An Evaluation of Factors Affecting Rotation Tasks in a Three-Dimensional Graphics System

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ABSTRACT

Two types of joysticks, velocity and positional, were compared in terms of time, accuracy and preference for rotating a three dimensional computerized image. Each of six subjects performed 32 tasks - sixteen with each type of joystick. Eight shapes were used: four rectilinear and four non-rectilinear. These were each displayed twice, with initial rotations of 100 degrees and 160 degrees. Subjects used the joysticks to position the rotated shape to match the position of an adjacent unrotated shape. Pairwise comparisons indicate a slight difference in joysticks in terms of time and preference in favor of the velocity joystick. The results also showed a tendency for quicker and more accurate rotation for rectilinear shapes.

INTRODUCTION

An increasing number of computer applications are using three dimensional graphics as a display technique. The display of three dimensional objects presents a new problem in control design. According to Foley, Wallace and Chan (1984) "one of the most important elements in the design of interactive user-computer interfaces is the selection of the devices and techniques by which the user performs elementary tasks." (p. 13)

Although we live and operate in a three-dimensional world, humans primarily have experience interacting with two-dimensional displays. The display of three dimensional objects introduces the third dimension of manipulation. How can devices be adapted to accommodate this new dimension? The UNC-CH graphics laboratory has experimented with several types of devices, including joysticks, trackball, and knobs, with varied success but with no means of quantifying the differences between them.

The present study was conducted to compare two control devices on several parameters. A positional joystick, the device currently favored in the lab, was compared with a velocity joystick. It was hypothesized that the velocity joystick would result in better performance than the positional joystick on several performance measures: time, accuracy and preference.

Britton, Lipscomb and Pique (1978) discuss the relative merits of various locater devices for three-dimensional manipulation. They discuss attributes of locater devices that may affect selection. Their recommendations are based on two and a half years of observation of users and personal use. They state that a user should be able to control interactive images "in ways related to his thoughts by kinesthesia or convention." (p. 222) They argue that "subimage motion in a three-dimensional computer graphic system is much easier for the user to control if the subimage moves the same direction as his hand while he manipulates the control device." (p. 222) They observed that this correspondence in motion between the user's hand moving a device and the movement of the image increases user productivity. They referred to this correspondence as "kinesthetic correspondence."

Foley, Wallace and Chan (1984) use the term "naturalness" to describe this correspondence between the user's actions and the control movements. They state that "naturalness captures the idea of transfer of activity from other everyday activities." (p. 19) For example, using a foot lever to stop an industrial machine operation is analogous to using the foot brake to stop a car. "Naturalness is also a consequence of input devices that control displays in ways analogous to action-reaction in the real environment." (p. 19)

We believe that the velocity joystick allows a more natural correspondence between hand movements and display movements than the positional joystick. According to the ideas of kinesthetic correspondence and naturalness, the velocity joystick should result in better performance than the positional joystick.

Foley et al discusses the effect of the control-display ratio on the use of controls. The control-display (C/D) ratio of a device describes the magnitude of display motion caused by a movement of the control device. In a device with a low C/D ratio small control movements cause large display movements. A device with a high C/D ratio makes big control movements with resulting small display movements. There are two main components of motor tasks: gross adjustments for large, swift positioning, and fine adjustments, for careful, detailed positioning. It is best to have a device with a low C/D ratio for gross adjustments. A device with a high C/D ratio is best for performing fine adjustments. For most efficient control design it is necessary to find a compromise between a high and a low C/D ratio. "Studies by Jenkins et al have shown that the C/D ratio of a control device is critical to the operator's performance." (Foley et al, p. 32).

The two devices used in the study have different C/D ratios. The positional joystick has a fixed ratio while the velocity joystick has a variable ratio. When the velocity joystick is in a position far from the starting position, display movement is fast. This comprises a low C/D ratio which is good for gross adjustments. Moving the velocity joystick a small distance from the starting position yields slow display movement. This comprises a high C-D ratio which is good for fine adjustment. The velocity joystick is able to accommodate both motor task components because of its flexible C/D ratio. For this reason it is believed that the velocity joystick will yield faster and more accurate performance than the positional joystick.

This experiment used a rotation task for comparing the two types of joysticks. Two views of the same three dimensional shape were shown, one of which was displayed at an initial angle of either 100 or 160 degrees. The task was to position one shape to match the other. It was hypothesized that objects at a smaller initial angle of rotation will be positioned faster than objects starting out at a larger angle of rotation. This may be supported by studies of mental rotation by Shepard and Metzler (1971) in which subjects were asked to report whether two three-dimensional shapes were the same or mirror images. Results indicated that the time taken to make the decision is a "linearly increasing function of the angular difference in the portrayed orientations of the two objects." (Shepard and Metzler, p. 701).

The shapes rotated in the study fell into two categories, rectilinear and non-rectilinear. Rectilinear shapes are those which have definite right angles and identifiable sides, tops and bottoms. Non-rectilinear shapes are less regular. It was hypothesized that rectilinear shapes will cause better performance in terms of time to rotate and accuracy of rotation than non-rectilinear shapes. Pinker describes theories on shape recognition which suggest that humans develop feature detectors from their environment. Since the man-made world is largely straight edged, we may have developed more feature templates for recognizing rectilinear structures. These detectors may make it easier for humans to work with straight-edged objects than with curvilinear objects.

METHOD

Subjects

Six subjects participated in the study, five males and one female. All subjects were graduate students or faculty in the fields of Computer Science (2), Psychology (3), or Chemistry (1). Computer usage was frequent across the sample, with half using it daily and half a few times per week. All subjects used computers for word processing and data entry; four of six subjects did programming, graphics, games, and statistical analysis; three or fewer used office applications, computer instruction or spreadsheets. No subjects had any prior experience with three-dimensional graphics although two were frequent players of video games. The remainder had little or no experience with video games. All had used cursor keys for entering data. Four of six subjects were experienced with the mouse, joystick, touch panel, and trackball. Two had experience with a lightpen.

Apparatus

1. Input devices

Two joysticks were used for this study, a positional joystick and a velocity joystick.

a. The positional joystick is a modified Model 525 joystick manufactured by Measurement Systems, Inc. It consists of a vertical shaft mounted on a base. A handle protrudes from the shaft. The handle and the vertical shaft are each about 8 cm long. The device is mounted on a metal and plastic base which also contains controls for other uses.

By moving the handle the user can control two of the three axes. Initially the handle extends perpendicularly from the vertical shaft; by moving the handle either up or down the user controls one axis. By turning the shaft around the vertical axis the user controls the second axis. The user controls the third axis by turning a knob which is mounted on the base 4 cm to the right of the vertical shaft.

This device gets its name "positional" from the fact that the user, in setting the controls at a particular configuration, sets the position of the image on the screen. The image on the screen stops moving when the user stops moving the input device.

b. Velocity Joystick

The velocity joystick is a Model CC303 III Graphics Control manufactured by Computer Communications Corp. The joystick has a shaft which extends vertically from the control panel base. The shaft has spring return; the user moves the shaft, but the shaft returns to the original, vertical position when it is released.

The shaft can be moved in two dimensions, left/right and away-from-the-user/closer-to-the-user, and thus the user controls motions in two axes. The third axis is controlled by a knob mounted directly on top of the shaft. This knob also has spring return; when released it returns to its original, central position. This device is also mounted on a metal and plastic base. A 2-axis velocity joystick shares the base, along with other control knobs, none of which were used in this study.

The device gets it name "velocity" from the fact that the user, by holding either control (the shaft or the knob) at some position away from the starting position, determines the velocity of rotation of the object on the screen. As long as the control is held in this position the object continues to rotate with a fixed velocity. The user can also vary the velocity of rotation; the further the control is moved away from the starting position the faster is the velocity of rotation.

2. Computer and Monitor

A VAX 11-780, running Unix, was used for the study. A Tektronix 690 SR color monitor was driven by an Ikonas microprocessor/frame buffer.

3. Software

The software consists primarily of a program developed by Michael Pique of the UNC-CH Computer Science Department. This program, written for molecular-graphics research, displays and rotates three-dimensional objects composed of solid shaded spheres. The program was modified for the following purposes:

a. To enable the recording of data.

b. To enable use of the velocity joystick. Originally the program was compatible only with the positional joystick.

c. To allow side-by-side viewing. The display was programmed to present two images on the screen simultaneously. One image remained fixed (on the left side of the display) and the other image could be rotated with the joysticks.

In addition to this program, numerous shell scripts were written. The shell scripts are files of high level commands. These executed the following operations: centering the objects within their space; rotating the mobile view with respect to the stationary view; and executing all the commands necessary to run training and experimental sessions.

4. Objects

Nine three dimensional objects were developed for the experiment - one practice shape and eight experimental shapes. The objects were constructed of spheres. Each sphere was randomly assigned one of eight colors (gray, blue, green, cyan, red, magenta, yellow and white). There were two types of shapes - rectilinear and non-rectilinear. Four rectilinear and four non-rectilinear shapes were created for the experiment. One rectilinear object was used for training.

The experimental rectilinear objects were made of 30 to 36 spheres (30, 31, 32, 36.) The experimental non-rectilinear objects were made of 21 to 31 spheres (21, 28, 30, 31). The practice object was a simple rectilinear shape of 16 spheres.

The size of the rectilinear objects on the screen ranged in inches (width x height) from 1.25 x 1.5 to 1.5 x 2 (1.25 x 1.5, 1.75 x 1.75, 1.7 x 1.5, 1.5 x 2) while the non-rectilinear objects ranged from 1.875 x 1.375 to 2.75 x 1.75 (1.875 x 1.375, 1.5 x 1.875, 1.625 x 2, 2.75 x 1.75). Each object was shown on the screen with an initial rotation of either 100 degrees or 160 degrees. The combination of x, y, and z degree rotations necessary to match the target position was the same for each object (either 100 or 160 degrees) but differed between objects. All rotations discussed in this paper refer to rotation around the center of the object. For example, like with great circle rotation on a globe, the maximum possible rotation would be 180 degrees. Typically a rotation will contain components in each of the x, y, and z axes.

5. Spatial abilities test

The spatial abilities test was compiled by Dr. M. Lansman and was modeled after the shapes used in Shepard and Metzler's 1971 study.

Procedure

Subjects were brought into the test area and seated at a graphics workstation within the graphics laboratory. The experimenter briefed the subjects on the purpose of conducting usability studies and informed them of their rights as test participants. A copy of the briefing script is included in the appendix. The subject completed a background questionnaire consisting of questions about education and experience with three-dimensional graphics. The subject also completed a spatial abilities test, as it was thought that spatial ability may affect the subject's ease of performing the rotation task.

Subjects received training on each type of device. The order of training was counterbalanced between subjects: half the subjects received training on the velocity joystick first, and half received training on the positional joystick first. A simple cube shape was used as the training shape for both devices. Training consisted of a demonstration of the device by the experimenter in which each direction of rotation was described. The subject then had two minutes to become familiarized with the directions of rotation caused by moving the joystick in the various directions. Then the experimenter demonstrated the rotation task, after which the subject was given several trials to practice the rotation task. The experimenter provided additional practice tasks by randomly scrambling the practice shape. This was repeated until the subject was able to rotate it correctly in five minutes or less. Training was then given for the second device in the same way.

With training complete, the subject was allowed to practice on the first device for another two minutes. Before each set of trials with a new device the subject had two minutes to become re-acquainted with the joysticks' directions of motion. The task consisted of showing the subject a split screen. The left side of the screen contained a picture of a three dimensional object. On the right side the same object was shown but it was rotated 100 or 160 degrees. The subject was told to use the manipulation device to rotate the object on the right to match the position of the one on the left.

A total of 32 trials were given in four blocks of eight trials each. The subject completed one block with the first device and one block with the second device. Then the subject took a ten minute break, followed by another eight trials on each device. The eight shapes were presented in random order during each 8-trial block, rotated either at 100 or 160 degrees. Before each trial with the positional joystick the joystick was returned to its original position. The velocity joystick was tweaked to ensure its return to the starting position. The order of presentation of devices was counterbalanced across subjects.

On completion of all trials the subject completed a final questionnaire asking for preferences and opinions on each of several control parameters. A copy of the final questionnaire is included in the appendix.

Data Collection

Raw Data

Log files were set up for each subject to capture three pieces of data over time: a time stamp, a rotation matrix, and a position vector. The time stamp logged the time, from the beginning of the trial, at most ten times every second. This enabled determination of how long the subjects took to rotate the object to a given position.

The rotation matrix was a three dimensional matrix defining the object's position on the x,y, and z axes. It was also collected at most ten times per second. The rotation matrix would change every time the object was moved to correspond with joystick movement. The rotation matrix and the time stamp allowed determination of when an accuracy criterion was reached in terms of number of degrees off the target, and how long it took a subject to reach that criterion on each trial.

The position vector was a set of numbers indicating the position of the joystick (either one) on each of the three dimensions. As the device was moved, the position vector changed, corresponding to the new position of the joystick. This was also captured at most ten times per second.

Since each of the 32 trials lasted anywhere from 30 seconds to three minutes, there was the potential for the log files to get very large. To save space, data was captured only if the rotation matrix or position vector changed. If there was no change in either of these, no entry was made to the log file.

Definition of Successful Trial

A successful trial was one in which the final position of the movable object was a 90% match or better. A 90% match is defined as one in which the object is less than 10% or 18 degrees from the target position. Data from unsuccessful trials was thrown out. The exception occurred for trials which attained a 90% match during the trial, but for which the final match was unsuccessful. For these trials, the time to the 90% match was included in that calculation.

"Fiddling"

One behavior the experimenters had not anticipated was coined "fiddling." This behavior occurred when the subject had a 90% match between the object and the target position but decided he could do better and continued rotating the object.

Calculations done for each subject

The following results were calculated for each trial by each subject by a C program run on the log files.

1. Total time. The total time was calculated as the time between the first appearance of the object on the screen, and the subject's indication that the trial was complete.

2. Time to 90% match. The time to the first 90% match was calculated as the time between the appearance of the objects on the screen and the first time the movable object attained a 90% match.

3. Final Error (in degrees and %). The final error was calculated as the difference between the movable object and the target position. This was expressed in terms of degrees away from a perfect match and as a percentage of how close the object came to a perfect match.

4. Successful Trials. The number and percentage of trials where subjects attained a 90% match were calculated. These trials were considered successful.

5. Close Trials. "Close" matches were defined as those where the final position of the movable object was within 3% (5.4 degrees) or a 97% match of the target position. The number and percentage of close trials were calculated.

Summaries calculated for each subject

The following results were calculated by entering the numbers generated above into a Multiplan spreadsheet.

For each of the above variables (total time, time to first success, etc.) several means were computed. These were:

- mean time for the positional joystick
- mean time for the velocity joystick
- mean time for the rectilinear objects
- mean time for the non-rectilinear objects
- mean time for the 100 degree rotations
- mean time for the 160 degree rotations
- mean time for a rotation task by this subject

Overall means were calculated over subjects for each variable.

RESULTS

Joysticks

Pairwise comparisons performed on the means partially support the hypothesis that the velocity joystick is better than the positional joystick for rotating three-dimensional computer images to match the position of a target image (see table 1). Results for total time were in the predicted direction, but not significant. If the results are considered only in terms of time spent until the subject matched 90% (no more than 18 degrees off), the difference is marginally significant, $t=2.39$ $p<.06$, with subjects spending somewhat less time rotating the objects with the velocity joystick than the positional joystick.

The amount of time subjects spent fiddling with the device after they had reached a 90% match does not differ between the two devices. Although the means appear to be quite different, the variance between subjects is too large to conclude that there is a difference between the devices in terms of time spent after they were in range of matching the target.

Table 1--Time between joysticks (in seconds)

	total time	time to 90%	fiddle time
Velocity joystick	62.74	22.79*	39.95
Positional joystick	87.76	38.24*	49.52

* $p<.06$

There was no difference in accuracy between the two joysticks in terms of final error (in number of degrees from a perfect match, see table 2). There was also no difference between the two devices in percentage of trials that matched 90% and percentage that matched 97%. Thus our hypothesis that the velocity joystick would be better than the positional joystick in terms of accuracy was unsupported.

Table 2--Accuracy between joysticks

	final error (degrees)	%trials to 90%	%trials to 97%
Velocity joystick	4.73	88.54	28.13
Positional joystick	4.78	87.5	28.13

Results from a questionnaire assessing personal preference for one device over the other showed a preference for the velocity joystick (see table 3). An overall preference score was computed by equally weighting all the "preference parameters", adding them, and dividing by five. A mean of 2.8 suggests that subjects slightly preferred the velocity joystick.

Table 3--Preference data

	Mean*
better	2.0
easier	3.2
more precise	3.0
quicker	2.8
prefer	3.4
overall	2.8

* on a scale of 1-7 where 1=strongly prefer velocity joystick and 7=strongly prefer positional joystick.

Pearson product moment correlations were performed between each of the preference parameters and total time and time until a 90% match. Correlations for the preference parameters with total time ranged from .33 to .52, (see table 4) with a .55 correlation between overall preference and total time. The preference parameters correlated between .48 and .66 (see table 4) with time until a 90% match. Overall preference correlated .69 with time until a 90% match. Time spent using a joystick tended to coincide with a subject's preference for that joystick.

Table 4--Correlations between preferences and time

	total time	time to 90%
better	.33	.48
easier	.53	.64
more precise	.45	.54
quicker	.53	.66
prefer	.52	.63
overall	.55	.69

Objects

Table 5 presents the means of total time, time until a 90% match, and amount of time spent fiddling with rectilinear objects versus non-rectilinear objects. The pattern of results closely matches that for the joystick comparison on total time and time until a 90% match Total time spent rotating rectilinear objects was less than time spent rotating non-rectilinear objects, but is not quite significant. Time until a 90% match was significantly less for rectilinear objects than non-rectilinear objects, $t=-3.10$ $p<.02$. Subjects did not spend any less time fiddling with rectilinear objects than non-rectilinear objects (see table 5).

Table 5--Time between objects (in seconds)

	total time	time to 90%	fiddle time
Rectilinear objects	62.91	25.70*	32.21
Non-rectilinear objects	87.97	35.59*	52.38

* p<.02

Results do show, however, that final error is less with rectilinear objects than non-rectilinear objects, t=-2.93 p<.03 (see table 6). There was a slight, but insignificant difference between the objects for the percentage of trials that matched 90%, but subjects were much more likely to attain a "close match" (a 97% match) when rotating rectilinear objects versus non-rectilinear objects, t=5.29 p<.003.

Table 6--Accuracy between objects

	final error (degrees)	%trials to 90%	%trials to 97%
Rectilinear objects	4.02*	90.63	43.75**
Non-rectilinear objects	5.57*	85.43	12.50**

* p<.03
** P<.003

Angles

Table 7 presents the mean time for rotating smaller angles (100 degrees) versus larger angles (160 degrees). Our hypothesis that larger angles would take more time to rotate than smaller angles was unsupported for total time, time until a 90% match, and amount of time spent fiddling.

Table 7--Time between angles (in seconds)

	total time	time to 90%
100 degrees	74.15	27.38
160 degrees	76.16	33.93

Mental Rotation Ability

Pearson product moment correlations were performed to determine if time to rotate the objects would be affected by a person's mental rotation ability as determined by a test based on Shepard and Metzler's objects. We would expect time to rotate the objects to decrease as one's mental rotation score increased. Thus a strong negative correlation was expected between the two results. A correlation of -.21 was in the right direction, but not strong enough to conclude that mental rotation ability affects time to rotate the objects. One subject's data was eliminated from this analysis, as the subject had considerable experience with the test prior to the experiment.

Color

The post-experimental questionnaire tried to assess whether color had any effect on the results. One question asked on a seven point scale, how much color helped in positioning the objects to match the target (1=very much, 7=not at all). The mean of all responses was 2.0, indicating that color did indeed help subjects position the objects to match. A second question asked whether color or shape was more important in positioning the objects (1=color much more important, 7=shape much more important), an overall mean of 3.0 indicated that color was somewhat more important.

Training

The questionnaire also attempted to determine whether subjects felt that the training session helped them to complete the task. On a seven point scale, (1=helped very much, 7=did not help at all) the mean of all responses was 3.2 indicating that the training session helped somewhat.

DISCUSSION

Although the first hypothesis was only partially supported, it appears that novice users prefer the velocity joystick over the positional joystick for rotating three-dimensional objects to match a target object. All users preferred the velocity joystick on at least a few dimensions, while none of the users preferred the positional joystick.

There is a possible alternative explanation for the marginally significant time difference between the two joysticks. Observation of all subjects yielded data which suggests that the positional joystick is a two-handed device, that is, two hands are used to rotate an image in three dimensions, while the velocity joystick requires only one hand. It is possible that the slight time difference may be explained by the difference between one-handed and two-handed operation. Two-handed operation may require more coordination, which results in slower times when using the positional joystick. This does not, however, account for the fact that when time until a 90% match was considered, the velocity joystick demonstrated a stronger effect. A possible explanation for this fact is mentioned previously. Britton, Lipscomb, and Pique (1978) say that the velocity joystick has "kinesthetic correspondence" while Foley, Wallace and Chan (1984) might say that people would be quicker with the velocity joystick because of "naturalness". Post-experimental discussion with many of the subjects revealed the fact that they never really understood of how the positional joystick worked. The three dimensions for the velocity joystick match what one would think the three dimensions should be, forward and backward is one dimension, left to right is another dimension, and the knob on the top turns the object around. The positional joystick provides no such cues.

It is worth noting that preference for a particular joystick tended to correlate with a subject's time using that joystick. It is likely that the subject felt he was performing better with the velocity joystick and therefore rated it as preferable on all dimensions. Not only is it important for a user to perform better with a certain device, the user must also like the device and be willing to work with it. The fact that there is not a perfect correlation is explained by the fact that subjects were allowed to rate the joysticks on several different dimensions. Some subjects may have felt the positional joystick was, for example, more precise, but still may have preferred the velocity joystick overall. The correlation was even greater when time until a 90% match is considered. This indicates that preference is even more strongly related to time when we reduced the trial time to the 90% accuracy point. Subjects preferred the device which allowed them to attain a reasonable match in the shortest possible time.

The hypothesis that time to rotate the rectilinear objects would be less than the non-rectilinear objects is supported in terms of time until a 90% match. Subjects were able to match the rectilinear objects more closely in less time. The object used for all the training trials was a rectilinear object. Therefore, the subjects had more experience rotating rectilinear shapes. Subjects were able to achieve a closer match more quickly with the rectilinear objects, but they still tended to fiddle. As a result the total time for the trials is not significantly different for the two types of objects, but means are in the right direction.

The hypothesis that rectilinear objects will be more accurately matched was supported in terms of final error (in degrees) and percentage of trials until a 97% match. Logically, one would assume that the more regular objects could be matched better than the irregular objects, and therefore the final match should be closer.

Many of the rectilinear objects were "recognizable" objects, while the non-rectilinear objects were molecular structures unfamiliar to most subjects. Subjects could clearly see that one of the rectilinear objects was a chair, for example. Also, when the rectilinear objects were correctly positioned, there were some "straight lines" which did not occur with the non-rectilinear objects. The percentage of trials with a 97% match is significantly greater for rectilinear objects than non-rectilinear objects. This data may not be valid. One subject failed to achieve a 97% match on any trial therefore the mean is altered considerably by his score.

The hypothesis that larger angles would take longer to rotate than smaller angles was unsupported. It is possible that this study did not use enough of a variation in the size of the angles to show an effect. This study only used two angles, while the Shepard and Metzler (1971) studies used a much larger range of angles. The objects used in this study were considerably more complex than those used by Shepard and Metzler. Even the rectilinear objects used in this study are quite complex. The task was considerably different from Shepard and Metzler's studies. Subjects in this study actually manipulated the objects. They were also unfamiliar with the devices used to manipulate the objects. Another possible reason for the dissimilar results is that when the shape was presented, regardless of the angle of rotation, many subjects rotated it several times to see what the shape was. This may have nullified all effects of different starting angles. This study was different from Shepard and Metzler's work, therefore it is not surprising that we obtained dissimilar results.

There are some other issues worth discussing. Subjects indicated a strong use of color in order to match the objects. Therefore this was more of a pattern-matching task than a shape-matching task. This does not invalidate the results, but the task cannot strictly be considered one of shape-matching. Further research should be done to determine how much of an effect color had on the results. The same study could be conducted, but one of the independent variables would be absence or presence of color.

Subjects also indicated that the training did not help much. Further research warrants developing a training criterion and ensuring that all subjects achieve the same level of training before data collection.

This study attempted to determine which of two manipulation devices was "better" for rotating objects to match a target. Some subjects maintained that neither device was better, they were both difficult to use. If determination of the "best" manipulation device is deemed necessary, research should systematically investigate all the possibilities, and compare each of them until one device is found which clearly outperforms all the others. Also, applications must be considered. A device which is best for manipulating 3-dimensional molecules may not work well in a flight simulator. Further research could investigate the applications and what device works best with what application.

There are many potential applications for three-dimensional computer graphics, and each probably has its own uniqueness that warrants special attention in designing the human-computer interface. This study most closely resembles a molecular chemistry application. where rotation of three-dimensional objects is crucial, the velocity joystick appears to be marginally better in terms of time, but no more accurate than the positional joystick, although the velocity joystick is subjectively preferred. It is important to recognize that this study only had six subjects. Many of the results were not significant, but they were in the predicted direction. If more subjects were run, it is likely that significance would have been attained on several of the effects that were marginal, or just short of significance, such as time between the two devices.

This study also investigated some more basic issues. Subjects were able to correctly orient rectilinear objects quicker than amorphous objects. This fits well with theories of visual cognition, and the ideas that we are more accustomed to dealing with rectilinear objects (Pinker,1984). One of Shepard and Metzler's ideas, that as the angle of rotation increases so should the time to rotate the object, was not supported. This was not surprising in light of the differences between the two studies.

PROBLEMS

Several potential problems surfaced during the experiment, the impacts of which are discussed below.

Training-Related Concerns

1. Extent of training between subjects

   Although we intended that each subject receive the same amount of training, different training levels between subjects occurred. A training criterion of five minutes was used for the first device. That is, the subjects repeated the rotation task until they were able to complete it in five minutes or less. Some subjects performed the task in considerably less than five minutes on the first trial. Others took several trials to get below five minutes. Therefore, the subject began their tasks at a range of skill levels.

2. Extent of training between devices

   Subjects also achieved different levels of training between the two devices. Although equal training time was allotted for each device, in some cases the subject needed more training time to reach the same degree of proficiency with the second device. A five minute criterion was also used for the second device regardless of the time needed for the first. In some cases the subject was able to complete the task with the first device in under one minute but took the entire five minutes for the second device. For purposes of the test, that was considered acceptable. At least one subject halted his training on one device because he did not feel that he would understand how it worked in the allotted training time.

Subject-Related Concerns

1. Selection of Subjects

   The subjects consisted of classmates and friends. Not all subjects participated freely. There was one report of boredom with the task. Most subjects reported visual fatigue, and some reported arm fatigue. Neither sex nor handedness were taken into account. Handedness may be important because the way in which a particular motion of the joystick moves an object is perceived differently depending on the placement of the joystick. Although the experimenters tried to position the joystick directly between the subject and the display, the subjects (particularly left handed ones) moved the joystick into a more comfortable position. The study was done with novice users only. Graphics lab users who have reported satisfaction with the position joystick have a great deal of experience. Our results can only apply to novice users and may be totally irrelevant for experienced users.

2. Difference in final accuracy

   Final accuracy depended on each subject's perception of what was a close enough match. The subject often got further from the target position, unable to achieve the initial degree of accuracy. The result was that the final position was less accurate than at an earlier point.

Experimental Situation Concerns

1. Test Environment

   The experimental environment was difficult to control. The UNC graphics laboratory consists of one room with several monitors and several displays. There were from zero to eight other terminal users in the lab during the sessions. The noise level of the lab differed between subjects and during each experiment. Graphics laboratory users occasionally stopped to observe the subject. Any of these factors may have distracted the subjects and may have affected their performance.

2. Computer Load

   In the UNC graphics lab, one computer handles all graphics users. Although other users were requested to keep their work to a minimum during an experiment, the load varied both between experiments and within an experiment. As the load increases, the image is updated less frequently and the motion of the objects appears jerky.

3. Experimenters

   Five graduate students conducted the experiment, two Psychology students and three Computer Science students. Subjects were run by one student from each discipline. This lack of experimenter consistency may have led to differences in performance between subjects.

Rationalization

Several of these problems also occur in the actual usage of molecular modeling. The users are often graduate students who are novice users and not interested in the task at hand. Sex differences probably account for little or no difference in outcome (Jim Lipscomb, personal observation).

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