A Preliminary Study of the Influence of Interaction Techniques Integrating/Separating Degrees of Freedom on Users' Performances during 3-D Positioning Tasks

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Abstract

In the present paper, we investigate the impact of the coordination of the Degrees of Freedom (DOF) on the users' performances and cognitive load during a positioning task. For that purpose, we compare four techniques. Two of them (the Go-Go and Ray-Casting) are commonly used to position objects in virtual reality environments and allow users to manipulate all the three dimensions at the same time. With the two others, users are required to decompose the 3-D positioning into a 2-D plus a 1-D positioning. In order to study the influence of the coordination of the DOF, we propose a new behavioural measurement that quantifies the number of DOF simultaneously manipulated. We observe that even for the integrating techniques the integration is not complete. Moreover, the decomposition of the task can significantly increase the users' precision –especially when it allows the isolated manipulation of the depth dimension– without introducing any increase in the achievement times. We also observed that the task's decomposition largely decreases the amount of cognitive load. Our results suggest that the DOF's integration is not always the best strategy to achieve multiple DOF input tasks.

Keywords: Interaction, Virtual Reality, Degrees of Freedom, User Study

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

The recent advances of computer graphics technology enabled the emergence of high quality virtual reality (VR) environments. For some time past, VR environments (VE) spread out from the academic and industrial fields with the democratisation of stereoscopic displays such as the NVIDIA 3-D Vision^{TM}. The possibilities offered by VE are not limited to visualisation experiences. The use of the appropriate devices (e.g. a wand or data gloves) allows users to directly manipulate their surrounding elements using natural gestures such as grabbing and positioning. An example of a user manipulating a virtual object in a semi-immersive virtual environment (SIVE) –the context of our work– is given in Figure 1. Such direct interaction techniques [16] are often considered as more intuitive [10].

Applications such as geometric modelling applications require users to perform precise modifications on 3-D objects –such as warping, sculpting, extruding, etc. Intuitively, one could think that performing such 3-D tasks directly in a 3-D environment should be more comfortable and more precise than using a mouse on a desktop environment. However, the level of interaction proposed by many VR applications is often poor [3]. It seems that limitations in the users' precision curtail the type of applications developed for VR. The disappointing results obtained using such applications in VR suggest that users encounter numerous difficulties when manipulating in SIVE.

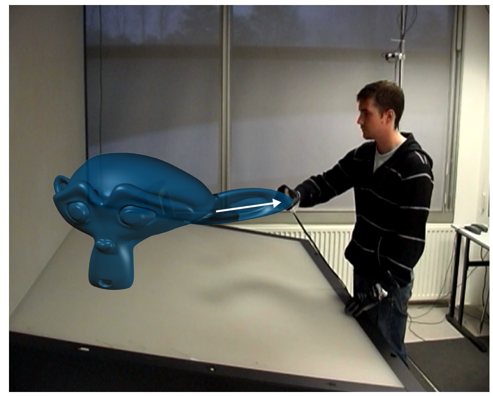

Figure 1: The user sees a virtual object in three dimensions and manipulates it directly using his hands.

These difficulties could be partially explained by the addition of the depth dimension's manipulation. Positioning an object in VR –i.e. moving an object from one position to another– requires to manipulate three dimension at the same time. The absence of any physical support introduces an increase of the number of DOF simultaneously manipulated. Although users interact in a 3-D space as in the real world, the tasks they are required to perform in VR are slightly different from what they are used to. Even if we act in a 3-D space, the physical constraints inherent to our world reduce the dimensionality of the tasks, i.e. the number of DOF involved in the task. For instance to position an object in VR users manipulate three DOF, whereas in the real world the gravity makes that an object usually lays on a support thus reducing the dimensionality of the task to two dimensions. Without any specific implementation such as the use of physical engines [6], these constraints are not present in VR worlds. Moreover, when interacting on a classical desktop the use of the mouse implicitly reduces and/or decomposes all tasks' dimensionality to two dimensions.

Many interaction techniques integrate the manipulation of the depth dimension among the others dimensions (e.g. the Go-Go [15], the Ray-Casting [2] or the Voodoo Dolls [14]). However, several studies showed that users are rarely able to combine all the tasks' DOF during their fulfilment [4] [20]. These results suggest

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that integrating the manipulation of all dimensions of a task may not always be the ideal approach.

In this study, we compare the performances offered by interaction techniques integrating and separating the DOF to position 3-D objects. In order to quantify the degree of integration the users reached, we designed a new behavioural measurement which gives the number of DOF simultaneously manipulated. Using this measurement we are able to observe possible decompositions during the fulfilment of the task.

In Section 2, we introduce the relevant works related to our study. Then, in Section 3 we describe the *Number of DOF Combined* measurement. This measurement provides a quantitative evaluation of the DOF's coordination. In Section 4, we describe the interaction techniques we propose. These techniques decompose the 3-D positioning task into a 2-D plus 1-D positioning. The two others (Go-Go and Ray-Casting) are not described in this paper. In Section 5 we present the experimental study we conducted. Then, in Section 6 and 7 we present the results we obtained and their analysis. Finally in Section 8 we provide some conclusions and perspectives to this work.

2 Related works

In this section we present the relevant works investigating the impact of the configuration of DOF on the users' performances. We also present the solutions which have already been proposed to try to improve the control of users during 3-D positioning. Finally, we describe the major works related to the coordination measurements.

2.1 Degrees of freedom

To describe the impact of the manipulation of multiple DOF during an interaction task, *Jacob et al.* [8] introduce the notion of the *perceptual structure*. Each device and each task has its own perceptual structure that gathers all the attributes that can be modified. The perceptual structure can be *integral* when the semantic distance between the attributes is low or *separable* if the semantic distance is important.

Jacob et al. studied the influence of the perceptual structures on the performances users reach. They showed that to obtain the best performances, the perceptual structure of the interaction device should match the perceptual structure of the task. Because the perceptual structure of the positioning task is integral, it suggests that we should always use an interaction device with the same perceptual structure to obtain the best performances. However the framework ignores the users' possible inability to manipulate all the DOF simultaneously when their number increases.

As presented in the previous section, in the physical world or on desktop stations, users do not usually manipulate as many DOF at the same time. In their work, *Casiez et al.* compared two elastic devices, the first one –the Spacemouse ©– integrating and the second one –the DigiHaptic– separating the manipulation of the three DOF. They showed that it was strenuous for the users to coordinate the manipulation of two and three DOF during a steering task even using the SpaceMouse [4]. Moreover, when the steering task required users to manipulate three DOF, the users reached the same level of coordination using both devices. This may suggest that the users control the DOF separately even if they are integrated.

To evaluate the impact of the DOF's integration on the performances of users, they used specific metrics to evaluate the coordination. The metrics proposed in the literature are described in the next section.

2.2 Metrics and coordination

The aim of coordination metrics is to provide a quantitative value to characterise the level of DOF's coordination. Typically, the higher the coordination users reached during the fulfilment of an interaction task, the larger the value provided by the metric. There are two major coordination metrics: the *efficiency* [21] and the $\mathscr{M}-metric$ [12]. However both measurements have several drawbacks.

The *efficiency* measurement proposed by *Zhai et al.* depends on the shortest path toward the target. However, it is not obvious that the path users may use spontaneously to achieve the task is the straight line joining the manipulated object and the target. The path may depend on the users' perception of the 3-D scene which could be biased [7].

The $\mathscr{M}-metric$ proposed by *Masliah et al.* integrates a measurement of the *simultaneity of control* which aim is to quantify the coordination of the DOF. However, it have three main issues. First, its computation depends on the movements of the manipulated object during the entire task. The fact that this measurement is global does not allow the identification of distinct separation and integration phases within the task. Moreover, because the measurement computation is based on a minimum function, it is not able to distinguish between a *full integration* –where all the DOF are manipulated– and a *null integration* –where only one DOF is manipulated. For instance, in a 3-D docking task, if the user is manipulating two DOF and not the third one, the measurement indicates no integration although the manipulation of two DOF over three may be considered as an intermediate level of integration. Finally, the simultaneity of control is based on a *normalised error reduction function* for each DOF. This function considers only the movements of the manipulated object toward the target and ignores all the other movements.

In the next section, we introduce the characteristics of several interaction techniques in the context of DOF's manipulation.

2.3 3-D positioning task

When interacting in a VE, the addition of the depth dimension in the interaction makes the task more complex. The issues researchers encounter to define a Fitts' law suitable for 3-D environments [17] illustrate the troubles to understand where the difficulties come from. *Fiorentino et al.* highlight the anisotropic nature of the pointing task in VR [5]. In their work, they show that it is harder for users to position the object along the depth axis than along the two others. To overcome this difficulty, they propose to adapt the *snap grid technique* –the position of the pointer is rounded to the nearest point on a 3-D virtual grid– to try to counter balance this anisotropy and provide the users with more precision. Nevertheless, the solution they propose helps users only at the end of the task and eludes the users' behaviour regarding this third dimension during the whole task.

Other works propose to decompose the task to improve the users' performances. This is the case for the six DOF assembly task. *Kiyokawa et al.* [9] introduce *geometrical constraints* –1-D translation, 2-D translation, 1-D rotation, 2-D rotation– users associate to blocks to focus on the manipulation of specific DOF. The *Balloon Selection* technique proposed in [1] is also based on the decomposition of the task. It was designed to select an object but this technique is also suitable to move an object within a 3-D space. Using this technique, the selection task is decomposed into two subtasks: move the selection cursor into the horizontal plane and modify the height of the selection cursor. *Benko et al.* were surprised by the performances offered by their technique regarding the direct manipulation. In addition to decrease the error rate, their technique does not increase the achievement time (the average time difference is 0.3 s) although it compels users to decompose the task. Even if they do not propose any explanation, the efficiency of the task's decomposition induced by their technique could be a possible explanation.

Such results can not be explained in previous frameworks such as the framework proposed by *Jacob et al.* Therefore, we propose to investigate the impact of the positioning task's decomposition on the performances of users. For that purpose, we propose two techniques that decompose the 3-D positioning. We compare these techniques to the Go-Go and the Ray-Casting, two techniques allowing the manipulation of all the DOF simultaneously and thus offering a high level of integration. In the next section we describe the *Number of DOF Combined* measurement. We use this measurement to compare the DOF's coordination using the different techniques used for the experimental study.

3 Number of Degrees of Freedom Combined

As illustrated in Figure 2, for any manipulation task users can reduce the number of DOF simultaneously manipulated, thus decomposing the task into more subtasks involving less DOF. Similar strategies could be used during 3-D positioning tasks. For instance, a user could place the object in the same xOy plane as the target to reduce the rest of the task to a two dimensional positioning task.

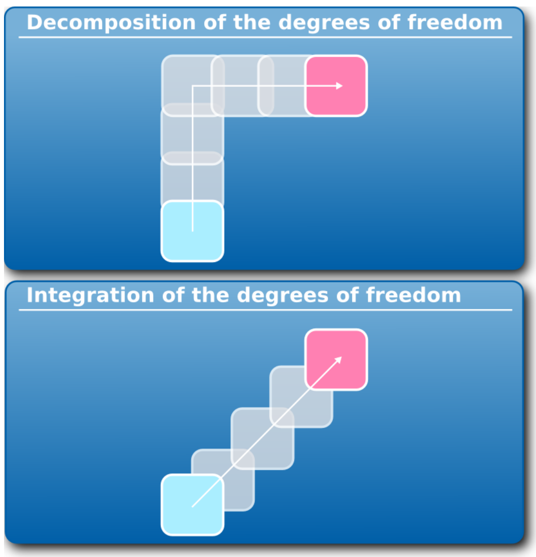

Figure 2: An example of two strategies to achieve a 2-D positioning task.

To investigate this hypothesis, we propose a new measurement to quantitatively measure the level of combination of the three DOF. To this purpose, we propose the *Number of DOF Combined* (NDC) measurement. It provides a real value which explicitly gives the number of DOF simultaneously manipulated between two step of time T and $T+1$. The value of the measurement is between 1 and 3, or equal to 0 if all the linear velocities are equal to 0. The evolution of the NDC measurement during the completion of the task is helpful to understand how the user handles the different DOF and to study the impact of possible strategies on the users' performances and satisfaction. Its mathematical formulation is the following:

$$NDC_T = 1 + (1 - MDS_T) \times 2 \tag{1}$$

The computation of NDC is based on the *Magnitude of DOF Separation* (MDS) measurement which provides quantitative information about the magnitude of separation of the DOF's manipulation. The MDS measurement is equal to 1 when the subject is moving the object along one specific axis. On the contrary when the user is moving the object along all the three axes at the same time and with similar amplitudes, the measurement is equal to 0. We illustrate the behaviour of this measurement on three examples. Let us consider that at a moment during the task, a user is moving the object –the linear velocities are LV_x, LV_y, LV_z (in meters per second).

1. $LV_x = 0$, $LV_y = 0.6$, $LV_z = 0$: the user manipulates one specific DOF and not the others. The MDS value is equal to 1;

2. $LV_x = 0.25$, $LV_y = 0.25$, $LV_z = 0.25$: the user manipulates all DOF at the same time with the same velocity so the MDS value is equal to 0;

3. $LV_x = 0.05$, $LV_y = 0.05$, $LV_z = 0.35$: 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 approximately 0.7 or 0.8.

To compute the MDS measurement, we consider the three curves representing the linear 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 profile for x, y and z dimension across the fulfilment of the task. The integral of these curves gives a quantitative measurement of the amplitude of the variation for each DOF. Each integral is normalised by the sum of all the integrals, to have a result which is independent of the total linear velocity. This gives us three values, one for each relative velocity, each of these values ranging between 0 and 1. We can also notice that the sum of these values is equal to 1. 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. Because 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 results in a sum close to 0. Therefore the measurement is normalised by 2 to obtain a value ranging from 0 to 1. The mathematical formulation of the MDS measurement is defined as:

$$MDS_T = \frac{|V_x - V_y| + |V_x - V_z| + |V_y - V_z|}{2 \times V_{tot}} \tag{2}$$

$$V_x = \int_T^{T+1} v_x(t)dt,\ V_y = \int_T^{T+1} v_y(t)dt,\ V_z = \int_T^{T+1} v_z(t)dt$$

$$V_{tot} = V_x + V_y + V_z$$

Using NDC, we are able to identify strategies of integration or separation of the DOF in the fulfilment of the task and study their impact on the users' performances and cognitive load. In the present study, we investigate how users manipulate the DOF using interaction techniques facilitating the integration of the DOF –called *integrating techniques*. We also study the coordination of the DOF using techniques that makes easier the decomposition of the task –called *decomposing techniques*.

4 Decomposing Techniques

We propose two interaction techniques which aim at facilitating the decomposition of the positioning task. As presented in Figure 1, the users are interacting on a SIVE. The specificity of this setup is that the lower screen is at arms' reach. Using the pressure sensors placed at the end of each of the five forefingers we can easily detect whether the user is touching the screen or not. Although it is similar to the use of a touch screen, the computation of the movements of the hands only rely on the optical tracking system and thus do not lead to a finger-tip level of interaction. This is important since the precision is influenced by the muscle groups involved during the manipulation [22]. Our aim is to use only this specificity to decompose the task.

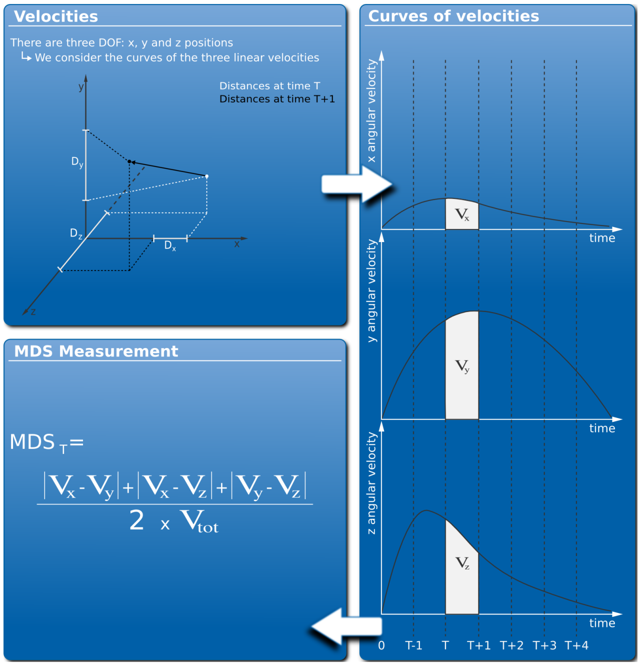

Figure 3: There are three DOF of position, one for each axis of the 3-D coordinate system. The three curves represent the linear velocities along each axis. The more the V_x, V_y and V_z values differ, the higher the MDS value.

4.1 Depth-Apart Technique (DA)

Users utilising this technique handle the depth dimension apart from the others. They move the object in the X-Y plane by shifting their dominant hand while touching the horizontal screen. Using their non-dominant hand users move the object along depth axis by shifting their hand back and forth, again while touching the screen. The technique is illustrated in Figure 4.

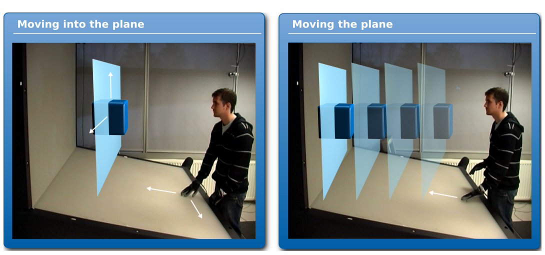

Figure 4: The mapping between the movements of the hands and the displacements applied to the manipulated object.

4.2 Height-Apart Technique (HA)

This technique is similar to the previous technique, except that the height dimension is handled apart from the others. Users move the object in the X-Z plane by shifting his dominant hand while touching the horizontal screen. They move the object along the y axis by moving the non-dominant hand back and forth while touching the screen. Figure 5 illustrates how the technique works.

5 Experimental study

In this section we describe the experimental study we conducted.

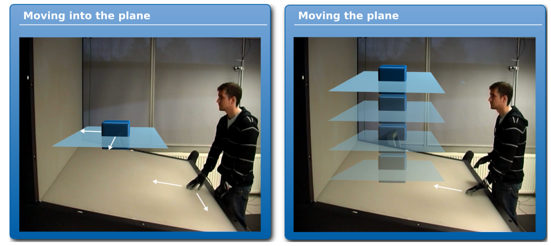

Figure 5: The mapping between the movements of the hands and the displacements applied to the manipulated object.

5.1 Experimental task

The subjects were required to achieve successive target matching tasks which consist of positioning an object onto a given target. Both the manipulated object and the target were cubes. The size of the manipulated cube was 15 cm and the size of the target cube was 5% larger (i.e. 15.75 cm). The size of both cubes did not change throughout the trials.

The initial positions of the manipulated object and the target were randomly placed into a 1 m x 1.3 m x 1 m volume centred at (0, 0, 0) in the 3-D environment. The initial distance between both cubes was always more than 20 cm. This ensures the visibility of both cubes at the beginning of the task and provides us with a wide variety of cases.

We asked the subjects to position the manipulated object as precisely as possible toward the target (i.e. make the centres of the two cubes as close as possible). A minimum precision of 2.5 cm was required to consider the task as achieved. When the subject reached this threshold, the manipulated cube turned green. We also indicated that the achievement time was an important variable. Therefore, the subjects had to find the correct balance between the final precision and the achievement time.

5.2 Subjects

Eight voluntary subjects (all male and right-handed) participated to the present preliminary study. They had little or no prior experience with VE. Each subject used four interaction techniques to achieve the positioning task.

5.3 Design

We used a within subject design. All participants were required to achieve four blocks of twelve trials, one block for the DA, the HA, the Ray-Casting [2] and the Go-Go [15] technique. We chose these two techniques because they require mid-air manipulation and allow the manipulation of all the task's dimensions at the same time. Moreover, they are easy to use by our subjects even if they had no prior experiences with VE. To avoid learning trade-off, the order of presentation of the interaction techniques was assigned through a random Latin square.

The session began with a short training of four blocks of three trials. During the training session, before the first trial of each block we presented the technique orally. Then we let them manipulate the technique as long as they wanted. The two others trials were used to familiarise them with the technique and also to help them find a balance between the achievement time and the final precision. For both DA and HA techniques, we explained to the subjects that they were able and allowed to use both hands at the same time to combine all the DOF.

After the training session, the subjects achieved the four blocks of twelve trials. To validate the current trial, we asked the subjects to put the dominant hand into a validation widget for one second (a red cube on the front bottom right corner of the environment). They then entered in a transitional mode where they could make comments on the interaction technique or rest their arms. To begin the next trial, they had to use the same procedure. The one second validation time was not taken into account in our measurements.

At the end of the four blocks we asked subjects to fill the NASA-TLX questionnaire on a web-based interface we developed. [19]

5.4 Apparatus

Each experiment was conducted on a Barco Consul, a 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 3 GHz Intel Quad Core and a NVIDIA Quadro FX 5600. The head and the hands tracking were provided by an ART tracking system and optical trackers. The users used two XIST Data Gloves to interact with the VE.

5.5 Measurements

We used a library [18] we developed to take several measurements during the task's fulfilment. The most relevant ones are the following:

- The manipulation time (MT, in seconds): the time between the first and the last movement of the manipulated object;
- The fine precision time (FPT, in seconds): the time the user needs to reach a given precision threshold fixed in this experiment as 0.05 m;
- The euclidean precision (EP, in meters): the euclidean distance between the target and the manipulated object at the end of the task;
- The NDC measurement: we used this measurement to compute the proportion of time users manipulated one, two and three DOF at the same time;
- The Weighted Workload (WWL): it is an estimation of the cognitive load provided by the NASA-TLX questionnaire.

5.6 Hypotheses

Regarding this study our hypotheses are the followings.

H1: The integrating and the decomposing techniques offer different degrees of the DOF's coordination. Using the integrating techniques users are able to manipulate three DOF simultaneously. Using the decomposing techniques, users achieve the task by manipulating two DOF when moving the object into the corresponding plane and one DOF when moving the object along the isolated dimension.

H2: Because the integrating techniques facilitate the manipulation of all the DOF at the same time, users are able to achieve the task faster than making use of the decomposing techniques.

H3: Because the decomposing techniques ease the decomposition the users benefit from it to achieve more precisely the task along the isolated dimension.

H4: The interaction techniques have a significant influence on the users' WWL. These techniques may reduce the WWL because of lower muscular fatigue.

6 RESULTS

For each of the measurements presented in Section 5 we ran a One-Way ANOVA (ANalysis Of VAriance) with the interaction technique (IT) as the independent factor. Then, we ran a post-hoc Tukey HSD (Honestly Significant Differences) test to compute the relevancy of the differences between the different techniques. The statistical relevancy threshold was fixed to 0.05.

6.1 Degrees of freedom manipulation

IT	NDC	Pair	ρ-value
Ray-Casting	1.987	Go-Go - HA	< 0.0001
Go-Go	1.966	Ray-Casting - HA	< 0.0001
DA	1.423	Go-Go - DA	< 0.0001
HA	1.371	Ray-Casting - DA	< 0.0001
		DA - HA	0.012

Table 1: The mean NDC during the task.

The IT has a significant influence on the NDC ($F(3,278) = 831.0341$; $\rho < 0.0001$). Table 1 shows the mean number of DOF simultaneously manipulated during the task. Except the difference between the Go-Go and the Ray-Casting, all the differences are statistically significant.

IT	1 DOF	2 DOF	3 DOF
Ray-Casting	6.7%	86.1%	6.0%
Go-Go	8.8%	84.6%	6.5%
DA	59.7%	39.8%	0.4%
HA	63.7%	36.1%	0.1%

Table 2: The mean proportion of time users are manipulating one, two and three DOF simultaneously during the fulfilment of the task.

There is a strong influence of the IT on the time users manipulate one DOF ($F(3,274) = 842.79$; $\rho < 0.0001$), two DOF ($F(3,274) = 615.78$; $\rho < 0.0001$) and three DOF ($F(3,284) = 220.87$; $\rho < 0.0001$). The significant ρ-values are given in Table 3. Using the Go-Go and Ray-Casting techniques the time users manipulate simultaneously two and three DOF is significantly higher than using the HA and DA techniques. Using the DA and HA techniques, the time users manipulate one DOF is significantly higher than using the Go-Go and Ray-Casting.

ρ-values for 1 DOF
DA - Ray-Casting: < 0.0001
HA - Ray-Casting: < 0.0001
DA - Go-Go: < 0.0001
HA - Go-Go: < 0.0001

ρ-values for 2 DOF
Go-Go - HA: < 0.0001
Ray-Casting - HA: < 0.0001
Go-Go - DA : < 0.0001
Ray-Casting - DA: < 0.0001

ρ-values for 3 DOF
Ray-Casting - HA: < 0.0001
Go-Go - HA: < 0.0001
Ray-Casting - DA: < 0.0001
Go-Go - DA: < 0.0001

Table 3: The ρ-value for each pairwise comparison and each number of DOF combined simultaneously.

The results presented in Tables 1 and 2 suggest that users are not able to coordinate the manipulation of all the DOF using the Go-Go and Ray-Casting. Moreover, the high percentage of time the users manipulate one DOF using the HA and the DA suggests that they try to go further in the decomposition proposed by our techniques by decomposing the in-plane positioning.

6.2 Performances

IT	EP	Pair	ρ-value
Go-Go	0.013 m	Ray-Casting - DA	0.0003
Ray-Casting	0.011 m	Go-Go - DA	< 0.0001
HA	0.009 m	Go-Go - HA	0.0019
DA	0.007 m		

Table 4: The mean euclidean distance between the manipulated object and the target at the end of the task.

There is a strong influence of the IT on the EP ($F(3,287) = 13.5845$; $\rho < 0.0001$). As it is illustrated on Table 4, the differences between the DA and the Go-Go and Ray-Casting interaction techniques are statistically significant. Moreover, the difference between the Go-Go and the HA is statistically significant. These first results suggest that the decomposition of the DOF can increase the precision.

IT	MT	FPT
Go-Go	8.92 s	2.15 s
Ray-Casting	9.33 s	2.77 s
HA	9.75 s	4.78 s
DA	9.44 s	4.73 s

Table 5: The mean MT and FPT for each interaction technique.

Table 5 shows the results regarding the MT. There is no influence of the IT on the manipulation time ($F(3,292) = 0.2768$; $\rho = 0.842$). It suggests that the decomposition of the DOF do not necessarily lead to an increase in the time to achieve the task. Regarding the FPT, there is an influence of the interaction technique ($F(3,284) = 38.5706$; $\rho < 0.0001$). Except for the difference between the Go-Go and the Ray-Casting ($\rho = 0.1779$) and the DA an the HA techniques ($\rho = 0.9981$), all the differences are significant. The ρ-values are given in Table 6.

ρ-values for FPT
DA - Go-Go: < 0.0001
HA - Go-Go: < 0.0001
DA - Ray-Casting: < 0.0001
HA - Ray-Casting: < 0.0001

Table 6: The ρ-value for each significant pairwise comparison.

These results suggest that the use of our techniques that ease the reduction of the number of DOF simultaneously manipulated may lead to an increase in the precision without any significant variation in the achievement time.

6.3 Weighted workload

Table 7 shows the mean WWL, mental demand (MD) and physical demand (PD) for each interaction technique. The technique has a strong influence on the WWL ($F(3,32) = 10.635$; $\rho < 0.0001$) and the PD ($F(3,32) = 9.1303$; $\rho = 0.0002$). However it has no influence on the MD ($F(3,32) = 2.0174$; $\rho = 0.1343$). The significant differences are presented in Table 8.

The Go-Go and Ray-Casting seem to induce the same WWL ($\rho = 0.83$). The use of both DA and HA reduces significantly the WWL regarding the others techniques. However, the difference between the DA and the HA is not significant ($\rho = 0.99$). These results suggest that the task's decomposition seems to reduce the WWL. The decomposing techniques seem to decrease significantly the PD and do not increase the MD required to achieve the task.

IT	WWL	MD	PD
Go-Go	59.67	50.0	56.25
Ray-Casting	52.92	36.2	55
DA	25.08	37.5	22.5
HA	23.92	26.2	17.5

Table 7: The MD, PD and WWL computed using the NASA-TLX questionnaire.

ρ-values for WWL	
Ray-Casting - HA	0.0063
Go-Go - HA	0.0007
Ray-Casting - DA	0.0090
Go-Go- DA	0.0010

ρ-values for PD	
Ray-Casting - HA	0.0031
Go-Go - HA	0.0022
Ray-Casting - DA	0.0115
Go-Go- DA	0.0083

Table 8: The significant differences for the WWL and PD.

7 Analysis

The results presented in the previous section suggest that the task decomposition may have a strong influence on the users' performances and the induced WWL during the task. The separation of the depth dimension during the decomposition seems to have also a strong influence on the performances.

7.1 Degrees of freedom coordination

Regarding the results presented in Table 2, we notice that the percentage of time the users manage to manipulate simultaneously all the task's dimensions is very low for the integrating techniques (around 6%). It suggests that users were not able to fully benefit from the integration. Moreover, the users often manipulate only two DOF at the same time –during more than 80% of the time. Both results suggests that users are only able to partially integrate the DOF.

Furthermore, using the decomposing techniques the users strongly decompose the task. The mean percentage of time users manipulate three DOF simultaneously using the DA and HA is close to 0% suggesting that they do not even try to integrate the manipulation of the three dimensions. This is not surprising since we thought that using the decomposing techniques the users would decompose the task into at least two sub-tasks:

- Positioning the manipulated object in the corresponding plane;
- Positioning the manipulated object along the isolated dimension.

However, Table 1 shows a low mean NDC value for both techniques. We also notice that the percentage of time the users manipulate one DOF is very high using these techniques. As we expected, the users decompose the positioning task, however they go further in the DOF's separation by also decomposing the plane positioning subtask. Thus, they decompose the 3-DOF positioning task into three 1-DOF subtasks.

The high degree of decomposition using the decomposing techniques and the incomplete integration the users reached using the integrating techniques may indicate that the simultaneous manipulation of all the DOF of the task may be too complex and may not always be the appropriate strategy to achieve the task. Indeed, the positioning task is usually divided in two phases [11]: the *ballistic* and the *control* phases. During the ballistic phase users coarsely position the manipulated object toward the target. Then, during the *control phase*, they perform small adjustments to precisely correct the position of the manipulated object. Coordinating the manipulation of the DOF may be an efficient strategy during the ballistic phase. However, it may be more efficient to manipulate one DOF at a time during the control phase. Since users spend the most of the time in the control phase, the fact that the cognitive load is increased for the integrating techniques and decreased for the decomposing techniques seems to confirm this explanation. Moreover, it may also explain the good results obtained by some of the interaction techniques based on the decomposition of the task [1] [9].

In the next section, we study the impact of the decomposing and integrating techniques on the users' performances.

7.2 Performances

7.2.1 Precision

Table 4 shows the mean EP offered by each interaction technique. With a mean of 0.013 m the Go-Go performs significantly worse than the decomposing techniques. This technique always requires the manipulation of all the DOF at the same time, thus preventing the users from performing adjustments along a specific dimension without affecting the others. The impossibility to perform directional adjustments may penalise users during the control phase thus limiting the EP users can reach. The better EP provided by the HA and DA techniques may highlight the efficiency of the task's decomposition during the control phase.

The Ray-Casting technique also requires users to manipulate all the task's DOF at the same time. However, it provides better EP than the Go-Go and similar EP than the HA. We think that this is mainly due to the fact that the Ray-Casting technique involves smaller muscles groups than the Go-Go and HA during the interaction (the wrist), which has been proved to significantly increase the users' precision [22]. Although the HA and DA techniques involves large muscles groups, they respectively provide similar and better EP than the Ray-Casting. The decomposition of the task may increase the precision users reached.

In relation to the EP offered by the Ray-Casting and the HA techniques, the only technique significantly increasing the users' precision is the DA (which is 85.71% more precise than the Go-Go, 57.14% than the Ray-Casting and 29% than the HA). This is quite surprising since using both decomposing techniques the users almost decompose the task into three one DOF subtasks. We think that the main reason of this difference comes from the isolated manipulation of the depth dimension which has been proved to be more difficult to manipulate [5]. We are still investigating what are the possible origins of this gain. The gain can result from a better control of the depth adjustments in the control motor space due to its isolated manipulation, or it can arise from the fact that the depth positioning may be considered as a specific task separated from the x and y positioning. The perceptual structure of the DA technique matching the task's structure, it should provide better EP than the other interaction technique –this is a consequence of the *Jacob et al.* framework [8].

These results partially confirm our third hypothesis. Helping the users decomposing the task increase their precision. However, the decomposition is not the only involved factor. It has to be appropriate to overcome specific difficulties for instance by isolating the manipulation of the DOF representing specific difficulties (the depth dimension in our case).

7.2.2 Manipulation time

Often, the integration of the manipulation of all the DOF is presented as a key feature explaining the better performances in comparison to techniques that decompose tasks, especially regarding achievement times [13]. However, the results presented in Table 5 suggest that the decomposing techniques do not introduce any significant increase in the achievement time. This is in opposition to our second hypothesis. Whatever was the technique, the users performed the task within similar amounts of time (about 9 seconds). This result is similar to the results obtained by *Benko et al.* [1].

As explained earlier in this section, the positioning task may be decomposed by users into a ballistic phase and a control phase. During the ballistic phase it may be appropriate to manipulate as many DOF as possible to move quickly toward the target. During this phase, the integrating techniques may be faster than the decomposing techniques. This is confirmed by the FPT given in Table 5. The integrating techniques are more than 2 s faster than the decomposing techniques to reach the 5 cm threshold. However, when precisely positioning the object during the control phase, the decomposing techniques may be more efficient. Since users spend a lot of time in the control phase, the time lost using the decomposing techniques during the ballistic phase may then be regained during the control phase, thus explaining the absence of difference regarding the MT.

7.2.3 Cognitive load

The WWL is a numerical value resulting from a weighted mean of several factors: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration Level. We investigate the impact of the decomposition of the DOF on the WWL, MD and PD.

The decomposing techniques reduce significantly the WWL – which is divided by more than 2– compared to the integrating techniques. The coordination of the three DOF during the whole task may be complex for users. This explains both the only partial coordination the users reached using the integrating techniques and the high level of decomposition using the decomposing techniques. The reduction of the WWL using the decomposing techniques may also result from the division of a complex three DOF task into successive more simple one DOF subtasks.

However, we thought that the use of the decomposing techniques increases the MD because they require a more complex planning of the task. However, there is no significant influence of the technique on the MD. This may be explained by the efficiency of possible strategies based on the decomposition of the task using successive alignments. We are investigating the influence of the task's decomposition on the strategy during the fulfilment of the task. We think that when users utilise the decomposing techniques they may use strategies based on successive objects' alignments –typically aligning the object along the depth axis and then aligning the object into the X-Y plane. Avoiding the fulfilment of the task for all the dimensions at the same time, the use of such a strategy may successively reduce the task complexity. We are designing a new behavioural measurement to investigate these questions.

Moreover, the decomposing techniques significantly increase the users' comfort by significantly reducing the PD. This is due to the use of the lower screen as hands support during the manipulation. Using the integrating techniques users manipulate in the mid-air. Such manipulation quickly introduce a large amount of fatigue.

8 Conclusions

In the present work, we investigate the effect of the DOF's integration and separation on the users' performances during a 3-D positioning task. Using a new measurement we propose, quantify and compare the degree of coordination of the task's DOF using two integrating and two decomposing techniques. We observe only a partial integration of the task using the integrating techniques and a strong decomposition of the task using the decomposing techniques –users decompose the 3-D positioning into three 1-D subtasks.

The decomposing techniques significantly reduce the WWL on the one hand by dividing a complex three DOF task into successive more simple subtasks, on the other hand by increasing the user comfort. The decomposition of the task does not introduce any significant increase in the MT thus suggesting that the integration of the DOF is not always the most efficient strategy. The decomposition seems to be more efficient than the integration especially at the end of the task when users try to precisely position the manipulated object. The decomposition also introduces a significant increase in the precision, especially when it allows the individual manipulation of the depth dimension, thus overcoming one major difficulty during the positioning.

We are further analysing the data of this experiment to identify and quantify the benefits provided by the integration and the decomposition during during the ballistic and control phase.

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