Direct Manipulation on the Virtual Workbench:
Two Hands Aren't Always Better Than One

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Abstract

This paper reports on the investigation of the differential levels of effectiveness of various interaction techniques on a simple rotation and translation task on the virtual workbench. Manipulation time and number of collisions were measured for subjects using four device sets (unimanual glove, bimanual glove, unimanual stick, and bimanual stick). Participants were also asked to subjectively judge each device's effectiveness. Performance results indicated a main effect for device (better performance for users of the stick(s)), but not for number of hands. Subjective results supported these findings, as users expressed a preference for the stick(s).

1   Introduction

There has been relatively little research conducted addressing the formal evaluation of interaction techniques used in semi-immersive large display environments like the virtual workbench and CAVE (Cruz-Neira, Sandin, Defanti, Kenyon, & Hart, 1992; Van de Pol, Ribarsky, Hodges, & Post, 1999). Numerous studies exist exploring novel interaction devices and 3D interfaces, but most of these studies are based on desktop (Herndon, Zleznik, Robbins, Conner, Snibbe, & van Dam, 1992; Hinkley, Tullio, Pausch, Proffit, & Kassell, 1994) or head-mounted display configurations (Bowman & Hodges, 1997; Forsberg, Herndon, Zeleznik, 1996; Mine, Brooks, & Sequin, 1997; Pierce, Forsberg, Conway, Hong, Zeleznik, & Mine, 1997). Semi-immersive and augmented environments present a unique set of issues to the interface design problem. Instead of the somewhat bland worlds presented by many fully immersive environments

and their interfaces, semi-immersive and augmented environments combine the digitally created elements of the scene with the naturally occurring objects and affordances of the real world. Importantly, these include the user's actual physical form and that of the interaction devices he/she employs. It must be the goal of the user interface designer to manage these additional elements in the environment so as to enhance the user's experience. At the very least, designers must ensure that they do not degrade the usability of the interface.

It is the goal of our research to identify and investigate the research and design issues associated with semi-immersive interfaces in order to inform the design and implementation process. In keeping with this goal, this paper presents the results of a formal user study conducted to investigate the performance differences among four interaction techniques, using two different devices, each in both one and two-handed configurations. We hope that the results of this study will be useful to designers and researchers in the domain of 3D user interface.

The interaction techniques described in this paper have been used in object manipulation, navigation and travel, and data visualization applications. For an extended review of design issues in 3D input, consult Hinckley and Pausch's survey (1994).

2   Overview of Current Experiment

The present study set out to evaluate four separate interaction techniques involved in a 3D object manipulation task. The four interaction techniques involved both one handed and two-handed interaction with two separate interaction devices, pinch gloves and a 6 degrees of freedom pointer or stick. Fully crossing number of hands with device type, four device/hand sets were established; unimanual glove (UG), unimanual stick

(US), bimanual glove (BG), and bimanual stick (BS). We were interested not only in any possible performance difference between unimanual and bimanual techniques, but also in any performance differences that might be attributable to the devices themselves.

The experimental procedure required participants to complete a simple object manipulation task on the virtual workbench. The task involved placing a rod into the open side of a five sided cube or "box" (see Figure 1). To begin each trial the box was presented at a random orientation and had to be manipulated so that the open side could be brought into view. After locating the open side of the box, the participant would proceed to place the rod into the opening.

{Insert Figure 1 about here}

In the case of the two-handed techniques, these tasks could be performed in parallel (one hand manipulating the box and the other the rod) if the user chose to do so. In keeping with Guiard's framework for object manipulation (Guiard, 1987), the box was always presented on the side of the users non-dominant hand, while the rod was always presented on the side of the dominant hand. Those unfamiliar with Guiard's work may refer to section 9.1 for a fuller explanation of his framework and its relevance to this research.

If, at any time during the manipulation, the rod were to collide with the side or edge of the box, the box would turn red and the participant would have to remove the rod from the box and reinsert it. When the rod was inserted into the box without collision, the box would turn green and a new trial could be initiated. Rotation and translation of both the box and the rod were necessary in order to complete the task. Completion time and number of collisions were measured for each device type/number of hands

combination in order to assess which was the most effective and precise interaction technique for this type of task.

3   Method

3.1 Participants

24 undergraduate students volunteered to participate in this study for course credit. Participants were screened for experience with stereoscopic displays, immersive interfaces, and other virtual/augmented reality technologies in order to ensure that only novice users would be included in the experimental sample. Both left-handed and right-handed individuals were allowed to participate in the study, but only one left-handed individual actually did.

3.2 Apparatus

3.2.1 Display. A Fakespace Immersive Workbench was used in this study to display the stereoscopic images. It consisted of an Electrohome Marquee 8500 Projection system, Polhemus 3Space Fastrak tracking system, and a CrystalEyes emitter and glasses package. Head position was tracked by connecting a tracker to the CrystalEyes glasses. This display equipment was serviced by an SGI Onyx2 with 4 processors and Infinite Reality graphics.

3.2.2 Pinch Gloves. Instead of utilizing a gestural grammar, Fakespace Pinch Gloves recognize 'pinches' or contacts made between the various contacts at the tip of each finger and in the palm. With this type of glove, different combinations of pinches between various fingers can be programmed to perform any number of actions. For the purposes

of this experiment, the only 'pinch' recognized by the system was that of the thumb and forefinger contacts. This mimicked the normal grasping of an object between thumb and forefinger, providing a natural manipulatory motion. All other pinch types were "turned off" to avoid user confusion, and any type of eccentric interaction.

Polhemus electromagnetic trackers were used to monitor the position of the glove(s) in this study. Pilot studies were conducted to determine the optimal tracker placement on the glove. The results indicated that placing the tracker on the tip of the index finger would cause great difficulty in properly releasing objects. For example, once an object was placed properly, the user would try to release it by opening the index/thumb pinch. The movement of the of the tracked index finger away from the relatively stationary thumb would cause the object to shift position before actually being released, traveling along with the index finger for a fraction of a second before being deselected. This made precise object placement extremely difficult and, to many users, absolutely frustrating. Ultimately, the tracker was connected to a large Velcro pad on the back of each glove, at the base of the middle finger.

{Insert Figure 2 about here}

3.2.2 Sticks. Also called button chord devices (Van de Pol et. al, 1999) the sticks are PVC tubes with five buttons placed on the surface of the tube in such a way that each finger can access one corresponding button. Numerous combinations of presses, or chords, can be defined on the device in the same way that multiple pinches can be defined to perform various actions with the gloves. For the purposes of this experiment, only the 'thumb' button (nearest the tip of the stick and set off from the other four buttons) was recognized by the system. Depending on the way the user chose to hold the stick, the thumb button could be depressed by the thumb (when the stick was grasped like the

hilt of a sword) or by the index finger (when the stick was held like a pencil of stylus).

These devices have proven utility in the navigation of large geographical data sets as depicted in figure one [VR'99 and VISSym'99 citation]. However, the sticks had not formerly been empirically tested or used expressly in the object manipulation domain.

{Insert Figure 3 about here}

4   Design

A randomized block, 2x2 fully between subjects design was used to test the effects of device type (stick vs. glove) and number of hands (one vs. two) on two dependent variables of interest; manipulation time and number of collisions. This design resulted in four task blocks, one corresponding to each device/hand set; bimanual stick (BS), bimanual glove (BG), unimanual stick (US), and unimanual glove (UG). Twenty four subjects were used to ensure that one and only one of each possible block ordering was included in the analysis (4! = 24).

Manipulation time was defined as the elapsed time between the user's first attempt at object selection (first button click or pinch) and the successful completion of the trial. As a data validation procedure, a measure called pause time (elapsed time between presentation of an unsolved trial and the user's first attempt at selecting an object) and manipulation time could be added together and compared to trial time (the elapsed time from presentation of an unsolved trial to its successful completion). Since manipulation time turned out to be the only time measure of empirical interest, it is the only one that will be discussed any further.

Number of collisions was collected as a measure of precision of manipulation. The device/hand sets that, in general and across participants, lead to fewer collisions could be considered more precise than those that lead to more numerous collisions. A

collision was counted each time any surface of the box intersected any surface of the rod. Collisions were signaled to the user by a color change of the normally gray box to red.

In addition to these explicit objective measures, a log file was created that tracked device usage throughout the experimental trials. This log file contained time stamped data on each button click or pinch and the hand by which it was initiated. This data allowed the researchers to analyze the temporal frequency with which both devices were actually employed during the bimanual interactions, that is to say, to measure just how "bimanual" the bimanual interactions really were. Quite simply, if a participant were given two interaction devices to use for a bimanual trial, but only used one, then the interaction becomes unimanual.

Subjective measures were also collected, addressing issues of user preference and subjective analysis of relative efficiency and precision. A questionnaire addressing the appropriate device/hand set was given to the participant after each block of trials, and then a comprehensive, comparative questionnaire was given at the completion of the session.

5   Procedure

At the beginning of an experimental session, the participant was briefly introduced to the virtual workbench and its supporting technologies. The most basic operation of the display itself, the stereo glasses, the trackers, and the interaction devices were explained in order to reduce anxiety and answer any general questions the participant might have. In order to reduce any tendency to "play" during the experimental tasks rather than concentrate on completing them, the participant was allowed to "play around" in an object manipulation environment unlike the one used in

the actual experiment. The authors felt that this preliminary session would reduce the

"gee whiz" factor associated with this type of technology, allowing the participant to

concentrate on the task and not be distracted by the novelty of the technology. The

introductory environment was a room full of furniture that could be picked up, moved

around, and stacked. The interaction technique used in the room was also substantially

different from the ones used in the actual experiment. The unimanual interaction

technique employed in the introductory task was distant instead of direct, using a small

visible cursor set of from the tip of the stick by approximately 3-5 inches. During the

experimental trials, the selection cursor was quite a bit larger, closer to the device, and

invisible. Also visible during the preliminary session was the virtual hand cursor (Van de

Pol et al., 1999) used in distant manipulation to select objects that are out of the user's

reach. The participant was instructed in the use of the virtual hand cursor if they

expressed any interest in it. Though participants were allowed to interact with the

furniture environment for as long as they desired, no one did so for more than two

minutes. This environment and the interaction techniques implemented in it were

sufficiently distinct from the experimental ones such that only negligible practice effects

might have arisen from its use.

Following this brief introduction to the virtual workbench, each participant

completed four blocks of 15 trials each. These four blocks were comprised of one block

for each of the four device/hand sets specified: unimanual glove (UG), unimanual stick

(US), bimanual glove (BG), and bimanual stick (BS).

To begin a block, the participant put on the stereoscopic glasses and picked up the

appropriate device(s). Once she/he signaled readiness, the initial trial was presented to

the participant. The rod was always presented on the side of the participant's dominant

hand, the box always on the side of the non-dominant hand. The participants would have to select the objects and then rotate and translate them so that the rod could be placed into the open side of the box. For each trial the box was presented at a random orientation, and often had to be manipulated before the participant could see the open side. The rod was always presented in the same orientation, lying flat on the surface of the table, extending horizontally across the participant's field of view as depicted in Figure 1. If at any time during the trial the box and rod collided, the box would turn from gray to red. In order to continue, the user would have to remove the rod from the box (or the box from the rod) completely. Only after complete separation would the box turn back to gray. When the rod was properly inserted into the box, the box would turn green and the next trial would be initiated. The rod would snap back to its original position and a newly oriented box would be presented.

Both subjective and objective performance measures were collected during the procedure. Objective measures included time of manipulation and number of collision errors. These measures were collected and recorded by custom code created by the second author. Subjective measures involved a rating instrument designed to assess each participant's personal preferences and impressions with respect to the interaction techniques employed. After each block of trials the participant filled out such a questionnaire, addressing the specific device/hand set they had just used. After all four blocks were completed, the participant filled out final questionnaire that asked her/him to make some comparative judgements about the device/hand sets in terms of relative efficiency and precision.

7   Results from Objective Measures

Repeated measures ANOVA coupled with Tukey HSD post hoc analyses uncovered significant differences in the collision data $(F(3,69) = 5.637, p=.002)$. Collisions per trial in the Unimanual Stick condition (M=.40) were significantly fewer than those in the Unimanual Glove and Bimanual Glove conditions (M=.66 and M=.84, respectively). There were also significantly fewer collisions in the Bimanual Stick (M=.48) than in the Bimanual Glove (M=.84) condition. Additional analysis indicated a significant main effect for device type (stick vs. glove) but none for number of hands (bimanual vs. unimanual). Cell means for number of collisions are presented in table one.

{Insert Table 1 about here}

Repeated measures ANOVA coupled with Tukey HSD post hoc analyses also uncovered significant differences in the manipulation time data $(F(3,69) = 4.728, p=.005)$. Pairwise comparison showed that the task was completed significantly faster in each of the stick conditions (M=9.9 and M=10.8, for Unimanual Stick and Bimanual Stick respectively), than in the glove conditions (M=13.5 and M=13.0, for Unimanual Glove and Bimanual Glove respectively). Here as well, additional analysis indicated a significant main effect for device type (stick vs. glove) but none for number of hands (bimanual vs. unimanual). Cells means for manipulation time are presented in table two.

7.1 Log File Analysis

Analysis of the interaction log file allowed the researchers to analyze the temporal frequency of dominant and non-dominant hand interaction during the bimanual blocks of the experimental session. For the purposes of this analysis, interaction was defined as

any hand movement initiated by a click or pinch and completed by a release of that click or pinch. Since only one left-handed individual participated in the experiment, those data were removed from this phase of the analysis. Consult Figure 4 and Figure 5 for a graphical summary of the log data.

7.1.1 Bimanual Stick Logs. The mean length of the Bimanual Stick trials was 10.8 seconds with a standard deviation of 7.9 seconds. When analyzed for the full time period from first selection attempt to trial completion for all Bimanual Stick trials, non-dominant hand interactions made up 33.7 percent of the total while dominant hand interactions made up the remaining 66.3 percent. During the first five seconds of interaction, non-dominant hand interactions comprised 51.9 percent of all interactions. During the second five seconds of interaction, non-dominant hand interactions dropped to 26.6 percent of the total. During the third five seconds of interaction, non-dominant hand interactions again dropped to 15.1 percent. For all interactions after 15 seconds, non-dominant hand interactions held at 15.1 percent.

7.1.2 Bimanual Glove Logs. The mean length of the Bimanual Glove trials was 13.0 seconds with a standard deviation of 9.8 seconds. Exhibiting much the same pattern, when analyzed for the full time period, as above, for all Bimanual Glove trials, non-dominant hand interactions made up 35.7 percent of the total while dominant hand interactions made up the remaining 64.3 percent. During the first five seconds of interaction, non-dominant hand interactions made up 56.4 percent of the total. During the second five seconds of interaction, non-dominant hand interactions dropped to 36.0 percent of the total, and during the third five seconds of interaction, that number dropped

again to 17.3 percent. For all interactions after 15 seconds, non-dominant hand interactions remained relatively stable at 14.2 percent.

8   Subjective Measures

When asked which device allowed them to perform the tasks most effectively, 20 of the 24 users chose the stick(s) (9 unimanual, 11 bimanual) (see figure 6) . When asked which device most hindered their performance of the task, 16 of the 22 users expressing a preference chose the glove(s) (6 unimanual, 10 bimanual). When asked which device would be most appropriate for tasks requiring more precision, 17 of 23 users expressing a preference chose the stick(s) (12 unimanual, 5 bimanual) (see Figure 6). Finally, when asked which device would be most appropriate for task requiring less precision, 18 of the 22 users expressing an opinion chose the glove(s) (7 unimanual, 11 bimanual).

9   Discussion

9.1 Unimanual vs. Bimanual Interaction

The obtained results indicate no effect for the number of hands involved in performance of the task (unimanual vs. bimanual). This may be an initially puzzling and somewhat unexpected result. It may be argued that the task was not truly bimanual in that the use of two hands was not necessary. While it is true that users were not required to use both interaction devices during the bimanual trials, analysis of the log file showed that when available both interaction devices were used. In fact the pattern of usage

displayed fits very tightly to Guiard's well established framework for bimanual action (1987).

Though derived from an analysis of handwriting tasks, Yves Guiard's model for bimanual action (1987) is often referred to by members of the 3D interaction community. As identified in Hinckley and Pauch's survey of spatial input design issues (1994), Guiard outlines three principles of bimanual action that are relevant to the bimanual results of the current study:

1) Motion of the dominant hand typically finds its spatial reference in the results of motion of the non-dominant hand.
2) The dominant and non-dominant hands are involved in asymmetric temporal-spatial scales of motion.
3) The contribution of the non-dominant hand to global manual performance starts earlier than that of the dominant hand.

During a writing task, the non-dominant hand positions and orients the page while the dominant hand performs the finer task of manipulating the writing utensil. During the bimanual phases of the experiment presented here, the non-dominant hand was used to position and orient the box, while the dominant hand was used to perform the finer manipulation necessary to insert the rod into the box without collision. With respect to the second point and third points, while writing, the non-dominant hand orients the paper and writing begins, but after this initial phase those movements that adjust the page are much less frequent than the rapid and complex movements of the dominant hand. It seems clear from the analysis of the log files that this holds true in the current study as

well, since non-dominant hand interactions, almost without exception, initiated each trial but then trailed off in temporal frequency as the trial went on. All this indicates that the bimanual task performed in this study does not differ greatly from the bimanual tasks we engage in in everyday life, nor from those we heretofore implement and encounter in virtual environments. That said, these results seem to suggest that there may be classes of tasks for which two hands are not better than one. Taking into account the current level of tracker accuracy and responsiveness, one such class of tasks specifically suggested by our results, would be those requiring precise, fine-grained manipulation. Beyond a spatial frame of reference, the non-dominant hand seems to add little to these types of bimanual tasks. This seems particularly true in cases where, once established by gross motor movements of the non-dominant hand, said frame of reference is maintained naturally by the environment and the non-dominant hand has nothing more to add. For example, during a writing task the vigorous action of the dominant hand on the paper requires that the non-dominant hand remain involved to prevent the paper from shifting [1]. In the task presented here, once positioning of the box was completed, the non-dominant hand had little of value to add to the performance of the task. Hence, the availability of the second interaction device did little to enhance performance when compared to the unimanual configuration. Since 3D user interface designers are always faced with the problem of parsimonious and elegant allocation of computational resources as well as issues of cost, it is important that cases such as this, where a second input device is unnecessary, be identified. Further, the establishment of classes of such interactions that do not benefit from the dual input devices will allow the user interface designer to

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[1] It bears considering that, when using a clip-board on a table, such "restraint" actions by the non-dominant hand would seem to be redundant, having little effect on the outcome of the task. Yet we still see the non-dominant hand involved, perhaps for other reason like support or angular manipulation.

leverage the availability of the non-dominant hand to perform some other type of action in parallel[2]. Again, we might speculate that one such class of interactions would be those requiring relatively precise movement by the dominant hand operating within a static or environmentally maintained spatial frame of reference.

It is important, however, to consider carefully the limitations of these findings. Though there is nothing to indicate a distinction between this task and other bimanual tasks, the authors have identified some factors that might point to programmatic and task specific determinants of the outcome. First of all, as already touched upon, there was no gravity in the environment. If an object was released, it would hang in space, negating the need for the participant to "hold" anything in place during the task. Because of this, even in the bimanual conditions, some users manipulated both objects primarily with the dominant hand. Defining a force of gravity in the environment might encourage two-handed users to maintain their grasp of objects in the non-dominant hand in lieu of placing them flat on the table. However, it can be argued that gravity is a force of the physical world that is not always included or necessary in a virtual environment.

A programmatic factor that might have led to some difficulty in the two-handed task was the invisibility of the selection cursors. During times of close-in manipulation, two-handed users might unknowingly overlap selection cursors and select objects with the wrong hand. This might lead to a momentary but nonetheless frustrating confusion. Future work including an experimental condition using a translucent cursor like Zhai's "silk cursor" would lay this issue to rest (Zhai, Buxton, & Milgram, 1994). The authors feel that these issues may effect the observed equity of the bimanual and unimanual

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[2] An example might be a 3D notation or drawing task where the non-dominant hand controls push button or selection based mode changes while the dominant hand performs the more complex actions so defined.

interaction techniques in a way that is likely task-specific in nature and not substantively robust. Future inquiry is required to further examine these factors.

9.2 Stick(s) vs. Glove(s)

With respect to device type, both the subjective and objective results suggested that the sticks may be a more precise and efficient interaction device than pinch-gloves in object manipulation tasks requiring a degree of precision. One clear benefit of using the stick(s) during interactions on the workbench is the fact that at no time is the user forced to break down the stereo effect by interposing his/her hand between the eyes and the object presented on the display. Doing this on the virtual workbench eliminates the illusion that one is interacting with three dimensional objects, and may considerably degrade the user's sense of spatial presence with respect to those objects. Hand placement on the stick(s), dramatically reduces instances of this visual breakdown, since the hand is place well aside and the tip of the stick does not obscure any selected object. This view obstruction by interaction widgets issue must also be addressed in other display environments, including the head-mounted display (Pierce et al., 1997). Unfortunately for workbench UI designers, it is impossible to make the workbench user's hands translucent as Pierce et al suggest by rendering the users appendages so in a head mounted display configuration (1997).

Tracker placement frequently becomes an issue in the design and implementation of 3D user interfaces. Early in the development of the experimental procedure used in this study, an electromagnetic tracker was attached to each glove at the tip of forefinger. This tracker placement caused difficulty in precisely placing objects. When released, the final position of the object could be a centimeter or two from its intended position before

the release. This was due in part to computational delay in the receipt of a glove pinch release but also attributable to the large displacement the forefinger experiences when users pinch and release. Simply, the forefinger moves a relatively large distance from the thumb upon release. Placing the tracker on the thumb reduced, but did not eliminate the displacement. Placing the tracker on the back of the hand seemed to eliminate the displacement, but isolated the fine manipulation possible through fingertip manipulation (Zhai, Milgram, & Buxton, 1996). It is important to consider that the loss of this fine finger manipulation may negate the advantage provided through use of pinch gloves. However, this tracker placement was very comparable to that used for the stick, making the interaction devices experimentally and programmatically parallel in terms of selection volume offset. To be sure, not all implementations of pinch gloves will share the tracker placement employed here.

It remains our feeling that these programmatic issues do not substantially weaken the overwhelmingly favorable performance of the stick(s) in this user study. Both the objective and subjective results indicate the performance benefits this and other similarly designed 6 degrees-of-freedom pointers offer to the user. Therefore, the authors endorse the sticks as a viable alternative to pinch gloves; an input device option worth consideration by 3D user interface designers.

Future research in this area should address the possible task specific nature of the benefits of one-handed vs. two-handed interaction techniques, endeavoring to determine the classes of interactions and tasks for which one hand is more appropriate than two and vice versa. It may be that those tasks necessitating temporally and spatially parallel work are more appropriate for bimanual implementations, while precise, fine grained manipulation tasks are just as suited to unimanual implementations. Future work should

also continue to investigate non-direct, or distant, manipulation in order to determine whether or not the performance benefits of the stick transfer to interaction paradigms in which object occlusion is not such a salient factor (Van de Pol et al., 1999).

The ultimate goal of this type of research is to inform the design process involved in the creation of production 3D interfaces and virtual environments. We plan to leverage the knowledge we have gleaned from this work to guide our future designs.

10　Acknowledgments

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Figures and Tables
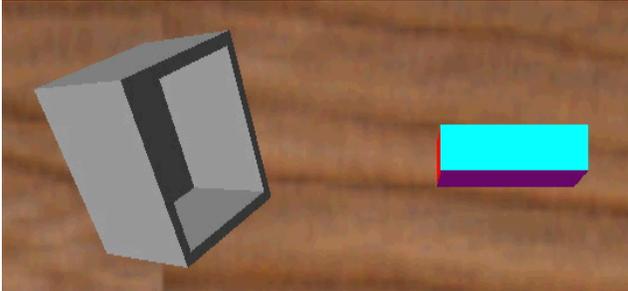
Figure 1. During the task, the multicolored rod (pictured at right) was placed into the opening in the gray box (pictured at left).
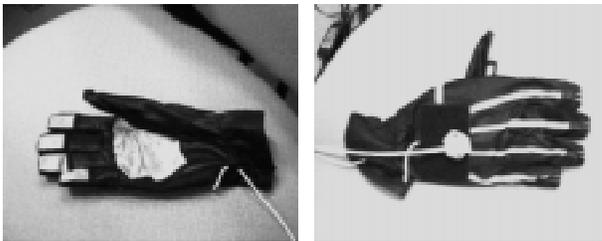
Figure 2. Pinch gloves are shown from both palm up (left) and palm down (right) views. Note the contact pads on each digit and palm in the palm up view (contact on thumb not pictured), and the placement of the tracker on the back of the glove in the palm down view.

Figure 3. The stick with attached tracker. Note the location of the thumb button on the dorsal face of the stick.
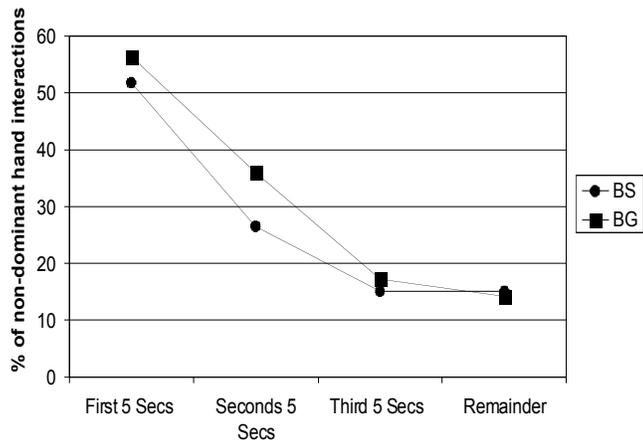
Figure 4. Percentage of non-dominant hand interactions shown across four time segments.
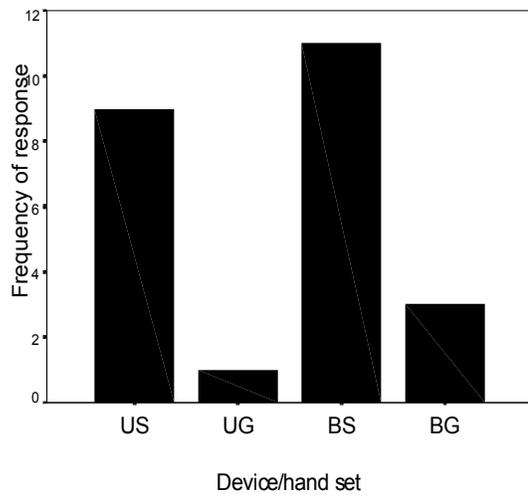
Figure 5. Participant responses with regard to the most effective device/hand set.
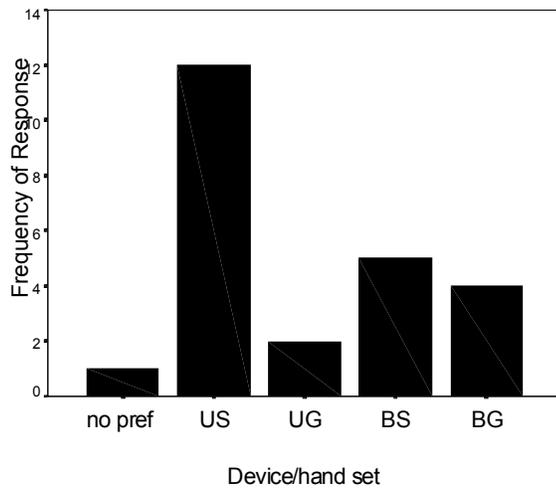
Figure 6. Participant responses with regard to the most precise device/hand set.

Table 1. Means for number of collisions per trial by number of hands and device type.

	Unimanual	Bimanual
Stick	.40	.48
Glove	.66	.84

Table 2. Means for manipulation time in seconds per trial by number of hands and device type.

	Unimanual	Bimanual
Stick	9.9	10.8
Glove	13.5	13.0

Figure and Table Captions

Figure 4. During the task, the multicolored rod (pictured at right) was placed into the opening in the gray box (pictured at left).

Figure 5. Pinch gloves are shown from both palm up (left) and palm down (right) views. Note the contact pads on each digit and palm in the palm up view (contact on thumb not pictured), and the placement of the tracker on the back of the glove in the palm down view.

Figure 6. The stick with attached tracker. Note the location of the thumb button on the dorsal face of the stick.

Figure 4. Percentage of non-dominant hand interactions shown across four time segments.

Figure 5. Participant responses with regard to the most effective device/hand set.

Figure 6. Participant responses with regard to the most precise device/hand set.

Table 3. Means for number of collisions per trial by number of hands and device type.

Table 4. Means for manipulation time in seconds per trial by number of hands and device type.