it is almost impossible to find the optimal rotation from one orientation to a target [Parsons 1995], it suggests that they are not appropriate to quantify the DOF's coordination during orientation tasks.

Therefore, we propose the *Magnitude of DOF's Separation* measurement –which does not depend on the optimal path– to study how users manipulate the three DOF of the orientation task. Since we think that the manipulation of three DOF is difficult for users, we propose an interaction technique that eases the orientation task's decomposition –such as the manipulation of sliders. We compared this technique to an interaction technique similar to the direct manipulation, which allows the simultaneous manipulation of all the task's DOF. Our aim is to study the level of coordination users reached using both techniques and then study the impact of the DOF's manipulation on the users' performances.

3 Magnitude of Degrees of Freedom's Separation

Because of the high complexity of the orientation task, the users may develop specific strategies to achieve this task. For instance, as illustrated in Figure 2, one can reduce the number of DOF simultaneously manipulated, thus decomposing the task into more subtasks involving less DOF.

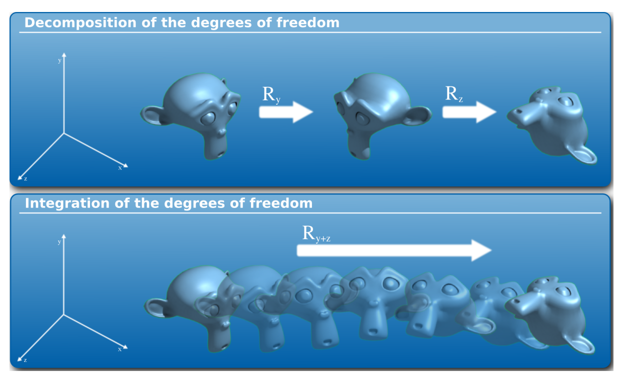

Figure 2: *The example of two strategies to achieve an orientation task. On the top of the image the user decomposes the task by manipulating one DOF at a time. On the opposite, on the bottom of the figure, the user combines the manipulation of two DOF.*

Our goal is to quantitatively measure the level of coordination of the three DOF. More specifically, we want to know if the user manipulates successively one DOF at a time, or on the opposite if the user manipulates several DOF at the same time. The evolution of this measurement during the completion of the task can be helpful to understand how the user handles the different DOF. For this purpose, we have designed the MDS (*Magnitude of DOF's Separation*) measurement to provide quantitative information about the magnitude of separation of the DOF's manipulation.

We want the MDS measurement to be equal to 1 when the subject is rotating the object around one specific axis. On the contrary when the user is rotating the object around all the three axes at the same time and with similar amplitudes, we want the measurement to be equal to 0. Intermediary values are obtained according to the level of separation. This value is computed using the respective proportions of the rotations around the three axes.

To compute the MDS, we consider three curves representing the angular velocities of each DOF (an example is presented in Figure 3). These curves, noted v_x, v_y and v_z, represent respectively the velocity's profiles for x, y and z axes measured during the fulfilment of the task. In this experiment, we used a sampling rate of 20Hz to build these digital curves. For each time step, the integrals V_x, V_y and V_z of these curves give a quantitative measurement of the amplitude of the velocity for each DOF (see Equation 1). Each integral is normalized by the sum of all the integrals, to have a result which is independent of the total angular velocity. This gives us three proportions ranging between 0 and 1, their sum being equal to 1.

$$V_x = \int_{t_i}^{t_i+1} v_x(t)dt,\ V_y = \int_{t_i}^{t_i+1} v_y(t)dt,\ V_z = \int_{t_i}^{t_i+1} v_z(t)dt \quad (1)$$

$$V_{tot} = V_x + V_y + V_z \quad (2)$$

In order to know how the user combines the different DOF, we compute the differences between each of these relative velocities in relation to the others. As each relative velocity appears two times in the sum, if one value is close to one –meaning that the others are all close to 0– the sum will be close to two. If all the relative velocities are similar, each absolute difference of the sum will be close to 0. This will result in a sum close to 0. Therefore the measurement is normalized by 2 to obtain a value ranging from 0 to 1. The mathematical formulation of the MDS measurement is defined as:

$$MDS_i = \frac{|V_x - V_y| + |V_x - V_z| + |V_y - V_z|}{2 \times V_{tot}} \quad (3)$$

When the MDS measurement is close to 0, the user rotates the object around the three axes at the same time and with the same amplitude. When the value is close to 0.5 the user rotates the object mainly around two axes. Finally, when the value is close to 1, the user rotates the object only around one axis. This measurement allows us to know how many DOF are simultaneously manipulated. We illustrate its behaviour on three examples. Let us consider that at a moment during the task, a user is rotating the object. The three angular velocities are AV_x, AV_y, AV_z (in degrees per second).

1. $AV_x = 0$, $AV_y = 70$, $AV_z = 0$: the user manipulates one specific DOF. The MDS value is equal to 1;

2. $AV_x = 25$, $AV_y = 25$, $AV_z = 25$: the user manipulates all DOF at the same time with the same velocity so the MDS value is equal to 0;

3. $AV_x = 25$, $AV_y = 25$, $AV_z = 150$: the user manipulates all DOF at the same time but is manipulating the third DOF more significantly than the other. In this case, the MDS value is approximatively 0.7.

We use this new quantitative description of the DOF's separation in an experimental framework to analyze how the users coordinate the task's DOF with two different interaction techniques and study the impact of the DOF's manipulation on their performances.

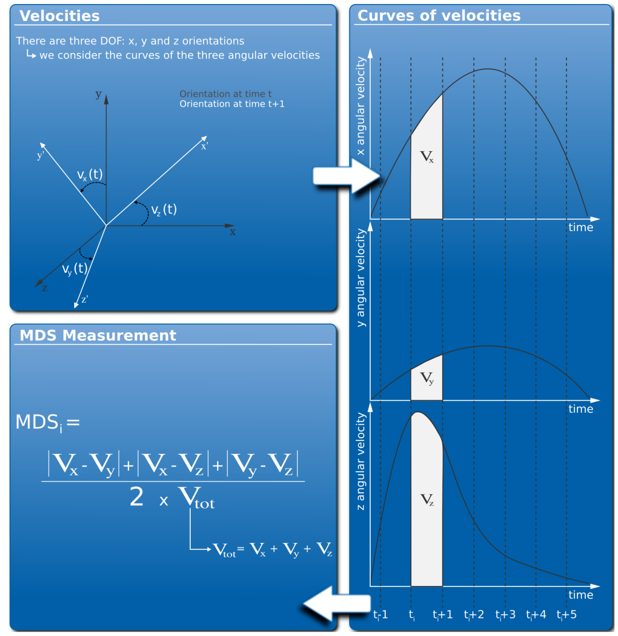

Figure 3: *In this example, there are three DOF of orientation, one orientation for each axis of the 3-D coordinate system. The three curves represent the angular velocities around each axis. The more values V_x, V_y and V_z differ, the higher the MDS.*

4 Experimental conditions and apparatus

We studied the behaviour of users when achieving the orientation task using two interaction techniques. The first one is similar to the direct manipulation and facilitates the simultaneous manipulation of all the task's DOF. The second one we propose eases the decomposition of the DOF. By comparing the level of the DOF's coordination users reached using both techniques we could observe the influence of the DOF integration or decomposition on two performances criteria, the precision and the achievement time.

4.1 Indirect Rotations

We wanted to use a condition where the user would carry out rotations directly by grabbing and rotating the object with one's hands, as it is the more immediate and intuitive way to interact in VR. However, such techniques have a limited range of action since the manipulated object must be presented within arms reach.

To allow the users to manipulate a remote object, we implemented a technique (called *IR*) were the user would grab a virtual manipulator –a cube in our case– positioned immediately at arms' reach. The user grabs the virtual manipulator with his dominant hand and then can orientate it just by rotating the hand. As illustrated in Figure 4, by rotating this object the user affects the manipulated object by the same rotation.

Using the IR technique, users are able to combine the three axes of rotation into a single gesture thus integrating the task's DOF. Moreover, since the technique's perceptual structure is in concordance with the tasks' perceptual structure, the use of this technique should lead to the best performances. According to the results obtained by *Chen et al.* [Chen et al. 1988], this should be the case especially when the users are required to perform complex orientations during which users are required to manipulate several axes of rotations.

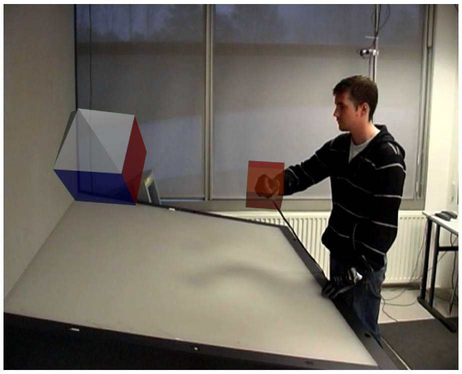

Figure 4: *The user is grasping and turning the virtual manipulator which is at arms' reach.*

4.2 Bi-manual Plane Constrained Rotations

This modality (called *BPCR*) takes advantage of our specific application environment. We wanted to propose to the users a technique that would not require a drift in the fulfilment of the task by switching the users' attention between the manipulated object and a manipulation widget. For this purpose, we decided to simulate the use of a touch screen by requiring users to touch the screen with their forefingers to realize a rotation.

The user commands a rotation around an axis of the object's coordinate system by moving his finger along the corresponding screen axis. The user can use both hands simultaneously or successively to perform rotations by touching the screen. The dominant hand gives him access to two specific axes of rotation and the non-dominant hand gives him access to the third axis. This is illustrated in Figure 5. This modality allows carrying out three DOF interaction for rotations while looking at the manipulated object. It also eases the decomposition of the task by manipulating one axis of rotation at a time. However, users could manipulate several DOF at the same time by using both hands simultaneously or by performing transverse movements on the screen.

Because the technique eases the decomposition, its perceptual structure does not match the task's perceptual structure. However, in some cases the users may benefit from the decomposition eased by this technique when achieving simple orientations (involving the manipulation of only one DOF) and large orientations (because it avoids ratcheting).

4.3 Apparatus

Each experiment was conducted on a Workbench Barco Consul, a two screen SIVE using stereoscopic display –resolution 1400x1050 refreshed at 120Hz– and CrystalEyes CE-2 glasses. The images were generated using two workstations (one for each screen) fit out with a 3Ghz Intel Quad Core and a NVIDIA Quadro FX 5000. The head and hands tracking was ensured by an ART tracking system and optical trackers. The users interacted with the environment with two XIST Data Gloves.

4.4 Experimental conditions

13 subjects with different levels of experience with SIVE participated to the study. They were required to rotate an object to match a given target's orientation. The orientation of the target did not change across the time and is represented as a unit quaternion. Since in similar researches subjects rotated a house [Hinckley et al. 1997] [Poupyrev et al. 2000] we used the same object for our experiments.

The session began with a presentation of the underlying concepts of the environment and the devices used during the experimental protocol. Subjects could then try the environment for a few minutes before starting the experiment. Afterwards, each subject was asked to realize 24 orientations with each technique. To avoid learning trade-offs, we used a Latin-square distribution of the rotation techniques between subjects.

We asked the subjects to position the house as precisely as they could. They were told to find the optimal compromise between speed and accuracy during the experiment. They stopped when they thought that the position was good, or that they could not reach a better precision. To validate the task, we asked them to put the hand into a validation widget for one second (a red cube on the bottom left corner of the environment). They then entered in a transitional mode were they could make comments on the interaction technique or rest their arms. To begin the next task, they had to use the same procedure. The one second validation time was not taken into account in our measurements.

In this experiment, we distinguished two types of orientation complexity:

- Simple Orientations (SIO): for these tasks, the house needed to be rotated around only one axis of his coordinate system to reach the targeted position;
- Complex Orientations (CO): for these tasks, the orientation required rotations around several axes.

For each technique, the subjects had to realize twelve simple and twelve complex orientations.

We also distinguished between small and large orientations regarding the minimal amplitude of the rotation to perform:

- Small Orientations (SMO): for these tasks, the house needed to be rotated by less than 60 degrees to reach the targeted position;
- Large Orientations (LO): for these tasks, the orientation distance was higher than 60 degrees.

4.5 Measurements

For each session we recorded several quantitative data: the orientation precision (distance between the orientation of the manipulated object and the target) and the position of the interaction devices. Using this data samples we computed several scales. The most relevant ones for the present study are:

- The Angular Distance (AD, in degrees): the final angular distance between the manipulated object and the target ;
- The Achievement Time (AT, in seconds): the time elapsed until the last rotation ;
- The Coarse Achievement Time (CT, in seconds): the first time the angular distance is lower than a threshold of 18 degrees ;
- The Finer Achievement Time (FT, in seconds): the first time the angular distance is lower than a threshold of 9 degrees ;
- The *MDS* measurement using angular velocities of the manipulated object: we use this measurement to compute the proportion of time users manipulate one, two and three DOF at the same time.

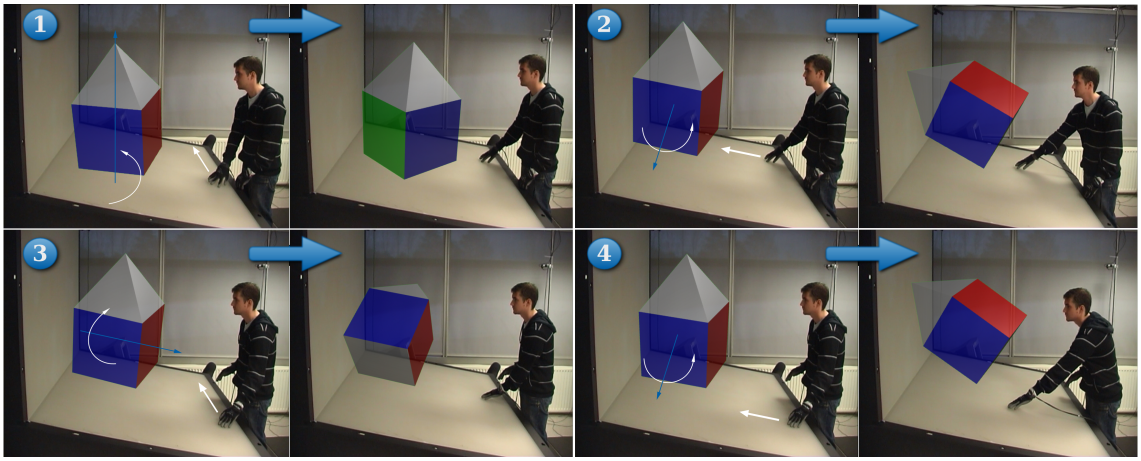

Figure 5: *The four mappings between the movements of the hands and the rotations of the object.*

We used all the collected data above to study how users manipulate the three DOF of the orientation task and observe the impact of the DOF's manipulation on the users' performances. We briefly present our hypothesis regarding this experiment.

4.6 Hypotheses

Regarding this study, we consider that the interaction technique has a strong influence on the users' performances.

H1: Because the IR technique allows users to perform small adjustments on the object's orientation, it will be more precise than the BPCR technique.

H2: For small orientations and complex orientations, the IR technique will be more efficient than the BPCR technique. Especially, because the IR allows the manipulation of all the DOF simultaneously the users would achieve the task faster.

H3: For large orientations and simple orientations, the BPCR technique will be more efficient than the IR technique. Since the BPCR technique helps the users to perform large rotations and manipulate one specific DOF, the users will achieve the task faster than using the IR technique.

We assume that the differences are due to the different strategies set up with regard to the DOF's manipulation.

H4: Mentally rotating an object around the three axes of rotations is extremely complex. Thus when fulfilling the orientation task, the users are usually not able to manipulate all the three DOF at the same time, even using an interaction technique integrating the manipulation of DOF such as the IR.

H5: When fulfilling the orientation task using the BPCR technique, the users decompose the task by manipulating one DOF at a time even if the technique allows the combination of DOF.

5 Results

We performed a post-hoc statistical analysis on the data collected. An ANalysis Of VAriance (ANOVA) was run to compare the techniques used. The dependent factors were all the measurements presented in Section 4.5.

5.1 Performances

Table 1 shows the results obtained for each interaction technique regarding the final angular distance. The difference between both techniques is not statistically significant ($F(1,620) = 1.127$; Standard Deviations: $SD_{IR} = 3.476$ and $SD_{BPCR} = 2.598$). There is also no significant interaction between the technique and the orientation complexity ($F(1,620) = 0.408$) or the orientation amplitude ($F(1,620) = 0.220$). These results suggest that both techniques offer the same level of precision whatever the characteristics of the orientation.

In Table 1 we see that the AT are similar for both techniques. In fact, there is no significant influence of the interaction technique ($F(1,606) = 0.852$; $SD_{IR} = 13.068$ and $SD_{BPCR} = 13.023$). They are similar for all the orientation characteristics. Again, there are no interactions between the orientation complexity ($F(1,606) = 1.456$) or amplitude ($F(1,606) = 3.208$) and the interaction technique. It suggests that in general, achieving the orientation task using IR does not introduce any significant gain in the AT.

However, there are statistically relevant differences regarding the CT and the FT. The interaction technique has a strong influence on the mean CT ($F(1,566) = 8.522$; $SD_{IR} = 7.303$ and $SD_{BPCR} = 5.562$) and the mean FT ($F(1,572) = 4.625$; $SD_{IR} = 8.009$ and $SD_{BPCR} = 6.584$). The mean CT is 16.72% lower for the BPCR technique than for the IR technique. The difference is significant in the cases of simple orientations and large orientations. However, it is not relevant for the complex and the small orientation cases.

There is also a statistically significant difference for the mean FT. Using the BPCR technique the users are 11.61% faster. It suggests that using the BPCR technique users are able to get close to the target faster than using the IR technique. Similarly to the results obtained for the CT, the difference is also significant in the simple orientation and the large orientation cases. However, it is not relevant for the complex and the small orientation cases.

5.2 Degrees of freedom's manipulation

In Table 3 we show the mean percentage of time during which users' manipulate one, two and three DOF at the same time. There is a strong influence of the interaction technique on percentage of time that the users manipulate one, two, between two and three and three DOF:

IT	Angular Distance					Achievement Time				
	AMPLITUDE		COMPLEXITY			AMPLITUDE		COMPLEXITY		
	SMO	LO	SIO	CO	Mean	SMO	LO	SIO	CO	Mean
IR	3.64	4.1	3.87	4.20	4.04	16.28	25.19	20.86	25.86	23.37
BPCR	3.48	3.83	3.46	4.09	3.78	19.59	25.10	20.71	27.92	24.31
$\rho - value$	0.772	0.228	0.215	0.737	0.264	0.175	0.934	0.919	0.144	0.346

Table 1: *The table shows the results for the main performances criteria, the precision and the achievement time.*

IT	Coarse Time					Finer Time				
	AMPLITUDE		COMPLEXITY			AMPLITUDE		COMPLEXITY		
	SMO	LO	SIO	CO	Mean	SMO	LO	SIO	CO	Mean
IR	5.73	**11.23**	**8.83**	12.03	**10.54**	7.17	**12.86**	**9.88**	13.61	**11.82**
BPCR	6.51	**9.36**	**7.21**	10.80	**9.03**	3.48	**11.14**	**8.03**	13.20	**10.59**
$\rho - value$	0.622	**0.002**	**0.043**	0.109	**0.006**	0.489	**0.010**	**0.034**	0.638	**0.045**

Table 2: *The mean coarse time and the mean finer time for each orientation characteristic.*

- One DOF ($F(1,539) = 9505.528$; $SD_{IR} = 7.334$ and $SD_{BPCR} = 10.659$);
- Two DOF ($F(1,584) = 2226.819$; $SD_{IR} = 10.931$ and $SD_{BPCR} = 9.434$) ;
- Between two and three DOF ($F(1,597) = 1994.999$; $SD_{IR} = 7.826$ and $SD_{BPCR} = 0.992$) ;
- Three DOF ($F(1,605) = 1315.824$; $SD_{IR} = 4.250$ and $SD_{BPCR} = 0.473$).

Except for the 1–2 DOF percentage, all the differences are statistically relevant. When users achieve the orientation using the BPCR technique, they manipulate one DOF during 79.27% of the time. They manage some times to manipulate two DOF at the same time but never manage to manipulate the three DOF at the same time. When they use the IR technique, they usually manipulate two DOF at the same time (during 51.789% of the time). We can also notice that they manipulate three DOF simultaneously only during 8.75% of the time. These results suggest that using the IR technique users are only able to partially integrate the DOF's manipulation. Also, using the BPCR users manipulate only one DOF at a time thus strongly decomposing the orientation task.

There are interactions between the technique and the orientations' amplitude regarding the percentage of time the users manipulate one ($F(1,539) = 23.872$), between two and three ($F(1,597) = 21.713$) and three ($F(1,605) = 16.016$) DOF. The significant differences are presented in Table 4.

	1 DOF		2–3 DOF	3 DOF
	IR	BPCR	IR	IR
SMO	**3.37%**	**86.79%**	**23.75%**	**10.86%**
LO	**6.44%**	**78.06%**	**18.78%**	**8.23%**
$\rho - value$	0.016	< 0.0001	< 0.0001	< 0.0001

Table 4: *The significant differences resulting from an interaction between the interaction technique and the orientations' amplitude.*

As illustrated in Table 5, there is also an interaction between the technique and the orientation complexity for the percentage of time users manipulate one DOF ($F(1,539) = 10.984$). The difference is statistically relevant for the BPCR. However, for the IR technique the difference is not statistically relevant. The results presented in Tables 4 and 5 may suggest that as the task become more complex, the users end up to decomposing it.

	1 DOF	
	IR	BPCR
SIO	5.77%	**81.81%**
CO	5.89%	**76.96%**
$\rho - value$	0.906	< 0.0001

Table 5: *The differences resulting from an interaction between the interaction technique and the orientations' complexity.*

6 Analysis and discussions

The results presented in Section 5 suggest that the interaction technique has a strong influence on how users achieve the task regarding DOF's manipulation and on the users' performances.

6.1 Performances

Usually in VR, the interaction techniques try to integrate the manipulation of all the DOF at the same time to achieve a task. This strategy has proven to be efficient in the context of the orientation task [Hinckley et al. 1997] [Chen et al. 1988]. The results of the study conducted by *Chen at al.* showed that using a six DOF device, users achieve the orientation task faster and with similar precision to the manipulation of sliders. Their explanation was that the increased performances were due to the integration of the manipulation of the DOF with the six DOF device.

However, the results we obtained suggest that the integration of the manipulation of all the DOF do not always lead to the best performances. Indeed, although using the BPCR technique users decompose the task, they reached the same precision as using the IR technique –which is in opposition to our first hypothesis–. Our results are better than the results reported in their study by *Poupyrev et al.* (6.8 degrees) [Poupyrev et al. 2000], *Hinckley et al.* (7.07 degrees) [Hinckley et al. 1997] or *LaViola* (3.9 degrees) [LaViola et al. 2008]. This last result obtained during experiments that were realized in immersive virtual environment and head tracking are

IT	1 DOF	1–2 DOF	2 DOF	2–3 DOF	3 DOF
IR	**5.83%**	8.45%	**51.789%**	**19.77%**	**8.75%**
BPCR	**79.27%**	9.01%	**11.834%**	**0.19%**	**0.07%**
$\rho - value$	< 0.0001	0.324	< 0.0001	< 0.0001	< 0.0001

Table 3: *The mean number of DOF simultaneously manipulated during the task. Because we use a threshold to distinguish between the different cases on the MDS, there are times during when the users manipulates between one and two DOF or two and three DOF.*

coherent with ours. They confirm *Hinckley*'s suggestion that the accuracy of the rotations might be less affected by the manipulation capabilities of the interface than by the difficulties subjects had in perceiving and adjusting the rotation error [Hinckley et al. 1997].

Similarly, the results obtained regarding the mean AT suggest that the task's decomposition is as efficient as the DOF's integration. Indeed, Table 1 shows that the performances are similar for both techniques, thus providing an example were the decomposition does not introduce any significant increase in the AT. Thus, similarly to the study conducted in [Poupyrev et al. 2000] we decided to look at the time users spent before getting under a given angular distance threshold. In the present study, we use two different thresholds, the first one is the *coarse threshold* (fixed to 18 degrees) and a second one fixed to 9 degrees called the *fine threshold*.

As illustrated in Table 2, the users are able to reach the coarse threshold 14.39% faster using the BPCR technique than using the IR technique. Using the BPCR technique they were also able to reach the fine angular threshold 10.38% faster than using the IR technique. We think that there is no significant difference regarding the AT because of the inappropriate hand filtering method we used for the BPCR technique. In fact, to avoid small parasitical rotations we used a velocity threshold requiring the users to move the hand fast enough to rotate the object. Because the threshold was fixed empirically, it was hard for some users to perform small adjustments. Therefore, the users spent a lot of time trying to make small adjustments. The use of a more reliable filter such as the PRISM filtering technique [Frees and Kessler 2005] could have led to other results.

In the cases of small and complex orientations, the users get to the coarse and the fine threshold with similar time using both techniques, suggesting that we were wrong about our second hypothesis. We thought that using the IR technique, the users would manage to benefit from the integration of the DOF's manipulation. Even if users seem to integrate a little more the manipulation of all the DOF (as shown in Table 4) they do not achieve the task faster. This may be due to the fact that the users are only able to partially integrate the manipulation of all the DOF (more details are given in the next section) thus only partially benefiting from it.

Now, considering the cases of simple and large orientations, the results show that the users were able to get to the coarse and fine threshold significantly faster using the BPCR technique. In the context of simple and large orientations, the users may benefit from the decomposition –this confirms our third hypothesis. This is in agreement with the results presented in [Chen et al. 1988] where the users were able to achieve the simple orientations faster using the sliders' manipulation (less than 10s) than using the Virtual Sphere (almost 15s). In the Table 4, we can observe that using the IR technique, the users try to decompose the task more for large orientations than for small orientations. The users may perceive the task as more difficult when asked to perform large orientations and thus end up to decomposing the task to simplify it.

Since the BPCR technique is similar to the manipulation of three sliders, we may reconsider the reasons why the sliders manipulation is not suitable for efficient object's orientation [Chen et al. 1988]. As a matter of fact, sliders manipulation is often presented as a cumbersome rotation technique because users are required to decompose three DOF orientations into successive one DOF orientations. However, it also requires users to select the slider widgets very often. This can lead to a large increase in the achievement time especially when performing little orientation's adjustments. This technique also requires users to switch their attention from the orientation task to the slider's selection. The addition of selection time and the successive attention's switching may explain the sliders' poor performances.

All the results we obtained suggest that the task's decomposition can be an efficient strategy which can lead to faster achievement times.

6.2 Degrees of freedom

In the results presented in Table 3 we can see that using the IR technique, users manipulate simultaneously the three DOF during only 8.75% of the time. During more than 50% of the time, they manipulate only two DOF at the same time –thus confirming our fourth hypothesis. This result suggests that during the orientation task, the users are only able to partially integrate the manipulation of all the DOF at the same time. One possible explanation is that because of the task complexity and the user's incapacity to find the optimal path toward the target, they may try to decompose the task into more simple orientations.

Using the BPCR technique, users manipulate one DOF at a time during almost 80% of the time, thus confirming our fifth hypothesis. The technique eases the task's decomposition and users benefit from it to decompose the three DOF orientation task into three tasks of one DOF each. Previous works propose to introduce tools to decompose tasks of high complexity to improve the users' precision. This is the case in *VLEGO*, the geometric modelling application proposed by *Kiyokawa et al.* [Kiyokawa et al. 1997a]. They introduced *geometrical constraints* to help users focusing on specific DOF's manipulation to achieve an assembly task. They noticed that the manipulation of all the six DOF at the same time makes the task too complex. By reducing the number of DOF simultaneously manipulated and decomposing the task they manage to provide the users with more precision [Kiyokawa et al. 1997b].

This may explain the only partial DOF's integration the users reached using the IR technique, the high degree of the task's decomposition using the BPCR technique and the better coarse and finer times the users reached with the BPCR technique. We think that in the case of the orientation task, the users may decompose the task into two phases. During the first phase, users try to coarsely orientate the manipulated object, thus maybe integrating more easily the DOF. During the second phase, they try to make small adjustments to precisely rotate the object. During this phase, users may orientate the object successively around the three axes of rotation. We also think that during the first phase users may try to perform successive alignments in order to simplify the task. There may be respective benefits from the integration and the separation during these two phases. We are designing a new behavioural measurement to identify these two phases and investigate these questions.

7 Conclusions and future works

In this paper, our objective was to study the impact of the DOF's separation and integration on the users' performances. For this purpose, we compared the performances offered by an interaction technique integrating (the IR technique) and another separating (the BPCR technique) the manipulation of the DOF of a 3-D orientation task. In order to formally study the impact of the DOF's integration and separation we proposed the *MDS* measurement to quantify the degree of separation of the DOF during the task's fulfilment.

Using this measurement we showed that using the BPCR technique, the users decompose one 3 DOF orientation task into three 1 DOF subtasks by manipulating only one axis of rotation at a time. Using the IR and the BPCR techniques the users were able to reach the same level of precision. However, for the thresholds we use the users were able to achieve the task faster using the BPCR technique. These results are in opposition to previous studies asserting that the interaction techniques should always integrate the manipulation of the DOF to obtain the best performances [Chen et al. 1988] [Jacob et al. 1994].

In addition, the MDS measurement allowed us to highlight that the users' were only able to partially integrate the manipulation of all the task's DOF even if they had the possibility. This may be explained by the increase in the task's complexity, especially in the orientation task where the identification of the optimal path toward the target is almost impossible. It may lead users to set up specific strategies which aim at decomposing the task into several less complex subtasks.

However, we need to do further analysis to understand what are these strategies. We think that users try to use strategies such as the use of successive alignments to achieve the orientation task. By aligning the object around one or two axes, users may try to simplify the task and get closer to the target orientation. We are trying to identify these strategies by defining a new quantitative measurement –similar to the MDS measurement– to investigate the impact of the decomposition and the integration on these strategies.

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