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Influence of Orientation Offset between Control and Display Space on User Performance during the Rotation of 3D Objects

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Abstract

This paper presents an exploratory investigation of the influence of orientation offset between control and display space on user performance in three-dimensional rotation tasks. A target-matching task was chosen as an experimental task; participants had to rotate an object (using an input device with 3 degree-of-freedom (DOF) in rotation) so that it matched the target, which was an object identical to the controlled object. Orientation of the controlled object was offset relative to the target's orientation by 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330 degrees. Those offsets were separately applied to each of the 3 axes of the target (vertical (X), horizontal (Y) and depth (Z) axes). Completion time and time series of orientation of the input device were collected. Results show strong effects of high values of offset (from 90° to 150° and from 210° to 270°) on user performance and user behaviour. In addition, there was a difference in user performance and behaviour between orientation offsets on the Z-axis and those on the two other axes, apparently due to the form of the input device that was used. The findings from this investigation may contribute to the design of 3D input devices (with regard to issues on physical form-factors and on supports for rotation in particular) and that of techniques for the manipulation of 3D objects.

Categories and Subject Descriptors (according to ACM CCS) H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces–Theory and methods; I.3.6 [COMPUTER GRAPHICS]: Methodology and Techniques– Interactive Techniques.

1. Introduction

In the real world, reorienting an object in hand to see its other face would take about one or two seconds. Through a formal study, Ware and Rose [WR99] empirically showed that it took 1.64 seconds on average to rotate an object in the right hand so that its orientation matches that of an identical object hold in the left hand. In another study, Wang et al. [W98] also showed that it took less than one second to rotate a real cube to match a similar three-dimensional cube, rotated by an angle of 45 degrees about its vertical axis and displayed on a screen. In general, rotation of real objects seems quite an easy and a low time-consuming task.

However, the time required for the rotation of a virtual 3D object seems much higher than that of a real object. For example, a time of 27.7 seconds for an orientation matching task was reported by Hinkley et al. [HTP*97]; a similar task took 17.5 seconds in a study by Chen et al. [CMS88]. Besides, there is also a divergence in the reported results; for example, a shorter time (4.5 seconds) for a similar task was reported by Ware and Arsenault [WA04]. On the one hand, the variation found in those results can be explained by the difference in input devices, interaction techniques, experimental conditions, etc. in each study. On the other hand, those results also show a much more complex nature of the rotation of 3D objects (3D rotation) than that of real objects.

In most of the cases, 3D rotation involves an *input device* for issuing the user's control actions and a *graphical display* for showing the user the result of his/her actions. The presence of these two additional elements makes the 3D rotation less "direct" than the rotation of real objects and increases the number of factors potentially influencing user performance and behaviour. For example, factors involving the *control space* (i.e. the working space of the input device), the *display space* (i.e. the working space of the displayed object) and the *mapping* between those two spaces certainly influence user performance and behaviour. While a gap in user performance between rotation of real objects and that of 3D objects still exists, a comprehensive understanding of the effect of those factors on user performance and user behaviour could be beneficial to the design of input devices, visual aids and/or interaction techniques facilitating the rotation of 3D objects. Hence, the present paper focuses on one of those factors: the mapping between

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control space and display space. In particular, this paper looks into the influence of *a mismatch between control and display space* on user performance and user behaviour in a 3D rotation task.

During a rotation of three-dimensional (3D) objects, a mismatch between the behaviour of input devices and that of the display may happen; for example, the rotation of the controlled object may be displayed in a direction opposite to the intended direction. This unintended effect of the manipulation of the input device could be unintentionally created by previous control actions of the user; for example, the user may have turned upside down the controlled object in one of his/her previous actions and the usual control for "turn left" now results in a "turn right" motion of the controlled object. Besides, this could also be the result of a difference between the shape of input device and that of the controlled object. The ideal condition for a 3D rotation should be a consistently perfect match between the shape and orientation of input device and that of the controlled object. However, the physical shape of hand-held input device and that of the controlled object are not usually identical. At the beginning of rotation, the user may define an imagined frame of reference for the controlled object, based on the present orientation and the form of the object, so that it matches the frame of reference of the input device. However, during the manipulation, control actions certainly change the apparent form and orientation of the controlled object, such that the initial user-defined match would be no longer valid.

In both cases, an offset between the control space and the display space has been undesirably created, resulting in a modified mapping between the frame of reference of the input device and that of the controlled object. This offset forces the user to control the input device in a different way in order to adapt to this modified mapping. Such an adaptation phase during a 3D rotation task could have strong effect on user performance (including completion time). Hence, this paper presents an exploratory investigation of the influence of orientation offset between control and display space on user performance in three-dimensional rotation tasks.

2. Related work

The problem of mismatch between control and display space treated in the present paper concerns the stimulus-response (S-R) compatibility which has been largely studied in cognitive psychology and ergonomics ([FS53; [WB98] to name a few). The S-R compatibility defines the degree to which a response matches a corresponding stimulus; in other words, the degree to which what people perceive is consistent with the actions they take. As stated by Fitts and Seeger [FS53], "*if an incompatible S-R relation exists, then a considerable amount of recording of information (such as the looking for meaningful associations, etc.) may be highly desirable*". A high level of S-R compatibility is thus believed to reduce cognitive load and enhance user performance.

Various studies in visual interfaces have taken into account the S-R compatibility, in particular two-dimensional (2D) user interfaces. For example, a cursor which dynamically reshapes itself to be compatible with the orientation of a pen (as input device) has been proposed by Tian et al. [TAW*07]; the effect of display position and control space orientation on user performance has been investigated in another study by Wigdor et al. [WSFB06]. Quite less attention, to our knowledge, has been given to the S-R compatibility in 3D user interfaces and 3D rotation. Most of previous studies with regards to 3D rotation have focused on comparing different rotation techniques [CMS88; HTP*97]. Rotation has been usually examined in combination with translation (in a docking task for example) as they have been both considered as the key elements of a manipulation task [ZM98; MM00; VM06]. To our knowledge, two studies which have related to the problem of mismatch between the control and display at some degrees are those conducted by Ware and his colleagues [WR99; WA04].

In the first study, Ware and Rose [WR99] carried out an interesting experiment studying the effect of shape mismatch on user performance in an orientation matching task. A handheld ball-shaped input device and a wooden handle similar to the manipulated object were used in the two comparative conditions of the experiment. Although subjects performed 7% better in the case of wooden handle, that difference was not significant. The ball-shaped input device could have played a certain role in that result. Rotational symmetry in all directions, the ball shaped input device might have reduced the cognitive problems (e.g. the visual mismatch between the input device and the controlled object) that would degrade user performance.

A deterioration of user performance when the orientation offset on the vertical axis (Y) approaches 90 degrees was also revealed though an experiment conducted by Ware and Arsenault [WA04]. The experiment task was to rotate a 3D object using a hand-held *ball-shaped input device* so that it had the same orientation as the target object. There were 9 levels of mismatch, varying from -90 to +90 degrees with 22.5 deg increments. User performance was U-shaped, i.e. the completion time for -90 and 90 degrees was highly increased, as compared to smaller mismatch values. However, the effect of mismatch on other axes and user performance when the mismatch is over 90 degrees stayed unknown.

We believe that a mental rotation process is implied in the execution of such a target matching task though rotation; since subjects have to compare the orientation of the controlled object to that of the target at different moments during the task execution to find the correct rotation path to match the controlled object with the target. Hence, we review here some related work on mental rotation which we believe can help us to interpret the results.

Shepard and Metzler [SM71] showed that the time taken to compare two similar shapes of different orientations increases linearly with the angular disparity (from 0 to 180 degrees) between the two shapes. This task has been since known as "mental rotation task". Wohlschläger [Woh98] showed a linear decrease in reaction time for the angular disparities from 180 to 360 degrees in a study on both mental rotation and manual rotation. In this study, the task, in terms of manual rotation, was similar to a mental rotation task; however, subjects had to turn the controlled object by mean of a knob, a 1DOF input device in rotation, around its horizontal (X), vertical (Y) and depth axes (Z) during the execution of the mental rotation task. Interestingly, the results gave similar reaction times in manual rotation compared to mental rotation; the reaction times increased linearly with angular disparities from 0 to 180 degrees and decreased linearly with angular disparities from 180 to 360 degrees.

A common point in the two experiments of Ware and his colleagues [WR99; WA04] and the experiment on manual rotation of Wohlschläger [Woh98] is that the end of each trial depended on the user's judgment. A precise match between the two objects was probably not required to get to the final answer. In the present study, we introduce a higher level of task difficulty (i.e., a higher level of precision required to finish the task) and a large set of levels of mismatch (from -180 to +180 degrees) to understand the influence of mismatch on two phases of rotational movements: the approaching phase to bring the controlled object in the vicinity of the target and the adjusting phase which could require fine movements to completely match the controlled object with the target. The mismatch on three axes of the target (vertical, horizontal and depth axes) is also taken into consideration. In addition, we adopt an analytic approach by analysing time-series data of orientation of the input device to get insight into the effect of mismatch on user behaviour.

3. Experiment

3.1. Subjects

Nine volunteers between the ages of 24 and 32 participated in this experiment (6 males, 3 females; 8 right-handed). All participants had normal or corrected-to-normal vision. Seven had little or no experience with 3D stereo vision.

3.2. Experimental design

The experiment was a three-way 3x11x 4 within-subjects design. The three independent variables were as follows: rotation axis with three levels (X, Y, Z), offset (initial orientation difference between the controlled object and the target) with 11 levels (30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, 330°), and block with four levels. The dependant variable was completion time.

The above conditions with nine subjects represent a total of 1188 trials. Trials were organized in four successive blocks. For each participant, each block consisted of 33 trials corresponding to the 33 different conditions (11 offsets * 3 axes); each trial corresponding to an offset on an axis. The order of presentation of the scenes randomly varied for each block and each subject. In order to avoid excessive fatigue the experimental task might cause, two experimental sessions were organized; the subject performed two blocks of trials in each session. A break of five minutes between the two blocks was also given to the subject. The two sessions were organized either in two different days or one in the morning and one in the afternoon.

3.3. Apparatus

The experiment was conducted inside a CAVE-like immersive virtual reality system of the Mediterranean Virtual Reality Centre. The hardware consisted of four projection surfaces: the front, left and right vertical walls and the horizontal floor. The 3 walls (3 meters wide and 4 meters high) were back-projected acrylic screens. The floor (a square with a side of 3 meters) was directly projected from above. Each projection surface received images with 1400 × 1050 pixels resolution, with a 60 Hz frame-rate. Stereoscopic projection of stimuli was achieved by two DLP ® (Digital Light Processing) projectors attached to each projection surface. Each projector addressed one eye. Stereoscopic separation between left and right eye images was ensured by colorimetric separation (Infitec ® technological solution). Infitec ® filters were installed in the projectors, while the subject was wearing glasses with the same filters. This guaranteed perfect separation of images between the two eyes. Finally, a real-time tracking system (ArtTrack ®), using infrared recognition of passive markers placed on the subject's glasses, was used to record the subject's head position and orientation and to update in real time the stereoscopic images relative to the subject's point of view. We used Virtools ® solution to build and control virtual scenarios, for experimental control and data recording.

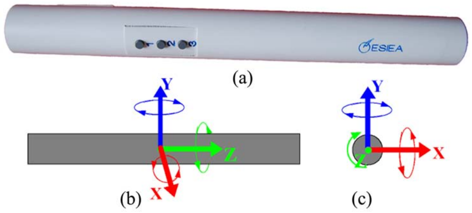

Figure 1: *The 3D stylus (a) and its coordinate system (side-view (b), front-view (c))*

A 3D stylus developed by ESIEA, a cylinder-shaped device of 22.3-cm-long and 2.5-cm-diameter, with three degree-of-freedom in rotation and 3 control buttons was used in the experiment (cf. Figure 1-a). This device had an inertial measurement unit composed of 3 accelerometers, 3 gyroscopes and 3 magnetometers, connected to the system by Bluetooth. The origin of the 3D stylus is at its centre (cf. Figures 1-b, 1-c).

3.4. Stimuli and Task

Subjects were seated in the middle of the CAVE. Stimuli were presented at eye level. Each trial consisted of two

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phases: a *calibration phase* followed by a *test phase*. Since the orientation of the input device varied at the end of each trial, the calibration phase, which marked the beginning of a trial, was introduced to oblige subjects to get the input device back to its starting condition so as to get it ready for the test phase. In the starting condition, the subject had to keep a specified end of the 3D stylus pointing toward the screen and hold the 3D stylus in his/her dominant hand in a direction perpendicular to the screen. Thanks to the calibration phase, the starting condition of the input device was kept unchanged in all trials.

A target-matching task was used in the calibration phase. Two identical graphical objects including a target and a cursor (cf. Figure 2-b) were displayed to the subject. The subject used the input device to rotate the cursor so as to have it match the target. In the starting condition of the input device, the cursor was brought very close to the target so that it required less effort from subjects to match the cursor to the target. The object used in the calibration phase was a graphical presentation of a 3D Cartesian coordinate system; the three axes were presented in different colours (red, green, blue) (cf. Figure 2-a).

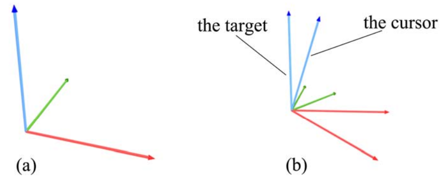


Figure 2: *(a) Stimuli used in the calibration phase; (b) the cursor and the target in the calibration phase*

A similar target-matching task was introduced in the test phase in which two identical graphical objects (a controlled object and a target) were displayed to the subject (cf. Figure 3-b). The graphical object used in the test phase was yet different. This object was similar to one of those used in the study of Shepard and Metzler [SM71] on mental rotation (cf. Figure 3-a), also known under the name of cube arrays. The cube arrays were also used in a study on PRISM, a 3D interaction technique, by Frees et al. [FKK07]. In the present experiment, all cubes were presented in white. The subject used the 3D stylus to rotate the controlled object so that it matched the target (i.e., the angle between the two vectors indicating the direction of the controlled object and the target was less than 2 degrees). The trial finished when the match had lasted more than 700 milliseconds.

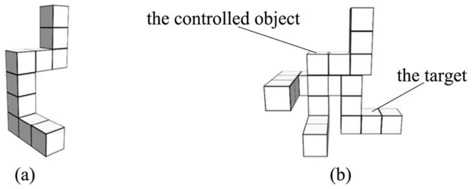


Figure 3: *(a) Stimuli used in the test phase, (b) there is an angular difference of 90 degrees on the Z-axis between the controlled object and the target*

For all trials, the position of both the controlled object and the target were at the centre of the screen. The orientation of the target and the initial direction of the 3D stylus were the same in all trials. In a trial, the coordinate system of the 3D stylus was offset from that of the controlled object depending on the condition about the rotation axis and the value of offset of this trial. Since an offset concerns to the relative relation between the input device and the controlled object, when the initial direction of the 3D stylus was kept unchanged in all trials (to keep the same starting condition for all trials) and at the same time, there was an offset between the 3D stylus and the controlled object, the orientation of the controlled target was unavoidably changed in each trial. Therefore, for each value of offset, there was both an orientation difference between the coordination system of the 3D stylus and that of controlled object and an initial orientation difference between the controlled object and the target which varied depending on the value of offset.

3.5. Procedure

Before starting the first session, each subject had to read a paper with written instructions. Then, a video showing a trial completion example was presented to the subject. Subjects were allowed to ask questions and for additional explanation only before the beginning of the test. After that, every subject was invited to sit on a chair, placed at 150 cm from the stereoscopic display. Six training trials were provided in order to let subjects become acquainted with the 3D scenes and the task. Afterwards, the real task began. Since the experiment involved an attention-demanding task, subjects were allowed to have a break anytime they wanted during the calibration phase of each trial. In addition, a time limit of three minutes was given for each trial. Before starting the second session, another six others training trials were provided to the subject to remind her/him about the experimental task.

A trial block was started with the calibration phase of the first trial. The subject had to put the 3D stylus to the starting condition and press a specific button to enter the test phase. This button was pressed only one time in the calibration phase of the first trial of each block to remove an eventual orientation offset between the 3D stylus and the cursor which might have been created in previous sessions. Once the test phase of a trial had been finished (i.e., the cursor matched the target during more than 700 millisecond), the calibration phase of the next trial was presented automatically to the subject. The subject put the 3D stylus back to its starting position to perform the calibration phase. Once the calibration phase had been finished, the subject continued with the test phase of this trial; and so on for other trials. After finishing the second session, subjects were requested to answer a short questionnaire to collect information about subjects' previous experience with 3D environment and their comments about the experiment. Each experimental session (including training trials) lasted approximately 45-50 minutes. Overall, each subject spent about 1h30 for the whole experiment.

4. Results and discussion

4.1. Observation

All subjects used both hands to manipulate the stylus during the experiment.

4.2. Data Acquisition and Analysis

Task completion time and time series data recording the input device's orientation (acquired at 60Hz) were collected during each trial. On the one hand, the behaviour of subjects with regard to different levels of offset could be revealed and compared though time series data; on the other hand, different possible phases during a trial could be indentified. An example of a movement profile showing how the subject rotated the cursor and matched it with the target is shown in Figure 4. This profile was plotted from time series data. The value shown on the Y axis is the cosine value of the angle between the vector indicating the direction of the controlled object and that of the target.

As mentioned above, we looked into the influence of orientation mismatch on two main phases: the approaching phase involving coarse movements to bring the controlled object close to the target and the adjusting phase for fine movements to match the controlled object with the target. We analyzed two sub phases of the approaching phase: *the first approaching phase*, from the start of trial to the moment when the value of angular difference was less than 10 degrees for the first time and *the second approaching phase* which is from the end of the first phase to the moment when the value of angular difference was less than two degrees for the first time. *The adjusting phase* was calculated from the end of the approaching phase to the end of trial. Those three phases are illustrated in Figure 4.

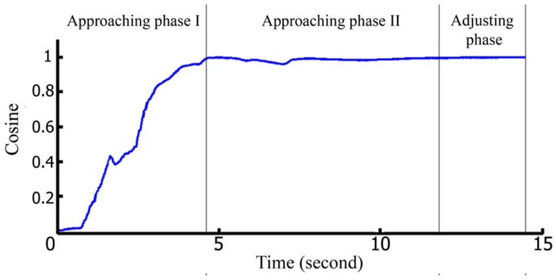
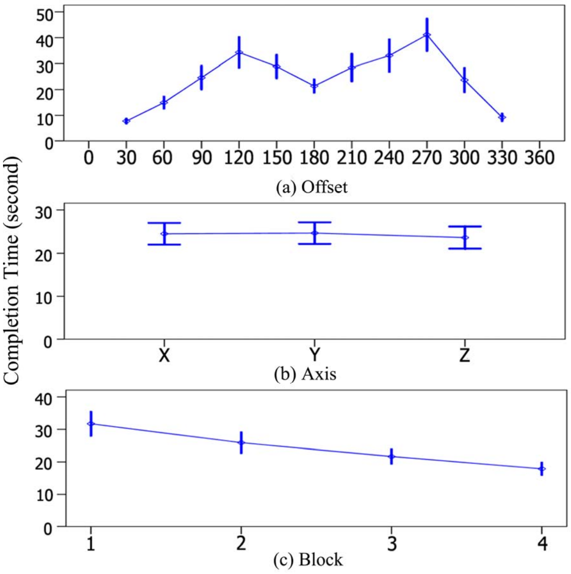


Figure 4: *A plot showing how the cursor was rotated in a trial: at the beginning, the angle between the target and the controlled object was 90° resulting in a cosine value of 0; the cosine value was close to 1 when the controlled object completely matched the target at the end of the trial.*

There were seven non-finished trials (five in the first block), representing a percentage of 0.59% of the total number of trials. Those trials were discarded from the analysis.

4.3. Completion time

The data of completion time were not normally distributed (Shapiro–Wilk test). Since time is continuous and parametric by nature, we applied a logarithmic transformation on the dataset of completion time to determine whether we could apply parametric tests for completion time. The transformed completion time was normally distributed; we thus applied parametric tests for the statistical analysis on completion time. For ease of comprehension, all numbers and figures are still presented according to the original, untransformed scale. A 3 (axis) x 11 (offset) x 4 (block) analysis of variance (ANOVA) was calculated on transformed completion time.



(a) Offset

(b) Axis

(c) Block

Figure 5: *Mean completion time by offset (a), axis (b) and block (c); vertical bars show 95% confidence interval (CI)*

There was a significant main effect for block [F(3,1049) =30.315, p < .001]. Group mean values of completion time for the first block was 31.72s [Standard Deviation (SD)=32.26]; for the second block 25.89s [SD=28.03]; for the third block 21.74s [SD=19.32] and for the fourth block 17.96s [SD=16.83] (Figure 5-c). Post-hoc comparisons conducted with the Tukey test revealed a significant difference among almost all blocks (p<.005) (except between block 2 and block 3). The learning effect was quite obvious; subjects' performance was considerably improved over blocks. The indifference between block 2 and block 3 might be explained by a long break between these two experimental sessions.

	30	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**
Time(s)	7.8	14.97	24.60	34.33	28.89	21.37	28.54	33.03	41.14	23.68	9.25
SD	5.2	12.24	24.07	31.11	24.01	13.57	27.85	32.41	32.80	24.91	7.93

Table 1. *Completion time by offset*

A significant main effect for offset was also found [F(10,1049) =68.208, p <0.001]. Group mean values and standard deviation (SD) of the completion time for 11 values of offset from 30° to 330° are shown in Table 1. This result was expected since different angular offsets between the target and the controlled object supposedly required different time cost and effort from subjects. We looked into the symmetrical aspect of the results by categorizing two groups of offsets: one with the offsets previous to 180° and the other one with those following 180°. An offset in each group had a symmetrical offset (with respect to 180°) in the other group. There were five such pairs of symmetrical offsets: [30°,330°], [60°,300°], [90°,270°], [120°,240°], and [150°,210°]. In all trials corresponding to the two offsets in each of those pairs, the smallest angular difference between the controlled object and the target was the same; for example, 30 degrees for the pair [30°,330°] or 150 degrees for the pair [150°,210°].

In order to fill that smallest angular difference, trials corresponding to one offset in each pair required a rotation direction opposite to those corresponding to the other offset. For example, a 30-degree clockwise and a 30-degree anticlockwise rotation, respectively for the two offsets 30° and 330° of the pair [30°,330°], were necessary to finish the target-matching task with the least effort. Since the 3D stylus was symmetrical in each of its three rotation axes, such difference in the rotation direction would not, supposedly, lead to the difference in subject performance among trials concerning the two symmetrical offsets in each pair. Post-hoc comparisons conducted with the Tukey test, however, partly confirmed this hypothesis. In fact, there were no significant differences in the completion time between the two offsets in the pairs [30°,330°], [120°,240°], and [150°,210°] ($p>.05$), but significant differences between the two offsets in the pairs [60°,300°] and [90°,270°] were found ($p<0{,}001$).

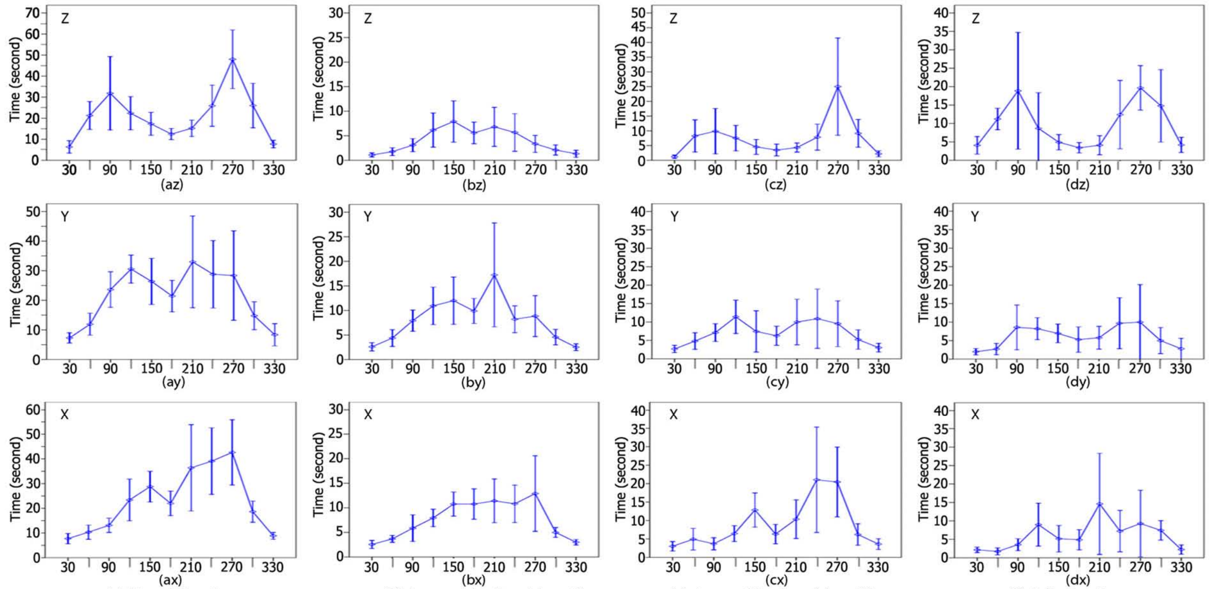
We examined two factors that might lead to those differences. The first factor was the subject's dominant hand. As previously mentioned, subjects used both hands to rotate the 3D stylus during the experiment. The cooperation between the two hands, in which the non-dominant hand serves as a reference frame support for the main manipulations carried out by the dominant hand (in the light of Guiard's Kinematic Chain Model [Gui87]), was practically different between the right-handed and left-handed subjects. The subject's dominant hand probably influenced the favourite rotation direction. In the experimental setup, the clockwise rotation was the direction taking advantage of the smallest angular difference (between the controlled object and the target) in trials with offsets smaller than 180°, whereas the anticlockwise rotation was the case in trials with offsets greater than 180°. The fact that almost all participants (8 of 9 subjects) were right-handed could have not been in favour of anticlockwise rotations - in other words, of trials corresponding to the offsets greater than 180°, resulting a potentially higher effort for the offset 300° than to 60° and for the offset 270° than to 90°.

The second factor was the value of offset in each pair. We noticed, during the experiment, that the subjects wrongly estimated the right rotation direction (i.e. the one taking advantage of the smallest angular difference to finish the task) on some occasions. In those cases, they either tried to get back to the initial orientation or continued to finish the target-matching task in the wrong direction. The more the controlled object was far from the target, the more the right rotation axis seemed difficult to identify and the higher the chance of making mistakes was. Depending on the value of offset, the confusion in the trials of some pairs might be more penalising than the others. Regarding the pair [60°,300°], confusions in the rotation direction might have required about five more times of effort (300° versus 60°) to finish the task. As for the pair [90°,270°], about three more times of effort and time cost (270° versus 90°) might have been necessary to finish the task in case of confusion.

Those two factors might partly explain differences between the two offsets in the pairs [60°,300°] and [90°,270°]. Regarding the remaining pairs, the difference between the two offsets in the pairs [120°,240°] and [150°,210°] was not probably high enough to produce any differences in completion time in case of confusion. The small value of the smallest angular difference for the pair [30°,330°] (i.e., 30 degrees) could have facilitated the correction in case of confusion, resulting in a less time lost and so a similar performance among trials corresponding to those two offsets. However, the previous discussion on the influence of the two factors was still speculative, further investigation would be required to get more insight on the influence of those two factors on the rotation direction.

Regarding the influence of different levels of offset on completion time, we only looked into the first half of offsets from 30° to 180° since 11 offsets were symmetrical with respect to 180°. As previously mentioned, Ware and Arsenault [WA04] found that the completion time increased when the offsets on the vertical axis varied from 0° to 90°, and a performance deterioration was observed when the orientation offset approaches 90 degrees. However, it was still unknown how user performance would degrade with orientation offsets over 90 degrees. More degradation was reasonably expected with the values of offset from 90° to 180°. The results in the present experiment replicated those reported by Ware and Arsenault [WA04]. However, an unexpected result was revealed: the completion time was increased when the offsets went from 0° to 120° and was then decreased with offsets going from 120° to 180°.

This unexpected result might be explained by the difficulty of subjects in finding the correct rotation axis (among the X-axis, Y-axis and Z-axis) when the controlled object was far from the target. The level of such a difficulty increased when no cue was provided to help subjects to determine the rotation axis. The relative orientation between the controlled object and the target was one of such cues. When the angular difference between the two similar objects is 90° or 180°, some parts of one object are perpendicular or parallel to those of the other, which might facilitate the judgement of the rotation axis. Such a cue is limited when the angular difference between the two similar objects is 120° or 150°. Once being misjudged, the rotation axis might become arbitrary; in that case, it would be even more difficult to find out the proper angle required to rotate the controlled object, as previously shown in a study of Parsons [Par95].



(a) Completion time (b) Approaching time (phase I) (c) Approaching time (phase II) (d) Adjusting time

Figure 6: *Mean completion time by axis and mean time spent in different phases of a trial; vertical bars show 95% confidence interval (CI) (based on subject means)*

Besides, the experimental target-matching task required a high precision in horizontal or vertical motions of the 3D stylus. The combination of the two hands seemed not stable enough to produce such highly precise motions due to the minor trembling of hand and arm motion. The longer the motion time was, the bigger the deviation from the desired direction might be. The jerk of the hand motion also seemed to complicate the correction of unwanted movements of subjects who, once they had noticed their wrong actions, tried to return to the previous orientation. According to some subjects, a support for letting them know whether their controls over the 3D stylus were well horizontal or vertical over time would be helpful for them to perform such precise movements.

Briefly, the difficulty of subjects in both judging the correct rotation axis and producing precise hand motions might explain higher effort and time lost in trials corresponding to the offsets in the vicinity of 120 degrees than in those concerning other offsets.

A significant main effect for axes was also found [F(2,1049) =3.795, p =0.023] . Group mean values of completion time for the three axes X, Y and Z were respectively 24.63s [SD=25.16], 24.67s [SD=25.17] and 23.68s [SD=25.85] (Figure 5-b). Post comparisons conducted with the Tukey test revealed a significant difference between the Y-axis and Z-axis (p=0.022). No other significant pair-wise differences were found (p>.05). The rotation around Z-axis seemed easier than that around the two other axes. Besides, there is an significant interaction between Offset and Axis [F(20,1049) =6.046, p <0.001]. Since the 3D stylus was not symmetrical in all directions as a ball-shaped input device, the form of the 3D stylus could have played a certain role in this difference. An analysis on completion time by axis would give more insight into the influence of the form of 3D stylus to subject performance.

The completion time by axis is shown in Figure 6-a. Regarding subjects' performance in trials with offsets on the X-axis (cf. Figure 6-ax), a model of performance quite similar to that of combined data on 3 axes (cf. Figure 5-a) can be observed: a highly increased completion time for the two values of offset 120° and 150° in the first group of offsets (from 30° to 180°) and for the three values of offset 210°, 240° and 270°° in the second group of offsets (from 180° to 330°). The same model of performance can be observed with offsets on the Y-axis (cf. Figure 6-ay). However, the model of performance with regards to offsets on the Z-axis (cf. Figure 6-az) was somewhat different: the completion time at the offset 180° was smaller than that at the two offsets 60° and 90°; whereas it was not the case for the offsets on the X-axis and the Y-axis. The form of the 3D stylus might explain this difference. In fact, while the rotation around the X-axis and the Y-axis was quite similar (cf. Figures 1-b, 1-c), the rotation around the Z-axis was carried out by rotating the 3D stylus around its physical axis (cf. Figure 1-c), which required rather less effort.

Regarding other interactions, the Block x Offset interaction was not significant (F(30, 1049) = 1.108, p > .05), as for the Block x Axis interaction [F(6, 1049) = 1.064, p > .05], and the Block x Axis x Offset interaction [F(60,1049) = 0.788, p >.05].

4.4. Time series data

We preliminarily analyzed the time series data to get more insight into the influence of rotation axis and offset in different phases of a trial. Regarding *the first approaching phase* which was quite easy - a low level of precision (less than 10° of angular difference) was required, a linear relation can be observed in the two groups of offset with regard to the Z-axis (cf. Figure 6-bz), to the X-axis (cf. Figure 6-

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bx) (with an exception of a highly increased approaching time for the offset 270°), and to the Y-axis (cf. Figure 6-by), with an exception of a highly increased approaching time at the offset 210°). This is an interesting point since a similar relation between the completion time and the angular difference (between the target and the controlled object) in a matching-to-sample task was found by Wohlschläger [Woh98] in an experiment on mental and manual rotation. When the manipulation task did not require high-precision controls of the input device, the linear relation between the subject performance and the offset seemed still hold at some degrees, despite a higher DOF input device (3DOF in the present study versus 1DOF in that of Wohlschläger [Woh98]) and a modified spatial mapping between the control and display space.

In *the second approaching phase* (cf. Figure 6-c) which required a high level of precision and in *the adjusting phase* (cf. Figure 6-d) which required a very high level of precision (less than 2° of angular difference), the influence of the values of offset from 90° to 150° for the first group and those from 210° to 270° for the second group was highly noticeable.

5. Conclusion

The present paper has presented an exploratory investigation of the effect of orientation offset between control and display space on user performance in three-dimensional rotation tasks. This work contributed to quantify user performance with 3DOF rotation offsets. Preliminary analysis on the experimental data showed a strong effect of high values of offset (from 90 to 150 degrees and from 210 to 270 degrees) on subject performance and behaviour. The degradation of subject performance at those high values of offset seemed due to a lack of support for subjects to find out the correct rotation axis and/or to make precisely horizontal, vertical movements in a spatial context with both hands.

Besides, the symmetry of results with regards to the two groups of offset (one with offsets previous to 180° and one with those following 180°) showed that the rotation direction, at some extent, had little influence on user performance; even though the right-handedness of subjects seemed to be in favour of trials in the first group (offsets previous to 180 degrees) and seemed partly contribute to a slightly higher completion time in some offsets in the second group.

Finally, the difference in user performance and user behaviour between orientation offsets on the Z-axis and those of the X-axis and Y-axis, mostly due to the form of the input device used in the experiment, provided supplementary evidence of the influence of the form factor on user performance and behaviour in interaction with 3D virtual objects.

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