Cooperative Bimanual Action

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ABSTRACT

We present an experiment on cooperative bimanual action. Right-handed subjects manipulated a pair of physical objects, a *tool* and a *target object*, so that the tool would touch a target on the object (*fig. 1*). For this task, there is a marked specialization of the hands. Performance is best when the left hand orients the target object and the right hand manipulates the tool, but is significantly reduced when these roles are reversed. This suggests that the right hand operates relative to the frame-of-reference of the left hand.

Furthermore, when physical constraints guide the tool placement, this fundamentally changes the type of motor control required. The task is tremendously simplified for both hands, and reversing roles of the hands is no longer an important factor. Thus, specialization of the roles of the hands is significant only for skilled manipulation.

Keywords

Two-handed interaction, bimanual asymmetry, virtual manipulation, motor control, 3D interaction, haptics.

INTRODUCTION

Two-handed interaction has become an accepted technique for "fish tank" 3D manipulation, for immersive virtual reality, and for 2D interfaces such as ToolGlass [3]. Unfortunately, there is little formal knowledge about how the two hands combine their action to achieve a common goal.

The present experiment was motivated by our experiences with the props-based interface for neurosurgical visualization [14]. This is a 3D user interface based on the two-handed physical manipulation of hand-held tools, or "props", and was designed to allow neurosurgeons to visualize volumetric medical image data. From the neurosurgeons's perspective, the interface is analogous to holding a miniature head (a doll's head) in one hand which can be "sliced open" or "pointed to" using a cross-sectioning plane or a stylus tool, respectively, held in the other hand (*fig. 2*).

Informally, we observed that the operation of the interface was greatly simplified when both hands were involved in the task. But in the early design stages, we were faced with many possible ways that the two hands might cooperate. An early prototype allowed users to use both hands, but was still difficult to use. The nonpreferred hand oriented the doll's head, and the preferred hand oriented the cross-sectioning plane, yet the software did not pay any attention to the relative placement between the left and the right hands. Users felt like they were trying to perform two separate tasks which were not necessarily related.

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We changed the interface so that relative placement mattered. All motion was interpreted as a distance relative to the doll's head in the left hand, resulting in a far more natural interaction. It was far easier to integrate the action of the two hands to perform a cooperative task.

Thus, informally we had observed that two-handed coordination was most natural when the preferred hand moved relative to the nonpreferred hand. The current experiment formalizes this hypothesis and presents some empirical data which suggests right-to-left reference yields quantitatively superior and qualitatively more natural performance.

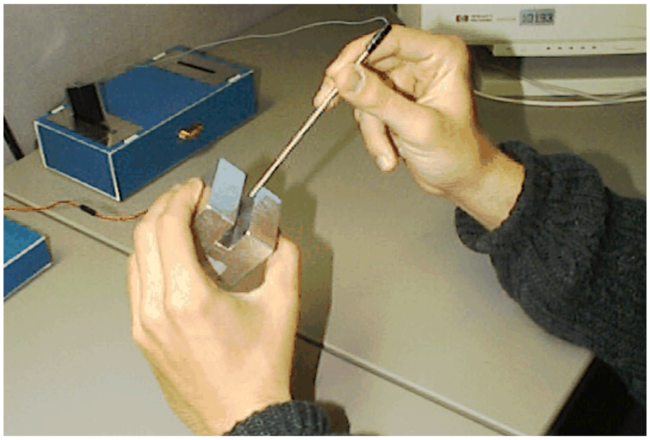

Figure 1: **A subject performing the experimental task.**

Beyond our experience with the props-based interface, there is good reason to believe that cooperative bimanual tasks represent an important area of study. Most real-world manipulative tasks utilize both the left and the right hands working. For example, writing is often considered to be a unimanual task, yet in practice the nonpreferred hand plays a distinct role to orient the page for the action of the preferred hand [9]. Interface designers have begun to realize that humans are two-handed, and it is time that we developed some formal knowledge in support of such designs.

In this spirit, the present experiment, which analyzed right-handed subjects only, contributes the following pieces of such formal knowledge:

- Our task, which represents a general class of 3D manipulative tasks involving a tool and a reference object, requires an asymmetric contribution of the two hands.

- For such tasks, performance is best when the right hand operates relative to the left. Reversing the roles of the hands significantly reduces performance both in terms of time and accuracy.
- Specialization of the roles of the hands is significant only for precise manipulation. This does *not* imply that two-handed input will be ineffective for tasks which afford symmetric manipulation, but instead restricts the scope of tasks where asymmetry factors will have important design implications.
- Qualitatively, our results held despite the strong tendency for subjects to adopt coping strategies which attempted to maintain the natural roles for the hands. For example, when roles were reversed, some subjects tried to hold the tool stationary in the left hand while moving the target object to meet it. Clearly, the constraints of the task limited the effectiveness of this strategy.

We only studied right-handed subjects because hand usage patterns in left-handers tend to be somewhat more chaotic than those in right-handers, which complicates experimental design. The issues posed by handedness are surprisingly complicated [11][12], and without a clear understanding of bimanual action in right-handers, it seems premature to address the unique behavioral strategies employed by left-handers. Nonetheless, we expect left-handers should exhibit a similar (but less consistent) pattern of findings to those reported here.

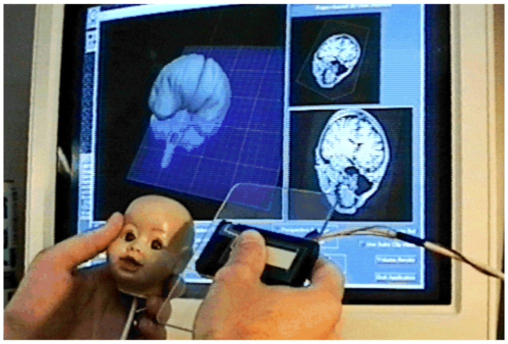

Figure 2: **The props interface for neurosurgical visualization [14].**

RELATED WORK

In the HCI, psychology, and motor behavior literatures, experiments studying hand lateralization issues have typically been formulated in terms of hand superiority by contrasting unimanual left-hand performance versus unimanual right-hand performance [2][18][27]. While such experiments can yield many insights, they do not reveal effects which involve simultaneous use of both hands.

For truly bimanual movement, most experiments have studied tasks which require concurrent but relatively independent movement of the hands. Example tasks include bimanual tapping of rhythms [7][25][34] and bimanual pointing to separate targets [20][22][33]. Since the hands are not necessarily working together to achieve a common goal, we cannot be sure that these experiments apply to *cooperative* bimanual action.[1]

There are a few notable exceptions, however. Buxton and Myers [5] demonstrated that computer users naturally use two hands to perform compound tasks (positioning and scaling, navigation and selection) and that task performance is best when both hands are used. Buxton has also prepared a summary of issues in two-handed input [6].

Kabbash [19] studied a compound drawing and selection task, and concluded that two-handed input techniques, such as ToolGlass [3], which mimic everyday “asymmetric dependent” tasks yield superior overall performance. In an asymmetric dependent task, the action of the right hand depends on that of the left hand [19][9]. This experiment did not, however, include any conditions where the action of the left hand depended on the right hand.

Guiard performed tapping experiments (Fitts’ task) with a bimanually held rod [11]. Subjects performed the tapping task using two grips: a preferred grip (with one hand held at the end of the rod and the other hand near the middle) and a reversed grip (with the hands swapping positions). The preferred grip yielded better overall accuracy, but had reliably faster movement times only for the tapping condition with the largest amplitude. Guiard also observed a distinct partition of labor between the hands, with the right hand controlling the push-pull of the rod, and the left hand controlling the axis of rotation.

A number of user interfaces have provided compelling demonstrations of two handed input, but most have not attempted formal experiments. Three-dimensional virtual manipulation is a particularly promising application area. Examples include MultiGen Smart Scene [23], the Virtual Workbench [26], 3Draw [28], Worlds-in-Miniature [31], and work by Shaw [30] and Abel [1]. There is also some interest for teleoperation applications [31]. In two dimensions, examples include Toolglass [3], Fitzmaurice’s Graspable User Interface [8], and Leganchuk’s bimanual area sweeping technique [20].

Bolt [4] has investigated uses of two hands plus voice input. Hauptmann [13] showed that people naturally use speech and two-handed gestures to express spatial manipulations.

Guiard’s Kinematic Chain Model

Since our experiment was in part suggested by Guiard’s Kinematic Chain (KC) model [9], a bit of background will be helpful. The kinematic chain model is a general model of skilled bimanual action, where a *kinematic chain* is a serial linkage of abstract motors. For example, the shoulder, elbow, wrist, and fingers form a kinematic chain representing the arm. For each link (e.g. the forearm), there is a proximal element (the elbow) and a distal element (the wrist). The (distal) wrist must organize its movement relative to the output of the (proximal) elbow, since the two are physically attached.

The KC model hypothesizes that the left and right hands make up a *functional* kinematic chain: for right-handers, the (distal) right hand moves relative to the output of the (proximal) left hand. This leads to three general principles:

1. *Right-to-left reference:* The right hand performs its motion relative to the frame of reference set by the left hand.

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[1] For bimanual rhythm tapping, conceptually the two hands *are* working together to produce a single combined rhythm. This task, however, does not address our hypothesis of right-to-left reference in bimanual manipulation.

2. *Asymmetric scales:* The right and left hands are involved in asymmetric temporal-spatial scales of motion. For example, during handwriting, the movements of the left hand adjusting the page are low frequency compared to the detailed work done by the right hand.

3. *Left hand precedence:* The left hand precedes the right: for example, the left hand first positions the paper, then the right hand begins to write. This is obvious for handwriting, but also applies to tasks such as swinging a golf club [9].

Looking beyond the hands, one might also apply the KC model to reason about multiple effector systems ranging from the hands and voice (playing a piano and singing [10]), the hands and feet (operating a car's clutch and stick shift), or the multiple fingers of the hand (grasping a pen).

THE EXPERIMENT

Task

The subject manipulates a *tool* (either a plate or stylus) in one hand and a *target object* (either a puck, a triangle, or a cube) with the other hand (*fig. 3*). Each target object has a rectangular slot cut into in it, at the bottom of which is a small gold-colored target area. There are two versions of the task, a Hard task and an Easy task.

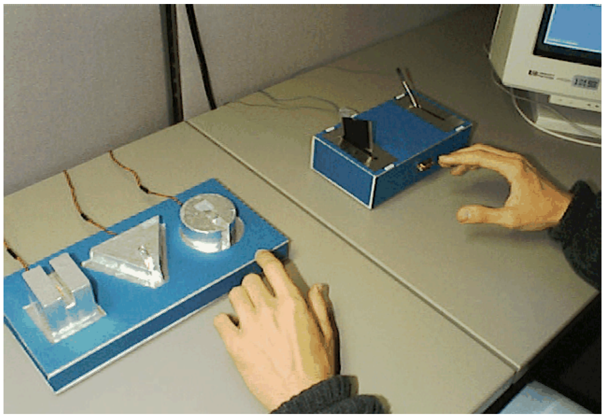

Figure 3: **Experiment configuration. The monitor seen at the right of the working area displays the stimuli for each trial.**

For the Hard task, the subject must mate the tool and the target object so that the tool touches only the target area (*fig. 4*). The target area is wired to a circuit that produces a pleasant beep when touched with the tool; if the tool misses the target area, it triggers an annoying buzzer which signals an error. The target area is only slightly larger than the tool, so the task requires dexterity to perform successfully. The subject was instructed that avoiding errors was more important than completing the task quickly.

For the Easy task, the subject only has to move the tool so that it touches the bottom of the rectangular slot on the target object. The buzzer was turned off and no "errors" were possible: the subject was allowed to use the edges of the slot to guide the placement. In this case, the subject was instructed to optimize strictly for speed.

Each subject performed the Hard and the Easy task using two different grips, a Preferred grip (with the left hand holding the target object and the right hand holding the tool) and a Reversed grip (with the implements reversed). This resulted in four conditions: Preferred Hard (PH), Preferred Easy (PE), Reversed Hard (RH), and Reversed Easy (RE).

Subjects were required to hold both objects in the air during manipulation (*fig. 1*), since this is typically what is required when manipulating virtual objects. Subjects were allowed to rest their forearms or wrists on the table, which most did. Subjects sat in a rolling office chair with armrests.

For the Hard task, the dependent variables were time and errors (a pass / fail variable). For the Easy task, since no errors were possible, only time was measured. Time was measured from when the tool was removed from the platform (*fig. 3*) until the tool touched the target area; this measure did *not* include the time to initially grasp the tool or to return the tool to the platform when done with the task.

Experimental Hypotheses

Our hypotheses were suggested by our experiences with the props-based interface and formalized with the help of Guiard's KC model. Our high-level working hypothesis is that the KC model can be used to reason about two-handed 2D or 3D tasks and interface design.

The specific hypotheses for this experiment are as follows:

H1: The Hard task is asymmetric and the hands are not interchangable. That is, the Grip (preferred, reversed) used will be a significant factor for this task.

H2: For the Easy task, the opposite is true. Reversing roles of the hands will not have a reliable effect.

H3: The importance of specialization of the roles of the hands increases as the task becomes more difficult. That is, there will be an interaction between Grip (preferred, reversed) and Task (easy, hard).

H4: Haptics will fundamentally change the type of motor control required.

Subjects

Sixteen unpaid subjects (8 males, 8 females) from the Psychology Department subject pool participated in the experiment. Subjects ranged from 18 to 21 (mean 19.1) years of age. All subjects were strongly right-handed[2] based on the Edinburgh Handedness Inventory [24].

Experimental Procedure and Design

Figure 3 shows the overall experimental set-up. The experiment was conducted using instrumented physical objects, rather than virtual objects. Since the purpose of the experiment is to look at some basic aspects of bimanual motor control, we felt that by using physical objects we could be certain that we were measuring *the human*, and not artifacts caused by the particular depth cues employed, the display frame rate, device latency, or other possible confounds associated with virtual manipulation. The physical objects also provided the haptic feedback needed to test hypothesis H4.

The experiment began with a brief demonstration of the neurosurgical props interface (*fig. 2*) to engage subjects in the experiment. We suggested to each subject that he or she should "imagine yourself in the place of the surgeon" and stressed that, as in brain surgery, accurate and precise placement was more important that speed. This made the experi-

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[2] The mean laterality quotient obtained in the Inventory was 71.7.

ment more fun for the subjects, who would sometimes joke that they had “killed the patient” when they made an error.

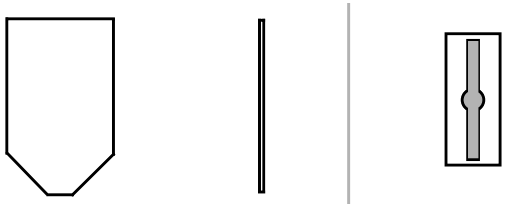


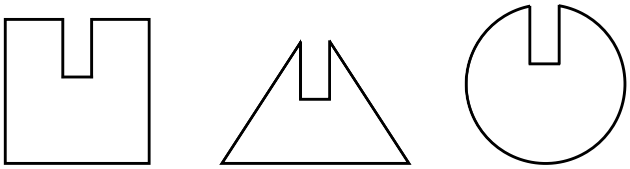
Plate tool: 3.5” X 2.125”, 0.063” thick, 0.5” wide tip

Stylus tool: 5.25” X 0.125” diameter

Target (shaded area): 0.625” tall X 0.12” wide. The rounded area has a 3/16” diameter.

Figure 4: **Dimensions of the Plate and Stylus tools (left); Dimensions of the target (right). For the Hard task, hitting anywhere outside the shaded area triggered an error.**

There were two tools, a plate and a stylus, and three target objects, a cube, a triangle, and a puck (*figs. 4, 5*). Using multiple objects helped to guarantee that our findings would not be idiosyncratic to one particular implement, as each implement requires the use of slightly different muscle groups. Also, the multiple objects served as a minor ruse: we did not want the subjects to be consciously thinking about what they were doing with their hands during the experiment, so they were initially told that the primary purpose of the experiment was to test which shapes of input devices were best for two-handed manipulation.



Cube: 2” X 2” X 2”

Triangle: 3.5” equilateral, 0.75” thick

Puck: 2.5” diameter, 1.0” thick

Figure 5: **Target Objects. A target *(fig. 4, right)* was centered at the bottom of each slot. Each slot is 0.75” deep by 0.375” wide.**

The subject next performed a practice session for the Hard task, during which we explained the experimental apparatus and task. This session consisted of 6 practice trials with the Preferred grip and 6 practice trials with the Reversed grip[3].

For the experimental trials, a within-subjects latin square design was used to control for order of presentation effects. For each of the four experimental conditions, subjects performed 24 placement tasks, divided into two sets of 12 trials each. Each set included two instances of all six possible tool and target combinations, presented in random order. There was a short break between conditions.

Details of the Experimental Task & Set-up

For each trial, the computer display (at the right of the working area) simultaneously revealed a pair of images on the screen, with the objects for the left and right hands always displayed on the left and right sides of the screen (*fig. 6*).

Two platforms were used, one to hold the tools and one to hold the target objects (*fig. 3*). The tool platform was instrumented with electrical contact sensors, allowing us to detect when the tool was removed from or returned to the platform. Returning the tool to the platform (after touching the target) ended the current trial and displayed a status report. The subject initiated the next trial by clicking a footpedal.

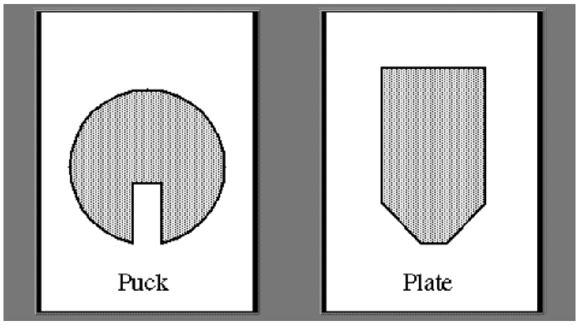


Figure 6: **Sample screen showing experimental stimuli.**

Each subject was seated so that the midline of his or her body was centered between the two platforms. The tool platform was flipped 180° during the Reversed conditions, so that the plate was always the closest tool to the objects. The platforms were positioned one foot back from the front edge of the desk, and were spaced 6” apart.

Figure 5 shows the dimensions for the cube, triangle, and puck target objects. Each object was fitted with an identical target (*fig 4, right*) which was centered at the bottom of the rectangular slot on each object. The objects were machined from delrin and wrapped with foil so they would conduct. The target area and the foil were wired to separate circuits; some capacitance was added to each circuit to ensure that even slight contacts would be detected.

When using the plate, subjects were instructed to use the entire 0.5” wide tip of the plate to touch the target. For the stylus, the subject was told to touch the rounded part of the target area (the stylus was thicker than the other parts of the target).

Limitations of the Experiment

There are a couple of factors which limit the sensitivity of this experiment. First, we ideally would like to have a range of experimentally controlled difficulties analogous to the Index of Difficulty (ID) for Fitts’ Law [21]. But Fitts’ Law applies to movement of one hand, and we are not aware of any adaptations which could handle movement of both hands together. Instead, we have opted for an *easy* versus *hard* difficulty distinction.

Second, our accuracy measurement yields a dichotomous pass / fail outcome. Thus, we have no quantitative information about the magnitude of the errors made when the subjects missed the target in the Hard conditions.

Even given these limitations, our results are quite decisive. Therefore, we decided to leave resolution of these issues to future work, and to demonstrate some effects with the simplest possible experimental design and apparatus.

RESULTS

For each condition, only the second set of 12 trials was used in our analysis, to minimize any confounds caused by initial learning or transfer effects across conditions.

A straightforward analysis of the Hard task shows a strong lateral asymmetry effect. For both the plate and the stylus tools, 15/16 subjects performed the task faster in the PH

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[3] This also doubled as a lateral preferences assessment, to ensure that each subject actually did prefer the “Preferred” grip to the “Reversed” grip.

condition than in the RH condition (significant by the sign test, $p < .001$). The difference in times is not due to a time / accuracy trade-off, as 15/16 subjects (using the plate) and 14/16 subjects (using the stylus) made fewer or the same amount of errors in the PH condition vs. the RH condition.

For the Easy task, as predicted by Hypothesis 2, the lateral asymmetry effect was less decisive. For both the plate and the stylus tools, 11/16 subjects performed the task faster in the PE condition than in the RE condition (not a significant difference by the sign test, $p > .20$). For at least one of the tools, 6/16 subjects performed the task *faster* in the RE condition vs. the PE condition.

Table 1 summarizes the mean completion times and error rates. No errors were possible in the Easy conditions. In the Hard conditions, the relatively high error rates resulted from the difficulty of the task, rather than a lack of effort. We instructed the subjects that "avoiding errors is more important than speed," a point which we emphasized several times and underscored by the analogy to performing brain surgery.

Table 1: **Summary of mean completion times and error rates.**

Condition	Mean	Std. dev.	Error rate
Preferred Easy (PE)	0.76	0.15	--
Reversed Easy (RE)	0.83	0.19	--
Preferred Hard (PH)	2.33	0.77	43.9%
Reversed Hard (RH)	3.09	1.10	61.1%

Qualitative Analysis

Before proceeding with a full statistical analysis, it seems appropriate to first discuss some of the qualitative aspects of the experiment. We videotaped some of the subjects, and our observations are based on these tapes and our notes.

We observed three patterns of strategies in our subjects when they were performing the Hard task:

- *Maintaining natural roles of hands*: In the RH condition, some subjects tried to perform the task by "holding the [left-hand] tool steady and bringing the [right-hand] object to meet it."
- *Tool stability*: Also in the RH condition, many subjects adjusted their left-hand grip to be as close to the tip of the tool as possible. This helped to reduce the effect of any left-hand unsteadiness.
- *Having the right view of the objects*: We placed the target at the bottom of a slot, so there was a restricted set of views where the subject could see the target. For the Hard task, subjects often performed the task with edge-on or overhead views, sometimes holding one eye closed to get the best view of the tool tip and target.

Subjects usually performed the RH task differently than the PH task. When using the Preferred grip, the left hand would first orient the object, and the right hand would then move in with the tool, so that at the time of contact the target object was usually stationary and only the tool was in motion. But in the Reversed grip, there often were several phases to the motion. The right hand would first orient the object, and the left hand would approach with the tool; but then the left hand would hesitate and the right hand would move towards it. During actual contact with the target, both the tool and the object were often in motion.

At first glance, it would seem that the primary difference between the RH and the PH conditions was the left hand's unsteadiness when handling the tools. For at least some of the subjects, however, it also seemed that the right hand had difficulty setting the proper orientation for the action of the left hand. So the right hand was best at fine manipulation, whereas the left hand was best at orientating the target object for the action of the other hand.

For the Easy tasks, we did not notice any specific strategies. Subjects were divided about whether or not the RE task was unnatural. Some thought it was "definitely awkward," others thought it was "fine." At least one subject preferred the Reversed grip; this preference was confirmed by a small Reversed grip advantage in the quantitative data.

Finally, when switching to the Hard task after performing a block of the Easy task, subjects often took several trials to adjust to the new task requirements. Once subjects became used to relying on physical constraints, it required a conscious effort to go back. To assist this transition, we instructed subjects to "again emphasize accuracy" and to "focus initially on slowing down."

Detailed Statistical Analysis

We performed a 2 × 3 × 2 × 2 analysis of variance (ANOVA) with repeated measures on the factors of Tool (plate or stylus), Object (cube, puck, or triangle), Task (easy or hard), and Grip (preferred or reversed), with task completion time as the dependent variable. Significant effects are summarized in Table 2.

Table 2: **Significance levels for Main effects and Interaction effects.**

Factor	F statistic	Significance
Grip	$F_{(1,15)} = 38.73$	$p < .0001$
Task	$F_{(1,15)} = 66.60$	$p < .0001$
Tool	$F_{(1,15)} = 5.22$	$p < .05$
Object	$F_{(2,30)} = 3.33$	$p < .05$
Grip × Task	$F_{(1,15)} = 24.83$	$p < .0005$
Tool × Task	$F_{(1,15)} = 16.57$	$p < .001$
Grip × Task × Tool	$F_{(1,15)} = 5.11$	$p < .05$

Overall, the preferred Grip was significantly faster than the reversed Grip and the easy Task was significantly faster than the hard Task. The Tool and Object factors were also significant, though the effects were small. The plate Tool was more difficult to position than the stylus: this reflects the requirement that the subject must align an additional degree of freedom with the plate (rotation about the axis of the tool) in order to hit the target. The cube Object was somewhat more difficult than the other Objects.

The ANOVA revealed a highly significant Grip × Task interaction, which speaks eloquently in favor of our Hypothesis 3: the importance of specialization of the roles of the hands increases as the task becomes more difficult (*fig. 7*).

There was also a significant three-way Grip × Task × Tool interaction (*fig. 9*). This indicates that the extent of the Grip × Task interaction varied with the tool being used (there was a larger distinction between the preferred and reversed postures with the stylus).

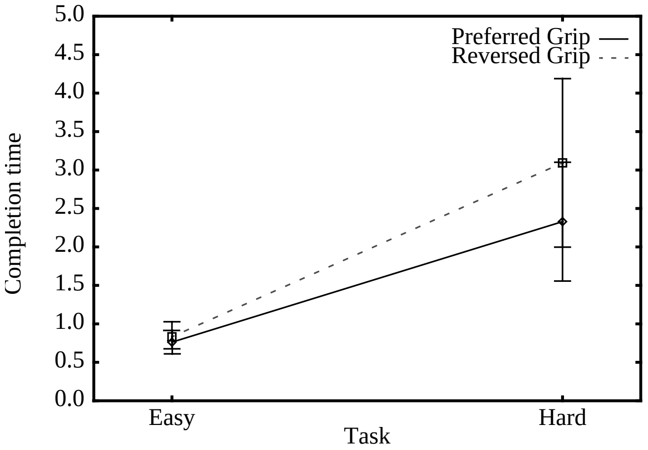

Figure 7: **Task X Grip interaction: The difference between the Preferred and the Reversed grips increases as the task becomes more difficult.**

Finally, the Tool ✕ Task interaction (*fig. 8*) was significant. This suggests that the Tools differed only for the hard Task, not the easy Task.

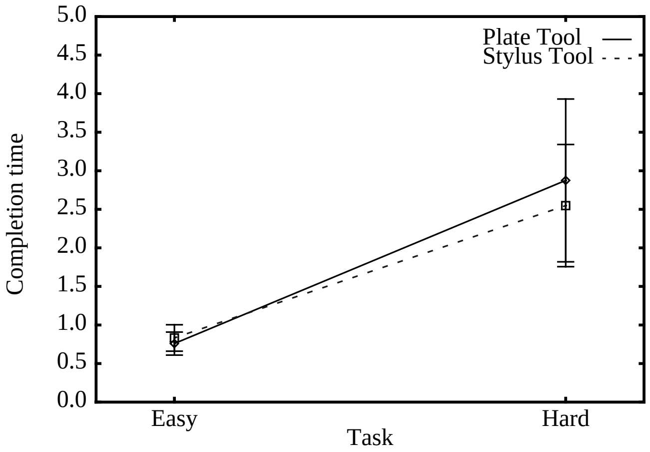

Figure 8: **Tool X Task interaction: the plate is slightly faster for the easy task, but is slower for the hard task.**

Table 2 reports pooled effects across the easy and hard Task and the preferred and reversed Grip. Based on our hypotheses, we also compared the individual experimental conditions. These are summarized in Table 3.

Table 3: **Significance levels for comparisons of experimental conditions.**

Contrast	F statistic	Significance
PE vs. RE	$F_{(1,15)} = 3.94$	Not significant
PH vs. RH	$F_{(1,15)} = 33.56$	$p < 0.0001$

The Grip factor is significant for the Hard task (PH vs. RH), but not the Easy task (PE vs. RE). This supports Hypothesis 1: the task is asymmetric and reversing the roles of the hands has a significant effect. The Grip factor was not significant for the Easy task. This evidence supports Hypothesis 2; reversing the roles of the hands has a significant impact on performance only for the hard task, and not for that easy task. Note however that this experiment does not prove that there is *no* effect of Grip on the easy task; it only proves that any such effect is relatively small.

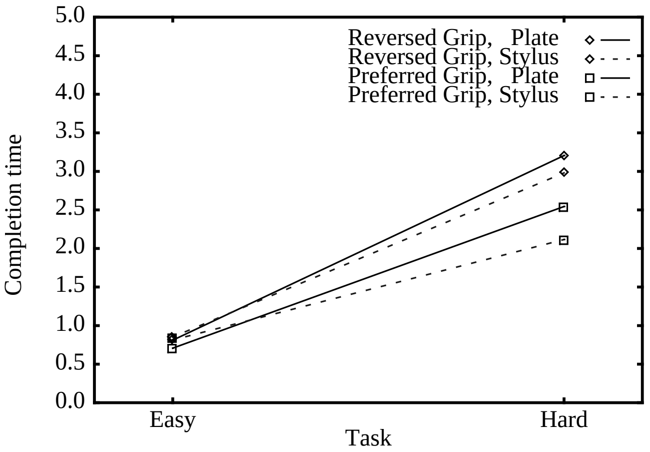

Figure 9: **Task X Grip X Tool interaction: The extent of the Task X Grip interaction *(fig. 7)* varies with the tool being used.**

Possibility of Order, Gender, or Error Biases

Our ANOVA included an analysis of the between-subject factors of Gender and Order of presentation to ensure that the experimental results were not biased by these factors. The Order of the experimental conditions was insignificant, as was the Order ✕ Condition interaction, indicating that the results are not biased by transfer or asymmetrical transfer effects.

There was a small, but significant, main effect of Gender, along with several significant interactions (*table 4*). Although this experiment was not designed to detect gender differences, this finding is consistent with the literature, which suggests that females may be better at some dexterity tasks [12].

Table 4: **Overall Gender difference effects.**

Factor	F statistic	Significance
Gender	$F_{(1,14)} = 5.55$	$p < .05$
Tool ✕ Gender	$F_{(1,14)} = 12.80$	$p < .005$
Task ✕ Gender	$F_{(1,14)} = 5.23$	$p < .05$
Tool ✕ Task ✕ Gender	$F_{(1,14)} = 20.90$	$p < .0005$

To ensure that Gender is not a distorting factor, we performed separate ANOVA's with N=8 male and N=8 female subjects. This is a less sensitive analysis, but the previous pattern of results still held: Grip, Task, and the Grip ✕ Task interaction were all significant for both groups (*table 5*).

Males tended to be more sensitive to which Tool was being used for manipulation, which accounts for the Tool ✕ Gender and Tool ✕ Task ✕ Gender interactions (*table 4*). The Task ✕ Gender interaction results from females being faster than males for the Hard task, but not the Easy task.

Finally, for the hard task only, the ANOVA also compared trials on which an Error occurred versus trials on which there was no error to ensure that the error trials did not distort the results. There was no significant main effect of Error, nor were there any interaction effects.

Therefore, on the basis of these analyses, we can confidently conclude that the differences between the experimental conditions are not biased by Order, Gender, or Error effects.

Table 5: **Results of separate ANOVA‘s for males and females.**

MALES		
Factor	**F statistic**	**Significance**
Grip	$F_{(1,7)} = 13.69$	$p < .01$
Task	$F_{(1,7)} = 44.59$	$p < .0005$
Grip × Task	$F_{(1,7)} = 9.24$	$p < .02$
FEMALES		
Factor	**F statistic**	**Significance**
Grip	$F_{(1,7)} = 29.93$	$p < .001$
Task	$F_{(1,7)} = 47.41$	$p < .0005$
Grip × Task	$F_{(1,7)} = 24.79$	$p < .002$

DISCUSSION

On the whole, the experimental results strongly supported our experimental hypotheses as well as our high-level hypothesis that Guiard’s Kinematic Chain model can be used to reason about bimanual performance for precision 3D manipulative tasks. Reviewing this evidence:

H1: The Hard task is asymmetric and the hands are not interchangable. This hypothesis was supported by the overall Grip effect and the Preferred Hard vs. Reversed Hard contrast, both of which were highly significant. The suggestion we see in this result is that maniplation is most natural when the right hand works relative to the left hand.

There are several qualities of the experimental task which we believe led to the lateral asymmetry effects:

- *Mass asymmetry*: When holding the tool, some subjects had visible motor tremors in the left hand; but when they held the target object, the greater mass helped to damp out this instability.
- *Having the right view of the objects:* As mentioned previously, in the Reversed condition, some subjects tried to hold the tool at a fixed orientation in the left hand and move the target object to the tool. But as the subject moved the target object, he or she would no longer have the best view to see the target, and performance would suffer.
- *Referential task:* The task itself is easiest to perform when the manipulation of one object can done relative to a stationary object held in the other hand.

Under virtual manipulation, one can overcome some of these factors (such as mass asymmetry), but not all of them. For example, many virtual manipulation tasks (such as our example task of cross-sectioning volumetric medical image data [14]) will require a specific view to do the work and will have a referential nature.

H2: For the Easy task reversing roles of the hands will not have any reliable effect. The Grip effect was much smaller for the Easy task, but was significant at the $p < 0.10$ level, so we cannot confidently conclude there was *no* Grip effect. Nonetheless, for practical purposes, lateral asymmetry effects are much less important here.

H3: The importance of specialization of the roles of the hands increases as the task becomes more difficult. The predicted Grip × Task interaction was highly significant, offering strong evidence in favor of H3.

H4: Haptics fundamentally change the type of motor control required. Taken together, the experimental evidence for H1-H3 further suggests that the motor control required for the Easy conditions, where there was plentiful haptic feedback in the form of physical constraints, fundamentally differed from the Hard conditions.

The evidence in support of this final hypothesis underscores the performance advantages that are possible when there is haptic feedback to guide the task. Subjects devoted little cognitive effort to perform the Easy task, whereas the Hard task required concentration and vigilance.

This suggests that passive haptic feedback from supporting surfaces or physical input devices such as “props”, or active haptic feedback from devices such as the Phantom, can have a crucial impact for some tasks. This also underscores the difficulty of using a glove to grasp a virtual tool: when there is no physical contact, the task becomes a hand-eye coordination challenge, requiring full visual attention. With haptic feedback, it can be an automatic, subconscious manipulation, meaning that full visual attention can be devoted to a high-level task (such as monitoring an animation) instead of to the “tool acquisition” sub-task.

These issues underscore the design tension between physical and virtual manipulation. The design challenge is find ways that real and virtual objects can be mixed to produce something better than either can achieve alone.

FUTURE WORK

This experiment demonstrated lateral asymmetry effects using physical objects. The next step, of course, is to demonstrate comparable effects for virtual manipulation.

In the Easy task of the experiment, movement was almost a complete switch to a bimanual symmetric style of motion. Exactly when do manipulative movements require asymmetric rather than symmetric bimanual action? Is there a smooth transition from easy to hard, symmetric to asymmetric manipulation, or is there a sudden crossover?

This work has focused on the motoric aspects of bimanual action, but we strongly believe that two-handed manipulation can have cognitive implications as well. For example, Leganchuk [20] has suggests that a bimanual technique for sweeping out rectangles can reduce cognitive load.

In other work, we have explored how the two hands together can help users to form a better sense of the virtual space in which they are working [16]. With two hands, users maintain a precise, body-relative representation of space which is not dependent on visual feedback. The experimental data suggest that two hands are not just faster than one hand. Using both hands can provide the user with information which one hand alone cannot; using both hands can furthermore change how users *think* about a task by influencing the user’s problem-solving strategy. When designed appropriately, two-handed interfaces can improve the bandwidth between the human and the computer, thereby helping users to perform significant intellectual tasks [17].

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