Object Manipulation in Virtual Environments: Relative Size Matters

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ABSTRACT

An experiment was conducted to systematically investigate combined effects of controller, cursor and target size on multidimensional object manipulation in a virtual environment. It was found that it was the relative size of controller, cursor and target that significantly affected object transportation and orientation processes. There were significant interactions between controller size and cursor size as well as between cursor size and target size on the total task completion time, transportation time, orientation time and spatial errors. The same size of controller and cursor improved object manipulation speed, and the same size of cursor and target generally facilitated object manipulation accuracy, regardless of their absolute sizes. Implications of these findings for human-computer interaction design are discussed.

KEYWORDS

Size effect, human performance, virtual reality, user interfaces, input device, graphic design, 3D, docking, controls and displays, Fitts' law.

INTRODUCTION

Object manipulation tasks in human-computer interaction (HCI) generally involve three elements: a controller, a cursor and a target. A controller is an input device such as a mouse manipulated by the human hand. A cursor is a graphic object on a display driven by and spatially mapped to the controller's movement. A target is a graphic such as an icon on the display that defines an object manipulation task. In a typical object manipulation scenario, a user controls an input device to move a cursor to a target. Object manipulation is the essential operation for direct manipulation interfaces, e.g., graphic user interfaces. One common spatial property of a controller, a cursor and a target is their sizes which can have significant effects on a user's object manipulation performance. The objectives of this study are to investigate how the size of controllers, cursors and targets affects human performance in object manipulation and to provide further understanding for human-computer interface design.

Previous research

Effects of target size in HCI have been extensively studied in light of Fitts' law and findings have been successfully implemented in human-computer interface design [1] [2] [4]. It is generally concluded that movement time increases with decreases in the target size in a pointing task. Most previous studies on target size used the same input device and a cursor of constant size and were limited to two dimensional pointing tasks (Fitts' tasks). Kabbash and Buxton conducted a study to compare the use of an area cursor with a typical "point" cursor for a two dimensional selection task [3]. In their experiment, the area cursor was a large rectangular area and the point cursor was a small circular dot. Their results showed the area cursor had effects that generally reversed target size effects on task performance. Since the size and shape of the cursor and target changed together for experimental conditions, it was not clear whether their results were due to the compound effect of cursor size and shape or the effect of cursor size alone. The role of the interplay of controller, cursor and target size in object manipulation has not been addressed.

Modern computer systems such as virtual reality usually require multidimensional object manipulation, e.g., graphic object docking and tracking. Relatively few studies on human performance have been conducted in multidimensional environments. Some studies found that it was rather difficult to control all dimensions simultaneously, depending on the specific task and interface systems [7] [8]. In the Virtual Hand Laboratory, Wang et al. reported that users had little difficulties in simultaneous control of object transportation and orientation [6]. They found that object transportation and orientation had a parallel and interdependent structure which was persistent

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over various visual conditions. Zhai et al. examined human performance on multidimensional object manipulation by comparing two, six degrees of freedom input devices, one attached to the palm, the other manipulated by the finger [9]. They suggested that the size and shape of input devices should be designed to allow better performance through finger manipulation. We are unaware of any study that examined the combined effects of the size of controllers, cursors and targets on object manipulation in virtual environments. This warrants further investigation into the effects of object size on human performance, providing implications for HCI design.

Research hypotheses

An experiment was conducted to systematically investigate the effects of size of controllers, cursors, and targets on object transportation and orientation in a virtual environment. The experiment was designed to test two research hypotheses.

Relative size hypothesis

We first hypothesize that it is the interplay of controller size, cursor size and target size that affects human performance rather than controller size, cursor size, or target size alone. Most previous studies only examined target size while keeping controller size, cursor size, or both constant. Fitts' results in 1954 suggest to us that it is the relative size that matters [1]. We predict that there will be strong interactions among controller size, cursor size and target size.

Same size hypothesis

Specifically, when the sizes of a controller, a cursor and a target are the same, the haptic feedback information on the controller size is consistent with the visual feedback information on the cursor or target size. The consistency between haptic and visual feedback information should facilitate human object manipulation. It is expected that human performance will be better, in terms of the faster completion time and less spatial errors, when the sizes of a controller, a cursor and a target are the same. We call this hypothesis the same size hypothesis.

METHOD

Subjects

Eight university student volunteers were paid $20 for participating in a two-hour experimental session. All subjects were right-handed, and had normal or corrected-to-normal vision. Subjects had experience using a computer. Informed consent was provided before the experiment session.

Experimental apparatus

A virtual environment was set up for this study in The Virtual Hand Laboratory, as shown in Figure 1. A Silicon Graphics Indigo RGB monitor was set upside down on the top of a cart. A mirror was placed parallel to the computer screen and the table surface. A stereoscopic, head-coupled graphical display was presented on the screen and was reflected by the mirror. The image on the mirror was perceived by the subject as if it was below the mirror, on the table surface. The subject was wearing CrystalEYES Goggles to obtain a stereoscopic view of an image. Three infrared markers (IREDs) were fixed to the side frame of the goggles and their positions were monitored with an OPTOTRAK motion analysis system (Northern Digital, Inc.) with 0.2 mm accuracy to provide a head-coupled view in a 3D space. The subject held a plastic cube on the table surface. Three IREDs were placed on the top of the plastic cube, IRED 1 at the center, IRED 2 and IRED 3 diagonally away from IRED 1. The plastic cube served as the six degrees of freedom (DOF) controller in this system. The cursor was a six DOF wireframe graphic cube driven by the three IREDs on the top of controller cube. The cursor cube was drawn to be superimposed on the bottom center of the controller cube. The target was a wireframe graphic cube that appeared on the table surface to the subject. The stereoscopic, head-coupled, graphic display was updated at 60 Hz with 1 frame lag of OPTOTRAK coordinates. Data from the OPTOTRAK were sampled and recorded at 60 Hz by a Silicon Graphics Indigo Extreme computer workstation. A thin physical L-frame (not shown in the figure) was used to locate the starting position of the plastic cube, at the beginning of each trial. The experiment was conducted in a semi-dark room. The subject saw the target cube and the cursor cube presented on the mirror, but was unable to see the controller cube and the hand. The Virtual Hand Laboratory setup provided a high fidelity system where display space was superimposed on the controller's workspace.

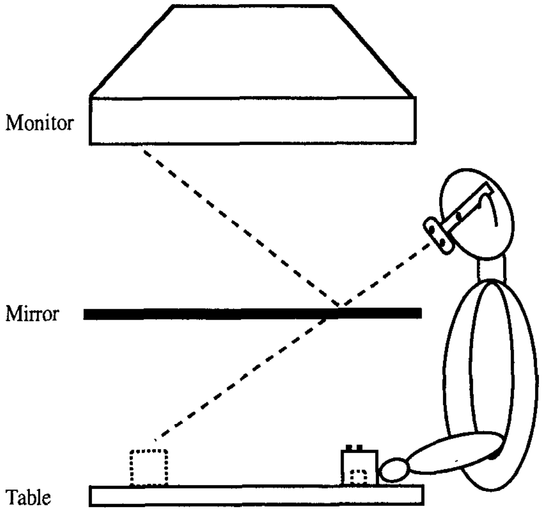

Figure 1. The Virtual Hand Laboratory setup. Shown in schematic are large controller (solid line), small cursor and large target (dashed line).

Experimental design

Independent variables for this experiment were controller size, cursor size, target size, target distance and target angle. Two sizes of the controller, the cursor and the target were used, 20 mm and 50 mm cubes, termed small and large respectively. Trials were blocked on the controller size and the cursor size. Target size was randomized over trials. The target cube was located 100 mm or 200 mm away from the starting position in the midline of the subject's body. The target cube was presented to the subject either 0 or 30 degrees clockwise. Target distance and angle were randomly generated over trials. In each experimental condition, 10 trials were repeated. In summary, we had a balanced experimental design with repeated measures: 2 controller sizes * 2 cursor sizes * 2 target sizes * 2 target distances * 2 target angles.

Seven dependent variables were derived from OPTOTRAK 3-D position data collected from two IREDs on the top of the controller cube. Data from the IRED on the top center of the controller cube were used for object transportation measures, and two IREDs on the top of the controller cube were used to calculate the angular value for object orientation measures. Time measures were: total task completion time (CT), object transportation time (TT), object orientation time (OT). Spatial error measures were: constant distance errors (CED), constant angle errors (CEA), variable distance errors (VED), variable angle errors (VEA).

Experimental procedure

In each experiment session, individual subject eye positions were calibrated relative to the IREDs on the goggles to provide a better stereoscopic, head-coupled view. The table surface and the cursor cube position relative to the controller cube were also calibrated. The subject was comfortably seated at a table, with forearm at approximately the same height as the table surface. The subject held the plastic cube with the right hand, with the thumb and index finger in pad opposition on the center of opposing cube faces which were parallel to the frontal plane of the body. The task was to match the location and angle of the cursor cube to that of the target cube as fast and accurately as possible. When the cursor size was different from the target size, the subject was asked to align the cursor cube and target cube at the bottom center so that the controller cube could finish on the table surface in all experimental conditions. To start a trial, a target cube appeared at one of two distances and two angles (Figure 1). Then, the subject moved the cursor to match the target's location and angle as quickly and accurately as possible. When the subject was satisfied with the match, he/she held the controller still and said "OK" to end that trial. At the beginning of each block of trials, subjects were given 20 trials for practice.

Data analysis

Data were filtered with a 7 Hz low-pass second-order bi-directional Butterworth digital filter to remove digital sampling artifacts, vibrations of the markers, and tremor from the hand movement. Original IRED 3D position data were interpolated and filtered only once, and then were used for the following data manipulation including angular data generation. A computer program determining the start and end of a pointing movement was used for the transportation and orientation processes separately, based on criterion velocities [2]. The start and end of each process were then confirmed by visually inspecting a graph of the velocity profile. A trial was rejected if the program failed to find a start and end or there was disagreement between experimenter's visual inspection and the computer's results.

ANOVAs were performed on the balanced design of 2 controller sizes * 2 cursor sizes * 2 target sizes * 2 target distances with repeated measures on all four factors. Only data with a 30 degree target angle are reported here so that a complete set of object orientation time measures can be presented; trials with zero target angle enabled randomization of the target angle, thus avoiding subject anticipation of the target angle during the experiment.

RESULTS

Time Measures

In general, object manipulation first started with the transportation process alone. After an average of 69 ms, the orientation process joined the transportation process. Both object transportation and orientation processes proceeded simultaneously until the orientation process finished. At the last phase of object manipulation, the transportation process continued alone for an average of 188 ms. In other words, the object transportation process temporally contained the orientation process, consistent with our previous findings [6].

Completion time (CT) and Transportation time (TT)

Average task completion time (CT) over all conditions was 909 ms. CT was dominantly determined by the transportation time (TT). TT took up 97.5% of CT. Results of CT analysis were similar to those of TT data. For brevity, only results on TT data are presented here.

It took 886 ms on average for a subject to complete object translation. There was a significant interaction between the controller size and cursor size ($F(1, 7) = 5.75$, $p < .048$), shown in Figure 2. The average TT was 862 ms when both controller and cursor were small, similar to the average value of 866 when both controller and cursor were large. When the controller was large and the cursor was small, TT increased to 896 ms. A small controller and a large cursor resulted in the greatest average TT of 921 ms. The controller size and cursor size also significantly interacted with the target distance ($F(1, 7) = 19.28$, $p < .003$). It appeared that TT was much slower at the target distance of 200 mm with a small controller and large cursor. However, at both distances, data had a similar pattern as shown in Figure 2. These results demonstrate that it was the relative size between the controller and cursor that significantly affected TT, as predicted in our relative size hypothesis. The same size hypothesis is also supported by the data in that when the controller size and cursor size were the same, the transportation time (TT) was significantly faster.

A significant interaction was also found between the cursor size and the target size ($F(1, 7) = 61.85$, $p < .001$), as shown in Figure 3. However, the nature of the cursor and

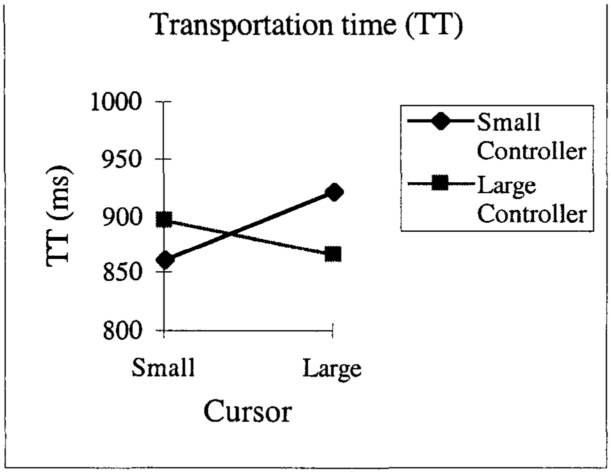

Figure 2. Interaction between controller size and cursor size on transportation time.

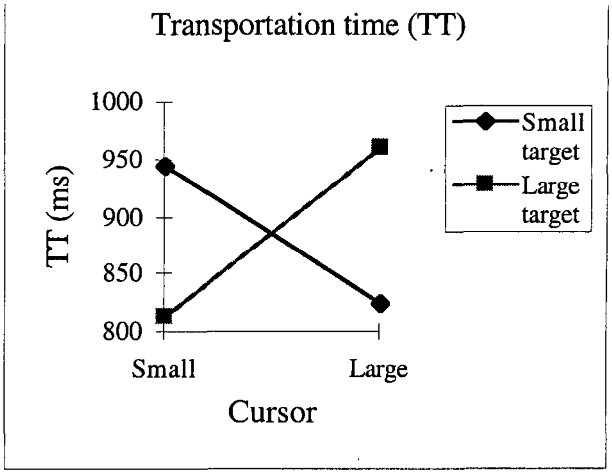

Fig 3. Interaction between cursor size and the target size on transportation time.

target size interaction was very different from the controller and cursor interaction mentioned above. It took a longer transportation time when the cursor and target had the same size than when they were different. When both cursor and target were small, TT was 946 ms, and when both were large, TT was 961 ms. It was much faster when the cursor and the target had different sizes, 825 ms with a large cursor and a small target and 813 ms with a small cursor and a large target. These results seem to be counterintuitive. Actually, the subjects took advantage of the strong visual feedback presented when the cursor and target had the same size to achieve higher accuracy. We will refer to this point when we examine the spatial errors later.

With no surprise, TT significantly increased with the target distance, F(1, 7) = 131.62, $p < .001$. The average TT was 786 ms at 100 mm, and 987 ms at 200 mm. No other main effects were found. Neither controller size, cursor size, nor target size alone had significant effects on the transportation time. This clearly demonstrates that human performance in object transportation was influenced by the relative sizes among the controller, cursor and target rather than their absolute size. Note, however, no significant interaction was found between the controller size and the target size.

Orientation time (OT)

The average orientation time (OT) was 630 ms, 71% of the task completion time (CT), much shorter than the 97.5% for transportation time (TT). Overall statistics on OT data were similar to those on TT data, but there were some differences in detail. As shown in Figure 4, there was a significant interaction between the controller size and cursor size (F(1, 7) = 20.69, $p < .003$). With both large controller and cursor, the orientation was fastest with a time of 564 ms. However, when both controller and cursor were small, the average OT was 656 ms, greater than the average value of 592 ms where the controller was larger than the cursor. The slowest OT occurred when a large cursor was driven by a small controller (706 ms).

There was a three-way interaction among the cursor size, target size and target distance, F(1, 7) = 6.20, $p < .043$, shown in Figure 5A and 5B. At the target distance of 100 mm, OT showed a similar cursor by target pattern as TT (Figure 3). At 100 mm, with the same sized cursor and target, it took longer to complete the object orientation (634 ms for both small and 621 ms for both large) than when the cursor size and the target size were different (Figure 5A). These results may be due to subjects' efforts to obtain a more accurate match by using the strong visual feedback when both cursor and target size were the same. In contrast, at the target distance of 200 mm, when both cursor and target are large, OT (689 ms) was significantly longer than the other three cursor by target conditions (647 - 650 ms), as shown in Figure 5B. It appeared that when the target was small and far away, the visual feedback presented by the cursor and target was not strong enough to make a difference on OT.

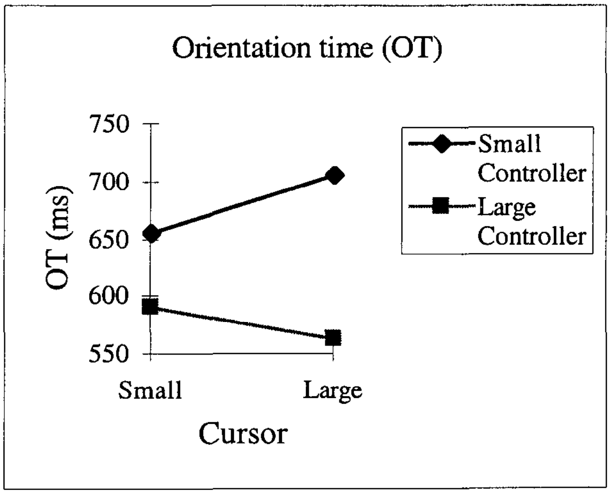

Figure 4. Interaction between controller size and cursor size on orientation time.

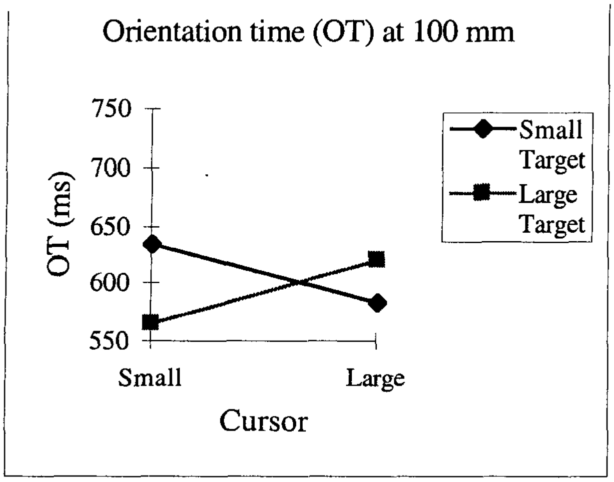

Figure 5A. Interaction between the cursor size and the target size on orientation time at target distance 100 mm

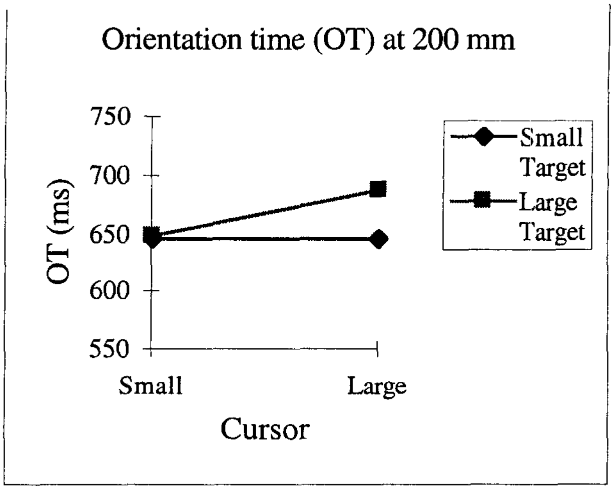

Figure 5B. Interaction between the cursor size and the target size on orientation time at target distance 200 mm.

Target distance had a significant main effect on OT , F(1, 7) = 35.90, p < .001. OT increased with the target distance, from 601 ms at 100 mm to 658 ms at 200 mm. Target distance can be considered as an input to the object transportation process, and therefore should have an effect on TT. OT, on the other hand, can be considered as an output of the object orientation process. The main effect of target distance on OT indicated that this input for the transportation process significantly affected the output of orientation process. This result confirms previous findings by Wang et al. that the transportation process and orientation process are interdependent [6]. There were no other main effects on OT. It was the relative size that affected the object orientation process. Similar to TT, again, there was no interaction between controller size and target size on OT.

Spatial error measures

Spatial errors were measured at the end point of a trial. Constant errors were defined as the mean difference between the target distance (angle) and the distance (angle) made on each trial. The constant errors are generally attributed to system features such as the quality of graphics, and individual subject bias [5]. Variable errors were the standard deviation of errors in each experimental condition. It is believed that variable error measures reflect human performance consistency under a certain interface system.

Constant distance errors (CED) and Constant angle errors (CEA)

On average, constant distance error (CED) undershot the target distance by 1.4 mm, significantly different from zero, F(1, 7) = 13.86, p < .007. CED increased significantly

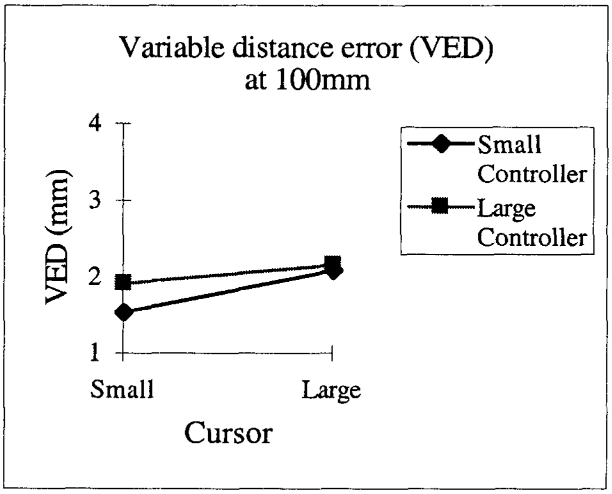

Fig 6A. Interaction between cursor size and controller size on variable distance errors at 100 mm.

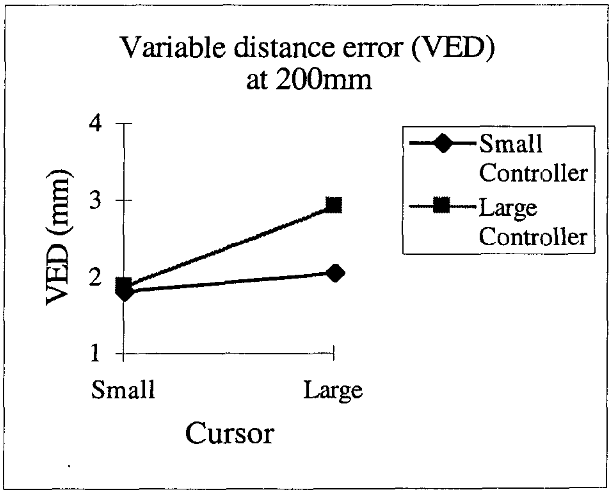

Fig 6B. Interaction between cursor size and controller size on variable distance errors at 200 mm.

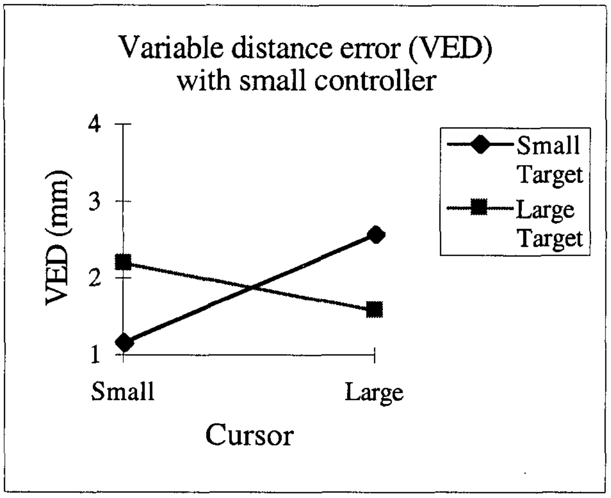

Figure 7A. Interaction between cursor size and target size with small controller on variable distance errors (VED).

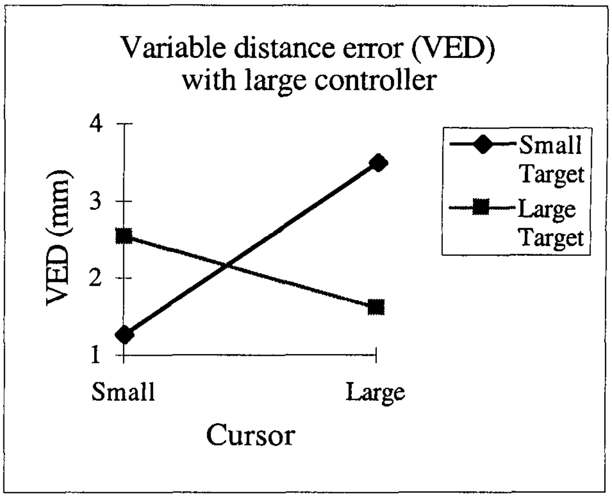

Figure 7B. Interaction between cursor size and target size with large controller on variable distance errors (VED).

with cursor size, from 0.6 mm with a small cursor to 2 mm with a large cursor. The effect of target size was also significant with F(1, 7) = 14.92, p < .006. CED was 2.1 mm with a small target, reduced to 0.6 mm with a large target. No other main effect or interaction was significant. It appeared that the visual display (cursor, target) had significant impact on CED. On average, constant angle error (CEA) was 1.1 degree under-rotated, but this was not significant.

Variable distance errors (VED)

The overall average VED was 2.1 mm. Both controller size (F(1, 7) = 6.30, p < .04) and cursor size (F(1, 7) = 15.11, p < .006) had significant main effects. VED increased from 1.9 mm to 2.2 mm with increases in controller size, and from 1.8 mm to 2.3 mm with increases in cursor size.

An interaction among controller size, cursor size and target distance was found, F(1, 7) = 7.06, p < .033. As shown in Figure 6A, when the controller and cursor were both small, VED was smallest at 100 mm target distance. In contrast, Figure 6B shows, at 200 mm target distance, VED was largest when both controller and cursor size were large. Combined with transportation time results, it appeared that object transportation was fastest and yet most accurate when both controller and cursor were the same small size.

There was a significant interaction between the cursor size and the target size, F(1, 7) = 55.76, p < .001. VED was smaller when the cursor and target had the same size than when they were different. This shows that subjects indeed took advantage of the visual feedback information where the cursor and target sizes were the same to achieve high accuracy. However, there was also a three-way interaction among controller size, cursor size and target size, F(1, 7) = 7.34, p < .03. The interaction of cursor size and target size was more pronounced for the large controller than small controller, as shown in Figure 7A and 7B. It appeared that VED was particularly large for a large controller, a large cursor and a small target, with a value of 3.5 mm compared to the average VED of 2.1 mm. This was the only time we found a three-way interaction among the controller, cursor and target sizes. No other interactions were found between the controller size and the target size in this study.

Variable angle errors (VEA)

The average VEA was 2.1 degrees across all conditions. There was a significant interaction between cursor size and target size, (F(1, 7) = 8.99, p < .02. As shown in Figure 8, VEA was less with the same sized cursor and target than with the different sized cursor and target. VEA was the smallest when both the cursor and the target were large, 1.9 degrees, compared to 2.2 degrees when both of them were small. When the cursor and target had different sizes, VEA was the same 2.3 degrees no matter which one was larger.

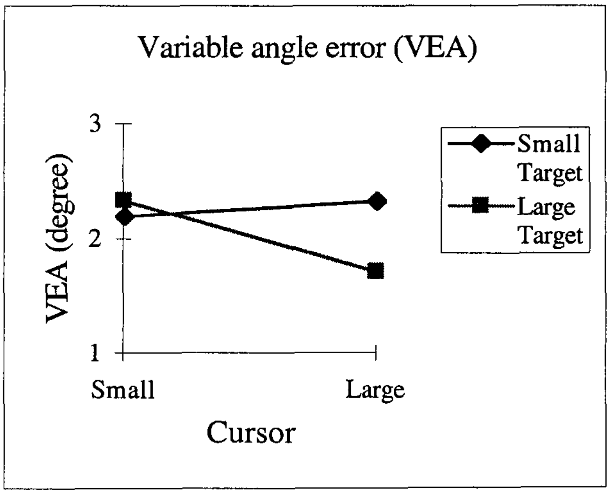

Figure 8. Interaction between cursor size and target size on variable angle errors (VEA).

DISCUSSION

Here we first summarize and discuss the results in light of our research hypotheses. We then relate our findings to theory and applications in HCI design.

Relative size hypothesis.

Results from this study supported the relative size hypothesis. As predicted, interactions among the controller size, cursor size and target size were found on all dependent measures.

In the temporal domain, there were significant interactions between the controller size and cursor size as well as between the cursor size and target size on the total task completion time (CT), transportation time (TT) and orientation time (OT). However, there were no interactions between controller size and target size. At the same time, neither controller size, cursor size, nor target size alone had significant effects on CT, TT or OT. The results did demonstrate that it was the relative size that mattered, rather than the absolute size of controller, cursor or target for temporal measures presented here.

In the spatial domain, the relative size of controller and cursor as well as cursor and target significant affected variable distance errors (VED). A three-way interaction was also found among controller size, cursor size and target size in VED data. It appeared that the interaction between the cursor size and target size was more pronounced with a large controller. This was the only instance in which controller size interacted with target size. For variable angle errors (VEA), the relative size between a cursor and a target showed significant effects. In conclusion, the relative size of controller, cursor, and target were important for spatial errors of object manipulation.

Same size hypothesis

We expected human performance to be better when the controller size, cursor size and target size were the same. We found that transportation times (TT) were faster when the controller and cursor both had either small or large sizes. However, TT was slower when the cursor and target size were the same, either both small or large. In the case of the orientation time (OT), OT was fastest when both controller and cursor were large. However, OT with both the small controller and small cursor was not as fast as that with the large controller and the small cursor. For the interaction between the cursor size and target size, the same size resulted in slower OT.

For spatial errors, VED was smaller when the controller and cursor were both small. VED was also smaller when the cursor and target were the same size, small or large. VEA had the smallest value when the controller size and cursor size or the cursor size and target size were both large.

In general, the above results indicated that the same size of controller and cursor facilitated object transportation and orientation processes in terms of faster TT and OT. On the other hand, the same size of cursor and target helped accuracy in terms of less VED and VEA. In turn, however, it took extra time of TT and OT to reduce VED and VEA for taking advantage of strong visual feedback presented by the same sized cursor and target. It also was noted that human performance appeared particularly better with the same small sized controller and cursor for object transportation, and with the same large sized controller and cursor for object orientation. These results support our same size hypothesis in the sense of speed-accuracy tradeoff.

Implications in HCI

Theory

It is interesting to note that results of this study do not fit Fitts' law [1]. In general, the task completion time did not increase as the target size decreased; this depended on cursor size. Actually, the target size alone showed no significant effects on either the task completion time, transportation time or orientation time. This demonstrates that multidimensional docking or matching tasks are not Fitts' tasks per se. This further suggests that human information processing for multidimensional object transportation and orientation may be very different from that for pointing.

The interplay of controller, cursor and target sizes affects object manipulation, as illustrated in Figure 9. There is a strong interaction between the controller and cursor, and also between the cursor and target, but not between the controller and target. The matched sizes of controller and cursor facilitate object manipulation speed, while the same sizes of cursor and target improve accuracy. The relative size between the controller and target generally has no significant effects on object manipulation performance.

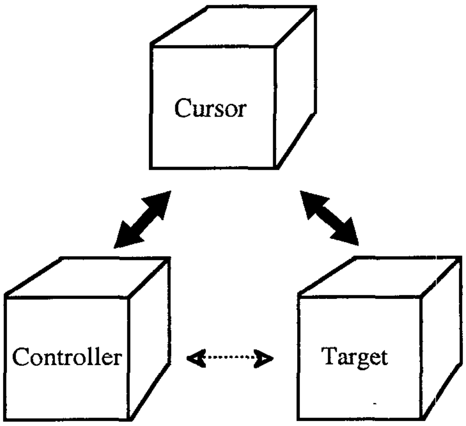

Figure 9. Interplay of controller, cursor and target size.

These findings provide insight into the underlying mechanism of human performance in HCI. Cursor and target are objects in the display domain, while a controller is in the control or hand domain. The cursor is the key which interacts with both controller and target. The intrinsic properties of a cursor such as size and shape are presented in the display domain. At the same time, a cursor can be considered as a visual representation of the controller. The extrinsic properties of a cursor such as location and orientation are determined by the controller in the control domain. In contrast, both intrinsic and extrinsic properties of a target are in the display domain, while both intrinsic and extrinsic properties of a controller are in the control domain. We suggest that it is the nature of domain separation between the intrinsic and extrinsic properties of a cursor that makes it unique: bridging between the controller and the target. Neither controller nor target have properties across another domain besides its own.

There may be different reasons for human performance improvement in speed and accuracy in the same size conditions. The fast object transportation and orientation processes of the same size controller and cursor may be due to the consistency between haptic information of the controller and visual information of the cursor, that is, what subjects feel is consistent with what they see. As discussed previously, the performance improvement in accuracy may be due to processing of visual feedback information when the cursor and target are exactly the same size.

Applications

HCI design should consider the relative size of controller, cursor and target altogether, rather than isolate each element. Particular attention should be paid to cursor properties in relation to the controller and the target. Any moving graphic object driven by an input device can be considered as a cursor. Therefore, the interaction of a controller with a cursor or other graphic is expected to occur in general graphic interaction applications such as animation and gaming. The size effect of a cursor has conventionally been ignored in either input device design or graphic design. As shown in this study, an appropriately sized cursor may significantly improve human performance in HCI.

The relative size of objects should be determined in the context of task requirements. If speed is the main concern, attention should be paid to the controller and cursor size; if accuracy is the main goal, emphasis should be directed to the cursor and target size. Small controller and cursor sizes may benefit object translation tasks, while larger ones may facilitate object rotation tasks. A tradeoff may be achieved by closely examining the size effect to meet the specific task requirements.

The size effect of controller, cursor and target should be taken into account in the experimental design in HCI research. For example, in previous input device comparison studies, the size of different input devices usually was not controlled or not reported in publications. The size of input devices may actually have a compound effect with other factors such as cursor sizes, and even target sizes. Thus, caution is specially needed to interpret results of studies on multidimensional object manipulation in virtual environments.

CONCLUSIONS

We conclude from this study:

1). Relative sizes of controller, cursor, and target matter in object manipulation.
2). Same sizes of controller and cursor improve human performance in object manipulation speed.
3). Same sizes of cursor and target improve human performance in object manipulation accuracy.
4). Relative size effects should be considered in HCI research and design.

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