Three Dimensional Object Orientation Using the Non-Dominant Hand

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ABSTRACT

The paper presents the "Turntable", a 3D input device for orienting objects using the non-dominant hand. The device supports two-handed manipulation by allowing the non-dominant hand to orient an object while leaving the dominant hand free to perform other actions. Two-handed input is a technique that can enhance the performance, simplicity and intuitiveness of CAD systems. These properties are obligatory for CAD systems dedicated to support the conceptual phase of the design process. An experiment has been conducted in which the performance of the Turntable was compared to that of a well known 3D orientation method, known in literature as the "virtual sphere". The virtual sphere is operated with the mouse using the dominant hand and is documented to be easy to use and efficient. The experiment establishes that a performance gain can be expected from a two-handed user interface that employs the Turntable for 3D object orientation with the non-dominant hand. In a single-handed interface users must switch between rotating and manipulating an object. In a two-handed interface however, task switching is unnecessary and an additional performance benefit can be achieved when there is temporal overlap in the execution of the two tasks. Experimental results show that the Turntable, operated by the non-dominant hand, is easy to learn and its performance and accuracy are nearly equal to that of the virtual sphere operated by the dominant hand. With these results it can now be expected that a two-handed interface utilizing the Turntable performs better than a single-handed one for manipulating objects in 3D.

INTRODUCTION

The IDEATE research projects at the Department of Industrial Design Engineering, Delft University of Technology in the Netherlands are concerned with the conceptualizing phase of the design process. In this phase the designer 1) creates an idea, 2) records it, with a sketch or a model and 3) decides whether she or he should continue to generate ideas. One area of interest is the use of computer-assisted geometrical modeling in these early stages. Systems designed for conceptual modeling have to meet high demands. It is of great importance that computer systems are highly intuitive and responsive so that they do not interfere with the designer's creativity and train of thought. Current CAD systems mainly support the preliminary and detailed design phases but fail to support conceptual design (Hennessey 1994). If the computer is introduced in the conceptual phase several advantages can be gained. The designer can generate more alternatives of a design and they can be evaluated better. Coupling with CAD systems for the later phases will save time when the design is transferred and when a redesign is necessary.

There is little literature that summarizes findings from existing systems in a way that enables the transfer to other 3D interfaces in development. Several studies have been focusing on developing 3D CAD systems for the initial stages of design. Examples include the 3DM three dimensional modeler (Butterworth et al. 1992), the Fast Shape Designer (van Dijk 1994) and the 3-Draw design tool (Sachs et al. 1991). Other research performs user studies to analyze individual phenomena in isolation, like the performance of input devices in 3D target acquisition tasks (Zhai et al. 1996). An integration of these two types of research would be desirable but there are limited numbers of papers on this issue. An exception is a survey by Hinckley (Hinckley et al. 1994) that lists several design issues for developing 3D interfaces. The survey is concerned with spatial input, which refers to free space 3D input techniques, like optical and electromagnetic trackers, as opposed to desktop devices such as the mouse or the Spaceball™. Although the focus of the article is on spatial input, the issues addressed are relevant to interfaces for 3D interaction using desktop devices as well.

One of the techniques described by Hinckley is two-handed input, a technique not well supported in current 3D modeling systems. This holds for most 2D graphical interfaces as well, as acknowledged by Chatty's (Chatty 1994) statement that the toolkits applied to build such interfaces should be more flexible with regard to input devices and event types in order to support the use of two hands.

Experimental systems like the 3-Draw and the THRED system by Chris Shaw and Mark Green (Shaw and Green 1994) have shown the potential of two-handed interaction. Sachs (Sachs et al. 1991) reports about the simultaneous use of two input devices in the 3-Draw system that it takes advantage of people's innate ability, knowing precisely where their hands are relative to each other. Also, people are quick in adapting to using two hands. An early study by Buxton (Buxton and Myers 1986) concludes that this kind of interaction was not only well within the bounds of novice's ability, but it also improved performance of both novices and experts in the tasks studied.

Two-handed input techniques have two potential performance related advantages. First, time can be saved if each hand remains within the same area. Assigning subtasks to two hands could lead to each hand remaining in a smaller space, resulting in less time spent moving. Second, the simultaneous use of two hands leads to a temporal overlap in the performance of the two subtasks assigned to the hands. When designing two-handed interfaces one is often tempted to simply split the task into two subtasks and assign them to the dominant and the non-dominant hand. The danger is that the performance increase is degraded by the growth of the cognitive load. The increases in time spent in processes like monitoring and planning could even lead to a situation where the two-handed approach is inferior to the single-handed one.

Design rules are needed to prevent the creation of inefficient two-handed interfaces. Guiard has created a theoretical framework for the study of asymmetry in the context of bimanual action (Guiard 1987). Although it is tentative and not formally demonstrated, it can be useful to predict which mappings are candidates for successful two-handed implementation. Assuming right handed dominance, Guiard proposes the following high order principles governing the asymmetry of human bimanual gestures:

- Right to Left Spatial Reference in Manual Motion. “Motion of the right hand typically finds its spatial references in the results of the motion of the left hand.” For example, in sewing, the left hand positions and orients the fabric, while the right hand performs the actual sewing operation by moving the needle relative to the fabric.
- Left-Right Contrast in the Spatial-Temporal Scale of Motion. In the sewing example the left hand movements are low in spatial and temporal frequency while the right hand performs more precisely and faster. In this respect the left and the right hands could be characterized as macrometric and micrometric.
- Left-Hand Precedence in Action. “The contribution of the left hand to global bimanual performance starts earlier than that of the right.” Before the action of the right hand starts, the fabric must have been brought to position and an orientation compatible with the privileged plane in which the loops of the needle will be formed.

Adherence to these guidelines is not a guarantee for a successful interface. In a study by Kabbash four different techniques for performing a compound drawing/color selection task were studied (Kabbash et al. 1994). A single handed technique, a two-handed technique where each hand was mapped to an independent subtask and two two-handed techniques with asymmetric dependent subtasks. The latter two techniques, the Palette and the Toolglass, both demonstrate Guiard’s principles. But results from the experiment show that only the Toolglass performed as expected, the Palette’s performance was below expectations. Based on qualitative evaluations, the authors reason that the difference is due to cognitive causes. Operating the Palette with the non-dominant hand requires subjects to focus attention on both subtasks alternately, introducing confusion about the appropriate strategy. It is clear that the design of two-handed interfaces for 3D manipulation is not a matter of implementing guidelines. There are a number of unknown factors waiting to be discovered and documented.

3D MODELING SOFTWARE

In our research we apply two-handed input techniques on 3D input and manipulation tasks. 3D modeling software and device drivers were created to study several device configurations and parameter mappings. The software supports multiple input devices operating simultaneously and all of them can be assigned to various dominant or non-dominant handed tasks.

First they can be connected to the system cursor, which is operated by the dominant hand. A tool metaphor is used to select the current mode of the program. Tools can be selected from a floating window using the system cursor. This is an example of time multiplexing, input devices are assigned to different tasks over the course of time.

Next, space multiplexing is supported where devices are assigned to specific tasks all of the time. Examples of those tasks include positioning and orienting the camera, the scene geometry and the selected objects. Two-handed input is possible by using a space multiplexed device with the non-dominant hand while operating the system cursor with the dominant hand. This is not advisable for the majority of combinations of tools and non-dominant hand tasks. Chances are that each hand executes an independent subtask, called an orthogonal assembly in Guiard’s terminology. The advantage of dedicating a device to a specific task is that the user can perform different actions without the need to switch tools. It has the additional benefit that functionality is linked with the device. If one wishes to enter a certain kind of input the appropriate device is used.

Finally, devices can be assigned to non-dominant hand tasks that assist the dominant hand tasks of the current tool. Non-dominant hand tasks are designed to have an asymmetric dependent assemblage, following Guiard’s guidelines. The mesh editing tool for example, uses input from a non-dominant hand device to position and orient the mesh being manipulated. The system cursor, operated by a device in the dominant hand, is used to select and manipulate mesh parts, like vertices, edges, and faces. There are no tools operated with two hands exclusively, care is taken to support single handed use of all the tools too. The mesh editing tool for example, can be used with one hand but to orient the object under manipulation, one must switch to and from the orientation tool.

TURNTABLE DEVICE

Originally inspired by an ergonomic analysis of household and workshop tools and later reinforced by Guiard’s framework, we imagined a 3D manipulation scenario in which one hand orients an object while the other hand alters its shape. Two input devices and computer software were created to test this scenario regarding its usefulness. One input device was called the “Turntable” and was used with the non-dominant hand (figure 1). The first version of the Turntable consisted of a disk that was rotated around a central axis. The disk could be tilted up and down. The amount of tilt was limited to about ±30 degrees by built-in control constraints. The Turntable was developed together with a device known as the “Grabber”, which was used with the dominant hand. The Grabber is a modified joystick with a shape such that it positions the hand into a natural grasping posture. A set of micro-contacts, just under the thumb and index finger, responded to a pinching action. Both devices were intended to be used on a desk.

The first version of the software supported the concurrent use of both devices in a simple CAD task. The Turntable controlled the orientation of a 3D object on the screen. There was a one-to-one mapping of the device parameters to the object orientation. To users it appeared as if the object is placed *on* the Turntable so that their attention could remain on the task executed with the dominant hand. Vertices were selected and manipulated with the Grabber. Observations of users operating the devices (and software) in a demonstration setting, indicated a clear potential for the application of two-handed input on 3D manipulation tasks. The Turntable was very easy to use and there was no difficulty using the device with one's less-dominant hand. Criticism of the Turntable device focused on the fact that it was hard to tilt (without clamping it to the table) and that, since the hand could not rest on the disk, more precise rotation could not be achieved. The Grabber showed poor performance, mainly due to the limitations of the joystick design. It was discontinued and replaced with a mouse.

Version two of the Turntable was developed to address the limitations of version 1 (figure 2). The tilt axis was moved to the center of the device making it possible to rest one’s hand comfortably on the disk.

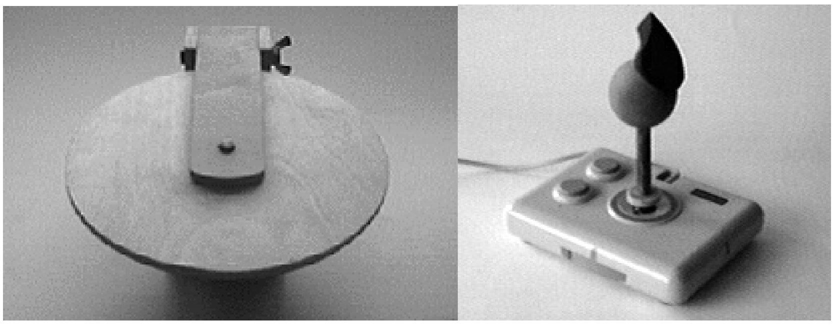

Figure 1, **Version one of the Turntable (left) and the Grabber (right)**

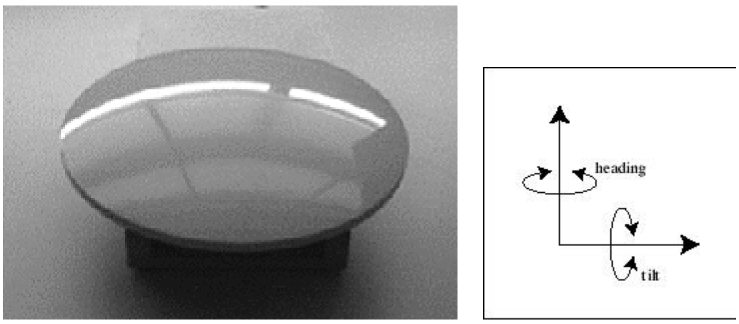

Figure 2, **Version two of the Turntable**

Although version 2 was an improvement over version 1, it still had shortcomings that prevented it from being used successfully in the 3D modeling system described earlier that is more comprehensive than the original software. The most important limitations include:

- It has a limited tilt angle range. The disk can only be tilted by about ±30 degrees, making it impossible to put an object upside down. Introducing a multiplication factor can increase the tilt range but it also introduces noticeable steps caused by the limited resolution of the optical encoders.
- There is no way to reset a mismatch between the object on the screen and the Turntable. This is not noticeable for the heading axis because the disk has no orientation, but for the tilt axis it is.
- There are only two rotation axes, roll is not supported. It can be frustrating to achieve a desired object orientation with combinations of rotations over two axes.

In version three of the Turntable (figure 3) the roll axis was introduced. The disk design, that separates the heading axis from the roll and the pitch axis, was continued. A button in the middle of the disk was introduced to provide a process known as “clutching” for the tilt and the roll axis. When the button is pressed output from the Turntable is ignored, the device can be now be oriented without influencing the task it is connected to. This is analogous to lifting the mouse when moving the cursor to a location out of reach. The introduction of the button eliminates both the limited tilt angle and the possible mismatch of the turntable and the object on the screen.

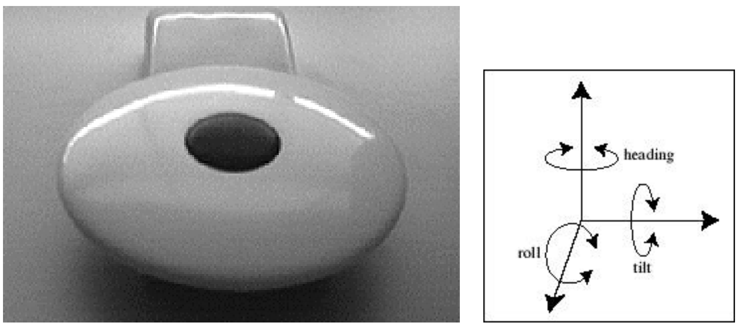

Figure 3, **Version three of the Turntable**

3D OBJECT ORIENTATION USING THE MOUSE

Unlike the Turntable, orienting a 3D object with a mouse requires a translation of the two displacements the mouse measures to three rotations about each coordinate axis. Several solutions, like Shoemake’s Arcball (Shoemake) and Chen’s “virtual sphere” controller (Chen et al. 1988) have been proposed for this purpose. The virtual sphere controller is known to be easy to use and efficient. A study using 500 subjects was conducted by Jacob (Jacob and Oliver 1995) comparing the performance of the controllers in Chen’s article on orientation and inspection tasks. The virtual sphere controller proved to be the best controller for the tasks in the study. The controller simulates the mechanics of a 3D trackball that can rotate freely about any axis. The user can imagine the object on the screen being encapsulated in a glass sphere. The mouse can be used to select a point on the sphere and subsequent cursor movements will rotate the object. The controller will maintain the point selected under the cursor as long as the cursor stays within the edge of the sphere. Movement outside the edge of the circle is equivalent to rolling the sphere at the edge and produces rotation about the axis perpendicular to the screen.

The controller used in this study is based on the virtual sphere controller and documented in the QuickDraw 3D user interface guidelines by Apple Computer (Apple Computer). In the original design the virtual sphere is not explicitly present in the 3D environment. The presence of the virtual sphere is indicated by a circle on the screen, representing the intersection of the sphere and the plane parallel to the screen through the center of the object. The controller proposed by the QuickDraw 3D guidelines uses 3D widgets for interacting with the virtual sphere. The term 3D widgets was proposed by Conner (Conner et al. 1992) and refers to objects in the 3D environment that encapsulate 3D geometry and behavior. The virtual sphere is represented by three mutually orthogonal circles, aligned to the object's local coordinate frame. At the six intersections of the circles a handle is present. The handles can be selected to rotate the object around the center indicated by the common center of the three circles (see figure 4, left side). The virtual sphere algorithm is used to translate the mouse movements to 3D rotations.

EXPERIMENT

To test different implementations of two-handed input for 3D manipulation tasks we planned to use the Turntable as an input device for the non-dominant hand. Since the Turntable produces no position data, it is not suited for dominant hand tasks that require the system cursor to be operated. The Turntable was designed for tasks containing a subtask that needs orientation input from the non-dominant hand. A single-handed execution of such a task forces constant switching between orientation and manipulation. Task switching is unnecessary when performing such a task with two hands, the actions could even take place simultaneously.

An experiment was conducted to establish whether the Turntable is effective for use with the non-dominant hand. In order to evaluate the performance of the Turntable in orientation tasks it was decided to compare it to the virtual sphere used with the dominant hand. Once the performance of the Turntable is known relative to that of the virtual sphere, it can be used when comparing the performance of two-handed and single-handed implementations of 3D manipulation tasks. Therefore, the Turntable is not tested used with the dominant hand and the virtual sphere is not tested operated with the non-dominant hand. Future experiments must prove whether the cognitive load imposed by the Turntable operated in concurrence with the dominant hand is low enough for successful use in two-handed input.

Experimental Set-up

Subjects

The experiment was conducted with thirty-two paid volunteers. All subjects are students of the Department of Industrial Design Engineering of the Delft University of Technology. Sixteen male students and sixteen female students were selected with ages ranging between eighteen and twenty-five and a median value of twenty-one. All the subjects were right-handed and familiar with the mouse and 3D CAD programs while none of them used the Turntable or the virtual sphere controller before.

Experimental Task

An orientation match task was used in this experiment. Subjects were asked to match the orientation of two identical objects as quickly and accurately as possible. The object resembles a house with each of it's walls colored differently so that there is only one correct match for the match object and the target object.

Figure 4 shows the screen of the test program presented during one of the exercises. The match object on the left is being manipulated with the virtual sphere to match the orientation of the target object on the right. Orientation of the match object with the Turntable did not require the presence of the virtual sphere widgets. Nevertheless, the extra geometry was presented in Turntable trials because the extra geometry could have influenced the match process. A button in the lower right corner of the screen was pressed once the subject felt she or he had achieved an accurate match. The completion time and the angle error in numerical and text format were shown to stimulate subjects to achieve fast and accurate matches. A textual representation of the sum of the angle errors (*e*) of each of the coordinate axes was presented in the form of four qualifications:

- try harder: $e > 12$ (deg)
- fair: 6 (deg) $\leq e < 12$ (deg)
- good: 2 (deg) $\leq e < 6$ (deg)
- excellent. $e < 2$ (deg)

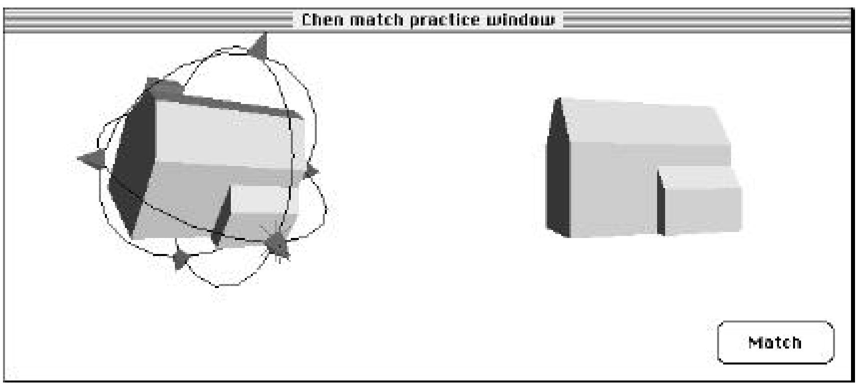

Figure 4, **An experimental configuration**

Prior to each trial a dialog box was shown on the screen containing a start button and, for a Turntable trial, a message that reminded the subject to reset the Turntable to its neutral orientation. At the end of each trial the test program saved the completion time and object orientations during the trial.

Experimental Design

Prior to the experiment a visualization test was administered to see whether the trial completion times and trial errors were correlated with the subject's individual 3D insight. The test ranks the subject's ability to transform images of spatial patterns into other arrangements. Corresponding edges were to be found in two representations, perspective and unfolded, of the same 3D object. Originally suggested by Thurstone, it was taken from the Kit of Factor-Referenced Cognitive Tests (Ekstrom et al. 1976).

After the visualization test, each subject was tested in one of the two conditions, virtual sphere or Turntable. The experiment started with an training session during which the experimenter was present. During the practices, subjects were encouraged to ask questions. They were instructed that speed and accuracy were of equal importance. A textual description of the Turntable or the QuickDraw 3D controller was presented and eight practice trials familiarized the subject with the orientation task they were assigned to.

The experimenter left the room when the experimental trials were about to start. Subjects had to execute a total of thirty-nine trials in three blocks. Each block contained a random distribution of the same thirteen configurations depicted in table 1. In the first three configurations the target object was rotated over one axis, so that it could be matched in one continuous gesture. In the next four configurations the target object was again rotated over one axis, now over angles large enough to force a clutching operation. The rest of the configurations needed rotations over more than one axis to align the match object with the target object. The experiment was concluded by an interview to evaluate either the virtual sphere or the Turntable.

Experimental Results

Analysis of the detailed results

Shown in figure 5 is a plot of the sum of the angle errors e for each coordinate axis and configuration number ten in the third block, performed with the Turntable. All trial plots showed this pattern, periods of device manipulation were alternated with periods of absence of manipulation. These periods were used for clutching or cognitive processes like evaluation of the current object orientation and planning the next manipulation. The first few seconds in figure 5 were idle time, used to plan the first device manipulation. Clutching was necessary when the match object and the target object had a difference in orientation too large to cover in one continuous

	1	2	3	4	5	6	7	8	9	10	11	12	13
X-axis	17	0	0	-97	0	160	0	-17	0	206	46	201	126
Y-axis	0	-11	0	0	0	0	103	0	109	206	23	229	40
Z-axis	0	29	29	0	-120	0	0	138	23	206	218	180	11

Table 1, **Configuration rotation values (deg)**

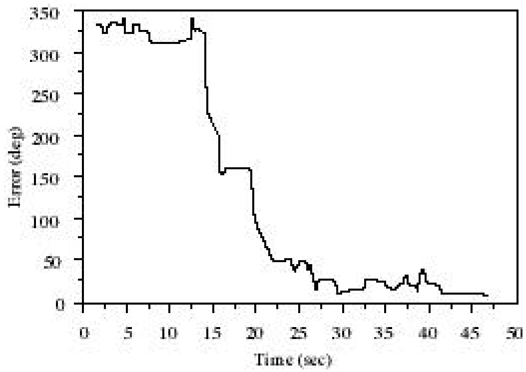

Figure 5, **Typical trial plot**

gesture. In the case of a virtual sphere trial this was overcome by releasing the widget currently selected and selecting the next one. In Turntable trials this was accomplished with a reorientation of the device while pressing the clutch button.

Analysis of the end results

Inspecting the end results with a correlation Z test we found that there was a significant negative correlation between completion time and the angle error *e*. In other words: the shorter the completion time, the larger the angle error (speed/accuracy trade-off). This result applied to the same extent for the mouse and Turntable conditions separately. No significant correlation could be found between the scores on the 3D spatial insight test and the performance variables completion time and angle error. All of the subjects achieved high scores. Significant differences between males and females were absent for the performance variables.

Shown in figure 6 on the left are the mean and the standard errors of the angle error for each of the blocks and the overall results. Using a t test it was found that the virtual sphere lead to a significantly smaller overall angle error of 20%: t =-2.049, p=0.0493. Both the virtual sphere and the Turntable showed a decline of the mean angle error over time (except for a small increase for the virtual sphere in block three). A near significant difference was found in the first block and in the second block a significant difference was found.

The mean and standard error of the trial completion times are shown in figure 6 on the right, overall and for each block separate. Although the Turntable showed larger mean completion times than the virtual sphere, overall and in all three blocks separate, the differences were not significant. As was the case for the angle error, we found that the mean completion times diminished from block to block for both the virtual sphere and the Turntable.

Comparing the angle errors in figure 7 on the left for each configuration separately, we find that the virtual sphere has somewhat smaller mean angle errors for almost all configurations. All differences between the mean angle errors of each configuration were statistically insignificant, except for configuration five.

Comparing the mean configuration completion times for each configuration separately (figure 7, right) we found that the Turntable produced somewhat shorter

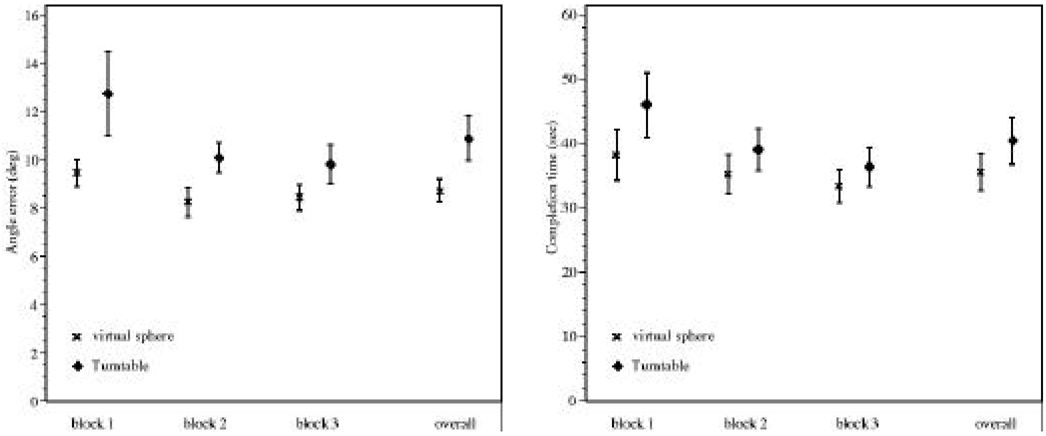

Figure 6, **Angle errors (left) and completion times (right) of virtual sphere and Turntable (error bars indicate standard error)**

mean completion times for the following configurations: one, two, seven and nine. Those configurations have in common that they exhibit a dominant heading action, executed with the Turntable by rotating the disk without the need to clutch. However, the differences in completion times for those configurations are not significant. The Turntable produced longer completion times in configurations five, eight and eleven where the main rotation axis is the roll axis. Of those three configuration only configuration eight led to the observation of a significant difference, a near significant difference was found in configuration eleven.

CONCLUSIONS

The most important conclusion we draw from the test results is that the performance of the Turntable, used with the non-dominant hand was close to that of the virtual sphere operated with the mouse in the dominant hand. Mean trial completion times were somewhat longer with the Turntable but the differences are statistically insignificant, overall and in the three blocks separately. Mean angle errors were larger with the Turntable but significantly different only in the two first blocks. Performance benefits can now be expected for tasks that can be split into two subtasks where the non-dominant hand subtask is operable with the Turntable.

In the interview succeeding the experiment no signs of fatigue were reported regarding either the Turntable or the virtual sphere. This was supported by the results

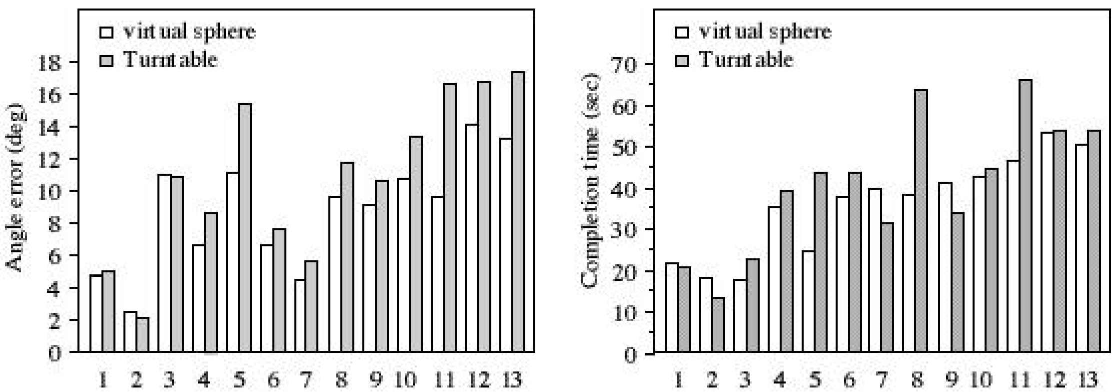

Figure 7, **Angle errors (left) and completion times (right) of virtual sphere and Turntable for each configuration** from the experiment. Mean trial completion times and mean trial errors decreased from block to block for both of the conditions. One exception to this trend was the small increase in trial error from block two to block three for the virtual sphere. The experimental data indicated that the results of the Turntable condition benefit the most by a longer learning time. A possible explanation is that the virtual sphere controller took less time to learn because of the familiarity of a mouse operated with the dominant hand, while none of the subjects had used the Turntable or any other input device for the non-dominant hand before.

A significant difference was found between the mean completion times for the Turntable and the virtual sphere in trials that had a dominant rotation about the roll axis. Looking at the joint actions involved we find that rotation about the roll axis is different from rotations about the pitch and the heading axis. The latter two are performed by using the wrist, whereas the forearm is used for rotation about the roll axis. The mechanical design of the Turntable limits the rotation angles about the pitch and roll axis to ± 30 degrees. These values are within the range of maximum supination and pronation as observed in several studies listed by van der Vaart (van der Vaart 1995). These measurements assume that the wrist is in home orientation when the thumb faces upward. However when the Turntable is in neutral orientation the wrist is exposed to a pronation of 90 degrees. This means that most users utilize half the maximum roll angle range of the Turntable. A redesign of the Turntable might be necessary to improve the performance of the Turntable for trials containing a lot of rotation about the roll axis. Designing a new version with the wrist in a neutral orientation would imply that the disk shape and the associated metaphor of a "turntable with an object on top" will be lost.

FUTURE WORK

Now that we have established how the performance of the Turntable as a non-dominant hand device compares to that of a dominant-handed orientation method, we plan to use it to study two-handed manipulation methods for 3D objects. Complex 3D input and manipulation tasks, like assembly, bends, sweeps and deformations are currently being implemented in a 3D modeling system. Single-handed implementation with the aid of widgets is done much like the implementation of sweeps, warps and blends proposed by Grim (Grim et al. 1995). A lot of parameters are needed to drive these kind of operations. Using two-handed input more parameters can be controlled simultaneously. Concurrent use of two hands for these operations could be in accordance with Guiard's principles while single handed operation is possible too. Methodical comparison of the most promising parameter mapping scenarios should generate more insight in the transfer of the theory of two-handed operation to the practice of a 3D modeling environment.

The Turntable is not the only device we plan to use in our future research. Our modeling program supports any input device for both dominant and non-dominant hand tasks. This enables us to evaluate several input devices under identical conditions. The results of this study will be applied to the development of new input devices. We are working on an improved version of the Turntable that does not require clutching and addresses the problems signaled regarding the limited roll angle range.

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