Two-Handed Virtual Manipulation

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We discuss a two-handed user interface designed to support three-dimensional neurosurgical visualization. By itself, this system is a “point design,” an example of an advanced user interface technique. In this work, we argue that in order to understand why interaction techniques do or do not work, and to suggest possibilities for new techniques, it is important to move beyond point design and to introduce careful scientific measurement of human behavioral principles. In particular, we argue that the common-sense viewpoint that “two hands save time by working in parallel” may not always be an effective way to think about two-handed interface design because the hands do not necessarily work in parallel (there is a structure to two-handed manipulation) and because two hands do more than just save time over one hand (two hands provide the user with more information and can structure how the user thinks about a task). To support these claims, we present an interface design developed in collaboration with neurosurgeons which has undergone extensive informal usability testing, as well as a pair of formal experimental studies which investigate behavioral aspects of two-handed virtual object manipulation. Our hope is that this discussion will help others to apply the lessons learned in our neurosurgery application to future two-handed user interface designs.

Categories and Subject Descriptors: I.3.6 [Computer Graphics]: Methodology and Techniques – Interaction Techniques; H.5.2 [Information Systems]: Information Interfaces and Presentation – User Interfaces – Input devices and strategies.

1 INTRODUCTION
The current paradigm for graphical user interfaces (GUI's) has been dubbed the "WIMP" (Windows, Icons, Menus, and Pointer) interface. Many WIMP graphical interaction techniques were originally designed for

\[1\] This research was performed while the first author was jointly affiliated with the University of Virginia Department of Computer Science and the University of Virginia Department of Neurological Surgery (under the auspices of the Neurosurgical Visualization Laboratory, a division of the Virginia Neurological Institute).

\[2\] During the course of this work, Randy Pausch was affiliated with the University of Virginia Department of Computer Science.

computers which, compared to modern machines, had low-powered processors and impoverished black- and-white displays [Baeccker et al. 1995]. Yet as computing technology becomes ubiquitous and the capabilities of processors, displays, and input devices continue to grow, the limitations of the WIMP interface paradigm become increasingly apparent. To get past this "WIMP plateau," devising new interface metaphors will not be enough. We need to broaden the input capabilities of computers and improve the sensitivity of our interface designs to the rich set of human abilities and skills.

There are many devices, displays, and interaction techniques which are candidates for the post-WIMP interface. Interestingly, no single candidate emerges as the "solution for all problems," but indeed post-WIMP interfaces seem to be characterized by a trend of divergence to special-purpose, application-specific interfaces and devices. Candidates identified by Nielsen [1993a] include virtual realities, sound and speech, pen and gesture recognition, animation and multimedia, limited artificial intelligence (in the form of "interface agents"), and highly portable computers. Kurtenbach et al. [1997] have explored a new GUI paradigm based on tablets, two-handed manipulation, and transparent user interface components. Weiser [1991] has proposed the ubiquitous computing paradigm, which suggests that networked computers will increasingly become integrated with ordinary implements and that computers will be embedded everywhere in the user's environment. We propose that multiple degree-of-freedom input with two hands is another such candidate for a style of post-WIMP interface.

Point designs (compelling demonstrations or examples) of post-WIMP interfaces exist for many of the areas mentioned above, but we assert that point designs alone will not be sufficient to take advantage of advanced interaction techniques. Parting with tradition is expensive and risky, and while a demonstration might be compelling, it cannot tell an interface designer how to generalize a proposed interface technique to a new situation. A demonstration also cannot answer questions about when a new interface technique should be used, why it should be used, or when it may (or may not) have measurable advantages for the user. One must perform careful scientific evaluation of interaction techniques to understand how to use a proposed technique as well as why a proposed technique may result in improved performance for the user. Without such knowledge, an interaction technique essentially must be re-invented every time a designer attempts to use it.

Perhaps the best-known archetype for how one should approach formal user interface evaluations is provided by Card's experimental comparison of the mouse and other input devices [Card et al. 1978]. Card formed mathematical models of each device and tested these models against observed performance data. Card found that the mouse was effectively modeled by Fitts' Law (see [MacKenzie 1992] for a good general discussion), which predicts movement time based on the amplitude of a movement and width of the target area. Furthermore, Card showed that the same model, with roughly the same parameters, modeled both movement with the mouse and movement with the hand alone. This suggests that designing an input device which allows one to point at targets more quickly than the mouse would be difficult to achieve.

Summarizing the philosophy of his approach, Card has written:

[User technology]... must include a technical understanding of the user himself and of the nature of human-computer interaction. This latter part, the scientific base of user technology, is necessary in order to understand why interaction techniques are (or are not) successful, to help us invent new techniques, and to pave the way for machines that aid humans in performing significant intellectual tasks. [Card and Moran 1995]

The work presented here seeks to follow Card's general approach: by formulating hypotheses and subjecting hypotheses to experimental tests, we not only describe a novel post-WIMP interface which incorporates multiple degree-of-freedom input devices and two-handed manipulation, but we also demonstrate fundamental mechanisms of human two-handedness and propose general design principles which suggest how and when our techniques may be useful.

1.1 What We Have Done

This work originated with a user interface for three-dimensional neurosurgical visualization (Figure 1). The user interface was designed and implemented with the support and collaboration of the University of Virginia Department of Neurological Surgery. The user interface is based on the two-handed physical manipulation of hand-held tools in free space. These user interface props facilitate transfer of the
neurosurgeon’s skills for manipulating tools with two hands to the operation of a user interface for visualizing 3D medical images, without need for training. From the surgeon’s perspective, the interface is analogous to holding a miniature head in one hand which can be "sliced open" or "pointed to" using a cutting-plane tool or a stylus tool, respectively, held in the other hand. The interface also includes a touchscreen which allows facile integration of 2D and 3D input techniques. Informal evaluations of over fifty neurosurgeons, as well as hundreds of non-neurosurgeons, have shown that with a cursory introduction, users can understand and use the interface within about one minute of touching the props.

![Image of a user viewing a cross-section of a brain using the interface props.](image)

Figure 1 A user views a cross-section of a brain using the interface props.

Although well-received both by neurosurgeons and by the community of human-computer interface (HCI) designers, the interface, by itself, is a point design which demonstrates multiple degree-of-freedom input with two hands. A primary goal for this work is to move beyond point design and to introduce careful scientific measurement of behavioral principles which were suggested by the original system implementation. Based on the synergy of (1) an interface design which has undergone extensive informal usability testing and (2) formal experimental evaluation, we make general points about two-handed interface design, virtual object manipulation, and human behavior, so that the lessons learned in the neurosurgery application can be applied to future user interfaces.

Before entering a more general discussion of two-handed interface design issues and our specific experimental studies, we describe our neurosurgical visualization system, its intended users, and their reactions to the interface. This will also motivate our experimental studies, and will ground these studies in a real-world application. But first, in the following section, we set the context for our research with a discussion of the related work in virtual environments and two-handed manipulation.

2 RELATED WORK

Researchers have explored uses for two hands in a number of experimental systems, including traditional 2D desktop interfaces, systems which (like ours) use two hands for a desktop virtual reality (VR) display, as well as fully immersive two-handed VR interfaces.

The VIDEODESK system [Krueger 1991] uses video cameras and image processing to track 2D hand position and to detect image features such as hand, finger, and thumb orientation. This approach leads to a rich vocabulary of simple, self-revealing gestures (such as pointing, dragging, or pinching) which do not require any explicit input device [Krueger 1993; Krueger et al. 1985]. For example, the index finger and thumb of both hands can be used to simultaneously manipulate four control points along a spline curve (Figure 2, left), or the finger tips can be used to sweep out a rectangle (Figure 2, right). The HoloWall provides another example of this style of interaction [Matsushita and Rekimoto 1997]. Recent work has also demonstrated real-time tracking of the human body under a wide range of viewing conditions [Wren et al. 1997].
The ToolGlass and Magic Lenses metaphor [Bier et al. 1993] consists of a semi-transparent menu which the user superimposes upon a target using a trackball in the nonpreferred hand. The preferred hand then moves the mouse cursor to the target and clicks through the menu to apply an operation to the target. Note that this integrates the task of selecting a command (or mode) from the menu and the task of applying that command to objects being edited.

The 3-Draw system is a computer-aided design tool which facilitates the sketching of 3D curves [Sachs et al. 1991]. In 3-Draw, the user holds a stylus in one hand and a tablet (similar to a painter’s palette) in the other. These tools serve to draw and view a 3D object which is seen on a desktop monitor. The tablet is used to view the object, while motion of the stylus is used to draw and edit the curves making up the object (Figure 3).

The Virtual Workbench [Poston and Serra 1996; Serra et al. 1997] displays 3D images on an opaque mirror in front of the user’s face (Figure 4, left). Since the mirror is opaque (rather than half-silvered), the images are completely computer generated, allowing correct occlusion cues to be maintained. The Virtual Workbench employs both hands to move physical tool handles which can have different virtual effectors attached to them, depending on the current mode. The Virtual Workbench has been developed with medical applications in mind, including support for tasks of interest in neurosurgical visualization, such as cross-sectioning a volume. Poston and Serra have not, however, performed any formal experimental evaluation of the design issues raised by the Virtual Workbench.
The Responsive Workbench [Cutler et al. 1997] provides two-handed manipulation on a stereoscopic, rear-projected tabletop VR display (Figure 4, right). The table top grounds the user in the environment and provides a natural working surface. Examples of two-handed interaction techniques supported by the system include two handed zooming, where the nonpreferred hand sets a focus point, while the preferred hand moves back and forth to zoom; rotation about an axis, where the nonpreferred hand specifies the axis of rotation, while the preferred hand performs the rotation; and "steering wheel" rotation, where both hands grab the model and twirl it.

Additional examples of two-handed interaction with free-space 3D input devices include the THRED two-handed polygonal surface design application [Shaw and Green 1994], the Worlds-in-Miniature3 metaphor [Stoakley et al. 1995], as well as recent work by Kiyokawa [1996; 1997] and Gribnau [1998]. Two-handed interaction using physical handles as input devices has been demonstrated by the Graspable User Interfaces project [Fitzmaurice and Buxton 1997; Fitzmaurice et al. 1995] and by the metaDESK [Ishii and Ullmer 1997; Ullmer and Ishii 1997].

Compelling commercial applications of two-handed interaction include Alias I Wavefront's StudioPaint [Alias I Wavefront Inc. 1997] (see also Kurtenbach's account of the research underlying this effort [Kurtenbach et al. 1997]), as well as MultiGen's SmartScene product [Multigen Inc. 1997] (based on research by Mapes and Moshell [1995]). Insightful examples from the research literature include Zeleznik's exploration of two-handed interfaces for SKETCH [Zeleznik et al. 1997; Zeleznik et al. 1996], the Ball and Mouse metaphor [Leblanc et al. 1991], and two-handed teleoperation [Stassen and Smets 1995]. Chatty has suggested general design issues for two-handed interfaces [Chatty 1994b] and has implemented a GUI toolkit which supports two-handed interaction [Chatty 1994a].

Applications for two-handed gesture with voice input have been explored by Bolt and Herranz [1992], Weimer and Ganapathy [1989], and by Hauptmann in a Wizard-of-Oz behavioral study [1989]. Recent work by Hinckley et al. [1998] also explores issues of integrating voice and two-handed manipulation.

2.1 Experimental Studies

Unfortunately, there are very few experimental studies which have analyzed two-handed interaction, and we are not currently aware of any formal studies which have analyzed two-handed tasks for three-dimensional manipulation. There is also an extensive literature of formal analyses of bimanual tasks in the psychology and motor behavior fields, but many of these studies have focused on hand lateralization issues (such as [Annett et al. 1979; Provins and Glencross 1968]) or tasks which require concurrent but relatively independent movement of the hands (such as bimanual tapping of rhythms [Cremer and Ashton 1981; Peters 1985; Wolff et al. 1977] and bimanual pointing to separate targets [Honda 1982; Marteniuk et al.]

3 We further discuss the Worlds-in-Miniature in the context of section 4.3.2 (Users Know Where Their Hands Are).
1984; Wing 1982). It is often difficult to interpret these findings from the standpoint of an interface designer.

There are valuable results in this literature, however. In particular, we have found work by Guiard [1987] in the motor behavior field to be extremely useful. Guiard’s work is unique because, instead of asking “Which hand is better?,” Guiard poses the question: “What is the logic of the division of labor between the hands?” This is much closer to the types of questions faced by designers of two-handed interfaces, who must decide which hand should perform what tasks, and who must define the mappings of two-handed input motion to output on the screen. We further discuss Guiard’s work in the context of section 4.1.3 (Connection with Guiard Work: Behavioral Principles Inform Design).

In the HCI literature, a classic study by Buxton and Myers [1986] demonstrated that two-handed input can yield significant performance gains for two compound tasks that were studied: a select / position task and a navigate / select task. Their results demonstrated that two-handed techniques were not only easily learned by novices, but also that the two-handed techniques improved the performance of both novice and expert users.

Kabbash et al. [1993] compared pointing and dragging tasks using the preferred hand versus the non-preferred hand. For small targets and small distances, the preferred hand exhibited superior performance, but for larger targets and larger distances, there was no significant difference in performance. Contrary to the traditional view that humans have one “good” hand and one “bad” hand, the authors concluded that “the hands are complementary, each having its own strength and weakness.” Guiard has extended the analysis of this study and has provided preliminary evidence which suggests that the nonpreferred hand exhibits a specialization for a larger scale of movement than the preferred hand [Guiard 1997].

A second experiment by Kabbash et al. [1994] studied compound drawing and color selection in a “connect the dots” task. The experiment evaluated the two-handed ToolGlass technique [Bier et al. 1993] described previously. The ToolGlass was used to select one of four possible colors for each dot. The results suggested that everyday two-handed skills can readily transfer to the operation of a computer, even in a short interval of time, and can result in superior performance to traditional one-handed techniques. This held true despite the benefit of years of practice subjects had with the one-handed techniques versus only a few minutes of practice with the two-handed techniques. Kabbash et al. also demonstrated that, if designed incorrectly, two-handed input techniques can yield worse performance than one-handed techniques.

2.2 Summary of Related Work

Two-handed input seems to be suitable for a wide range of tasks in both 2D and 3D interaction, although it is not clear in general what tasks are suitable for two-handed input, what input devices are required, or what advantages (or limitations) two-handed input might offer to the user. Using two hands for three-dimensional interaction is not in itself a new idea, but there are so few examples of such systems that the implementation and user interface design issues are still not well understood.

A handful of carefully planned and executed experimental studies have been performed, but to our knowledge no studies prior to our own work specifically address two-handed interaction in 3D. Such studies are needed to identify when and why two-handed interaction techniques should be considered, as well as to quantify human two-handed abilities, so that user interfaces that do incorporate two-handed interaction can be designed to match the underlying human skills.

3 SYSTEM DESCRIPTION

We now present the results of our own efforts to build a system incorporating two-handed interaction which supports the tasks of neurosurgical visualization. This in turn will set the stage for a detailed discussion of design issues and of the specific experimental studies which we have chosen to pursue.

Our system-building activities began not in a computer science laboratory, but rather in the office of an attending neurosurgeon who described to us some of his frustrations with commercially available 3D neurosurgical planning software. The software was so complicated that he could not use it. In order to view a model of the brain or to position a cutting plane with respect to the brain, the surgeon had to specify a set of six values with sliders labeled Yaw, Pitch, Roll, X, Y, and Z. As we talked, the surgeon picked up a
full-scale model of a skull from a table next to his chair. “When I'm thinking about a surgery, I'll often pick up one of these to help focus my thinking. Do you think you could do something like that? I want a skull I can hold in my hand.”

This was a classic case of an interface not speaking the user's language. Clearly our next step was to “know the user” by studying the intended users, their tasks, and their working environment [Nielsen 1993b]. We began to observe and learn about the needs and goals of neurosurgeons, their tasks of neurosurgical planning and visualization, and the context in which these tasks are performed. From these preliminary discussions and observations, our user interface and system design gradually took shape.

3.1 The Application Domain: Neurosurgery and Neurosurgeons

Neurosurgeons are driven to deliver improved patient care at a lower cost. While improving quality of care and reducing costs might seem to be at odds, in practice one can achieve both ends by reducing the time required to perform surgery. Operating room time itself is of course very expensive. But more importantly, the longer a patient's brain is exposed during a procedure, the greater the chance for expensive and life-threatening complications. A key factor to reducing operating room time is performing superior pre-surgical planning before the surgeon ever enters the operating room. Neurosurgery is inherently a three-dimensional activity; it deals with complex structures in the brain and spine which overlap and interact in complicated ways. To formulate the most effective surgical plan, the neurosurgeon must be able to visualize these structures and understand the consequences of a proposed surgical intervention, both to the intended surgical targets and to surrounding tissues.

Traditionally, neurosurgeons have planned surgery based on 2D slices, typically acquired through Magnetic Resonance Imaging (MRI). This restriction to 2D slices is not necessarily by preference. MRI is acquired as 3D volumetric data, and its presentation as a set of 2D slices is an artifact of limited computer technology. The 2D slice paradigm also restricts the images to appear in planes (known as the sagittal, coronal and axial planes) orthogonal to canonical axes through the patient's head. These three planes form the frame of reference in which medical students learn their anatomy, and as such they are the planes in which physicians can best understand and reason about the anatomy.

But many structures within the brain, and many surgical paths to these structures that are clinically useful, are oblique to these canonical views. For example, to reach a deep-seated structure, the neurosurgeon might follow a fold of the brain to reduce the amount of transected brain tissue. Traditionally, following an oblique trajectory to a target has been risky since it has been difficult or impossible to produce appropriate visualizations. This is why visualization of oblique slices is so important; it is difficult to understand the anatomy at oblique angles, so the surgeon wants to be able to see these views and relate them back to the more familiar canonical views.

3.2 Some System Requirements

All activity leading up to the surgery itself (including acquisition of the medical images, preparation of the patient in the operating room, and pre-surgical planning) occurs during a span of approximately 3-4 hours on the morning of surgery. To be clinically useful, a computer-based surgical planning system must be able to produce all of its results within this time window [Goble et al. 1995; Goble et al. 1994]. Since the principal neurosurgeon is extremely busy and may be providing care for several other patients, the actual time available for planning may be as little as fifteen minutes for the more straightforward cases.

Thus the user interface for a neurosurgical planning and visualization system must permit the surgeon to work quickly and efficiently. The surgeon must cope with frequent distractions, and therefore must be able to quickly detach from the user interface, both physically and cognitively. The interface must not encumber the surgeon with devices such as gloves or head-mounted displays that will be difficult to remove, and it must not have explicit modes that are easily forgotten during a phone call or a discussion with a colleague.

Software usability is crucial to get neurosurgeons to actually use advanced visualization software. We seek to facilitate use of our software by surgeons, without the need for technical assistance. Rather than typing in commands or moving sliders with a mouse, the neurosurgeon thinks in terms of real objects in real space; a three-dimensional user interface should allow the neurosurgeon to work and think in these same terms.
3.3 Interaction Techniques

3.3.1 Interface Design Philosophy
In our everyday lives, we are constantly confronted with tasks that involve physical manipulation of real objects. We typically perform these tasks with little cognitive effort, with both hands, and with total confidence in our movements. For many applications, a three-dimensional user interface should offer equally facile interaction.

To achieve this ease of manipulation, our interface allows the user to manipulate instrumented physical objects, which we call passive interface props [Hinckley et al. 1994a], in free space. Unlike traditional input devices, which exist solely to facilitate an artificial dialog with the computer, the input props also act as physical stand-ins (much like the “props” in a stage play) which help the user to reason about his or her task(s). The props have a dual nature: they not only facilitate communication with the computer, but they also help to make an abstract spatial relationship seem concrete to the user.

Although virtual reality gloves (for example, [Sturman et al. 1989; Zimmerman et al. 1987]) are based on the same six-degree of freedom magnetic tracking technology as our props\(^4\), we believe that glove-based input facilitates quite a different style of interaction than the dexterous physical manipulation afforded by the props. When using a glove to grab and manipulate imaginary objects, no matter how realistic the on-screen graphics are, the user does not experience the visceral kinesthetic and tactile feedback which comes from grasping a real-world object. When the user holds a physical tool, he or she has the haptic feedback provided by the tool itself to guide the motion of the hand, allowing all the degrees-of-freedom of the fingers, thumb, and palm to participate in the manipulation of the tool, giving the user considerably greater dexterity than is typically possible using a glove [Zhai et al. 1996b].

3.3.2 Real-Time Performance
Without the ability to render and manipulate images of the brain in real time, our approach to the interface would be infeasible. The system software has been designed to achieve high performance: typical interactive update rates are approximately 15-18 frames per second. During each frame, the system renders a simplified brain surface consisting of approximately 9,000 polygons and displays a cross-section from volumetric data which typically consists of 256 x 256 x 128 voxels (volume elements), each 2 bytes wide, for a total of 16 megabytes of volume data. The system software runs on a Hewlett Packard J210 workstation, with hardware polygonal acceleration.

3.3.3 Viewing Patient Data with a Head Prop
The surgeon uses a head prop to manipulate the individual patient's head data. The prop is a small doll's head which can be held comfortably in one hand. This is used as an absolute rotation controller: rotating the doll's head always causes the polygonal model of the patient's brain to rotate correspondingly on the screen.

The user can also control the image zoom factor by moving the prop towards or away from his or her body. Note that the zoom factor is actually based on the distance between the doll's head and the front of the screen. Furthermore, the virtual distance moved is actually a log transform of the physical front-back translation. Without this log transform, a front-back translation near the screen produces almost no effect on the zoom factor, whereas a movement near the user's body suddenly shoots the zoom factor beyond a useful range.

The doll's head provides only four degrees-of-freedom: three degrees-of-freedom for rotation plus one degree-of-freedom for the zoom factor. In the context of surgical visualization, moving the object left-right or up-down is typically not useful, so it is helpful to constrain the polygonal brain to appear at the center of the screen. This simplifies the manipulation task and users find it natural.

The scale of the doll's head does not match the scale of the actual patient data. The doll's head acts only as an orientation reference: touching the outer surface of the doll's head does not correspond to touching the outer surface of the virtual patient data. Scaling down the virtual patient data to roughly match the size of

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\(^4\) We use the Polhemus FASTRAK magnetic tracking system [Polhemus Navigation Sciences Inc. 1997].
the doll's head would result in a substantial loss of precision: one millimeter of real-world motion would then correspond to several millimeters of virtual motion.

Our original interface design envisioned a realistic skull-shaped prop, but we retreated from this approach because the doll's head provides sufficient tactile cues for manipulation and can be comfortably held in one hand. We also felt that using a realistic skull-shaped prop could lead to false user expectations. A neurosurgeon using a realistic skull might assume a precise registration between the real skull and the virtual head which simply does not exist. When using a more abstract form such as the doll's head, surgeons do not expect the prop to precisely match the brain model, so this false expectation does not arise.

We have tried using a small rubber ball instead of the doll's head, but users prefer the doll's head because it is much richer in tactile orientation cues. The orientation cues help users to feel the orientation of the input device without looking at it, and the cues suggest appropriate behavior for three-dimensional manipulation: a common first instinct is to roll the ball-shaped device on the desk [Hinckley et al. 1997c], but users will instead pick up the head. The doll's head itself also provides a certain amount of marketing appeal and serves as a memorable icon for the interface.

3.3.4 Slicing the Patient Data with a Cutting-Plane Prop

The surgeon can also employ a cutting-plane prop to specify the position and orientation of an oblique slice through the brain data. The prop is a rectangular plate with a housing for the tracker (Figure 5). Users can spread their fingers across the plate to get a direct haptic sense of how it is oriented in space. The appearance of the cutting-plane prop differentiates it from the head prop and makes its purpose immediately obvious.

![Figure 5](image)

Figure 5 The user indicates a cross section by holding a clear plastic plate up to the doll's head. The computer shows a corresponding virtual plane intersecting the virtual head, along with a cross-section of the volumetric brain data.

The cutting-plane prop is used in concert with the head prop rather than as a separate tool. The user holds the cutting-plane prop against the head to indicate a slice through the brain data. The computer shows a corresponding virtual plane intersecting the virtual head, along with a cross-section of the volumetric head data (Figure 5). The user can interactively sweep the cutting plane back and forth at different angles to explore the volume. Because of the real-time update rate, users can quickly develop a sense of the objects embedded within the volume. For example, structures which are difficult to visualize when viewing orthogonal slices can now be easily found and inspected: Figure 6 shows a user moving the cutting-plane prop, over a period of a few seconds, to expose the optic nerves. Note that the virtual representation of the cutting-plane prop is a semi-transparent rectangle. The transparency helps users to acquire a desired target: it provides a simple occlusion cue while maintaining the context of what is in front of or behind the plane [Zhai et al. 1996a]. Selecting a cross-section is much more difficult if the plane is opaque.
The reader can easily approximate our interface. Seat yourself in a chair with armrests. Grasp a ball in one hand and a small book in the other. While supporting your elbows with the armrests, hold the book up to the ball, and orient each as deemed necessary. This is all that the interface requires for cutting plane selection.

Note that the cutting-plane prop has an embedded thumb button, which acts as a clutch to allow or disallow movement of the virtual plane. The user holds down this button while moving the plane, and then releases it when the desired slice is found, thereby freezing the virtual plane in place so that it stays embedded in the polygonal brain. The thumb button is good for “walk up and use” demonstrations, but holding down or releasing the thumb button can interfere with manipulation. To allow for maximum precision and dexterity, we also provide a footpedal which can substitute for the thumb button.

To provide visual correspondence, the virtual representation of the cutting-plane prop follows all six degrees-of-freedom of the physical tool. But several of these degrees-of-freedom do not affect the cross-section of the object, because (mathematically) the resulting plane has only four degrees of freedom. In fact, all 12 degrees of freedom from both input devices can influence the display, but only 8 degrees of freedom are important. For example, rotation about the axis normal to the cutting-plane does not affect the cross section. Similarly, if the tool is moved left-to-right in the current plane, this does not affect the resulting plane equation. Thus, the potential problem of the two input props colliding is not a significant problem at all: holding the cutting-plane prop next to the doll’s head produces the same cross-section as if the two objects were physically embedded in one another.

3.3.5 Indicating Surgical Paths with a Trajectory Prop

The trajectory selection prop is a stylus-shaped tool (Figure 7) that allows the surgeon to specify 3D vectors and points. Moving the trajectory prop relative to the head prop specifies the position and orientation of a cylindrical virtual probe relative to the polygonal brain model. The trajectory prop indicates the vector by its orientation relative to the head prop. The target of the trajectory is indicated by the intersection of a ray cast from the virtual probe and the brain model’s surface. Points which lie on the interior of the brain model can be selected by first bisecting the volume with the cutting plane to expose the contents of the volume, and then selecting a point on the exposed surface. Note that in this case the plane not only exposes the interior of the data, but it also expresses constraint of the point indicated by the trajectory prop to a plane, without requiring an explicit mode to do so.
3.3.6 Touchscreens for Hybrid 2D and 3D Input

Our user observations suggested that the interface props excelled for 3D manipulation, but when 2D tasks such as panning or zooming an already-selected slice arose, we found that there was an awkward pause while the user put down the props to move the mouse or to use the keyboard. To address this shortcoming, we added a touchscreen sensor to the monitor used with the interface props [Hinckley et al. 1995].

With this straightforward change, 2D tasks became much more facile: the surgeon can move in 3D using the props, and then without having to put the props down, the surgeon can reach out and touch the screen, since the hand is sufficiently free to extend a finger or knuckle (Figure 8). This provides a consistent input medium for both 2D and 3D interaction: one interacts gesturally with the props to perform 3D operations; one interacts gesturally with the touchscreen to perform 2D operations.

The touchscreen graphical user interface supports tasks such as panning and zooming, adjusting image contrast and brightness, browsing or precisely stepping through slices along a constrained axis, rearranging the screen real estate (by dragging the tiled windows), and selecting images from a patient database. For example, once an oblique slice has been selected with the props, this is made available as a 2D slice; the touchscreen interface then allows the user to view adjacent slices that lie along the same oblique axis.

The touchscreen interface provides virtual thumb wheels (fig. 8, right) to allow manipulation of image brightness, contrast, and zoom factor, as well as constrained slice-by-slice navigation. When a user touches and drags the touchscreen thumb-wheels, a background texture displayed on the wheel slides back and forth, giving immediate visual feedback for the user's action. Using a standard scrollbar on a touchscreen completely fails in this regard, since the user's finger occludes the thumb of the scrollbar, robbing the user of all visual feedback from the widget.
While promising, our implementation of the hybrid 2D and 3D interface concept has some shortcomings. In particular, the surface acoustic wave (SAW) touchscreen technology which we use is not ideal because it can detect contact only from soft objects such as a finger, yet users often try to touch the screen with the props themselves. We expect that a resistive membrane (RM) touchscreen would support these interaction techniques well because RM touchscreens can detect contact from a much wider range of materials.

3.3.7 Informal Evaluation: Notes on User Acceptance

The most valuable tool for evaluating and improving the interface design has been informal observation of test users. Indeed, without the cooperation and close collaboration of neurosurgeons, this work would not have been possible. Over the history of the project about 50 neurosurgeons have tried the props-based interface during informal observation sessions. We have also tested the interface with many other types of physicians who work with volumetric data, such as neurologists, cardiologists, and orthopedic surgeons.

The methodology for testing was simple but effective. On some occasions we set up the system in the hospital or another location convenient for the surgeons, but more often surgeons would visit our Neurosurgical Visualization Laboratory for an informal demonstration. We began by briefly showing the system to the neurosurgeon. Many surgeons were eager to try it and would jump in themselves without needing an invitation. If the surgeon seemed to have difficulty using the interface, rather than immediately intervening with advice or suggestions, we would wait for the surgeon to ask a question or make a comment. In this way, we could understand a problem in the terms the surgeon was using to think about it. Surgeons usually offered opinions, advice or suggestions without any need for prompting. This would start a discussion where we would also ask the surgeon about particular problems we had observed, what they saw as capabilities or limitations of the interface, and how the prototype interface might be augmented to become a clinical tool.

Neurosurgeons have been very enthusiastic about the props-based interface. All of the neurosurgeons who have tried to use the interface were able to use it within about one minute of touching the props. This clearly demonstrates that with a cursory introduction, neurosurgeons who have never before seen the interface can rapidly apply their existing skills for manipulating physical objects with two hands, and can understand and use the interface without training.

We have also performed hands-on demonstrations to hundreds of users from a broad sample of the general public. These informal observations strongly suggest that people in general, and not just skilled and dexterous surgeons, can use both hands to perform 3D manipulation tasks.

4 TWO-HANDED MANIPULATION

A traditional common-sense argument for why two-handed interaction might offer advantages for user interfaces is that "two hands save time by working in parallel." This conclusion may be quite persuasive from the point of view of a computer scientist designing a two-handed interface and writing software to handle input events. As far as a program's input device handler is concerned, two-handed interaction simply provides a pair of concurrent input streams which can be used however the application deems fit. Without some knowledge about how humans use two hands, there is no reason to treat the degrees-of-freedom from one hand any differently than those from the other.

We would like to suggest that this may not always be the best way to think about the problem of designing and implementing two-handed interfaces. The common-sense argument is partially true, but it is also partially false. To demonstrate this, the common-sense argument has two main points that we would like to analyze:

Two hands work in parallel: While there may be temporal overlap in the action of the two hands, thinking of the hands as two abstract motors working in parallel is not always appropriate because there is in fact a structure to bimanual manipulation. Particularly in the case of precision tasks, the action of the preferred hand is organized relative to the dynamic reference frames formed by the nonpreferred hand.

Two hands save time: We believe that using both hands can indeed help users to perform tasks more quickly, but this is only half of the picture. With appropriate design, two hands are not just faster than one hand, but the two hands together can provide the user with additional information that one hand alone
cannot. Using both hands can also change how users think about a task by influencing the user’s problem solving strategy.

The above statements form the foundation for our subsequent analyses and experimental work. To support these statements, we will discuss how these points apply in the context of our neurosurgical visualization interface design, and we will also present an experimental study to formally address each point. We present our experimental studies and results in this article, but note that more complete treatments of each study are available elsewhere [Hinchley 1997; Hinchley et al. 1997a; Hinchley et al. 1997b]. We encourage experimenters wishing to precisely reproduce these studies (or readers interested in exhaustive data analyses) to consult the more detailed accounts. Our goal for this article is to present a unified overview of this work and its main results.

4.1 The Nonpreferred Hand as a Dynamic Frame of Reference

We claim above that there is a structure to bimanual manipulation. An important design principle is for the interface to preserve the mobile, dynamic role of the nonpreferred hand as a base frame of reference. Unlike a clamp (whether physical or virtual), the nonpreferred hand provides mobile stabilization [Guiard 1987]. The nonpreferred hand adjusts to and cooperates with the action of the preferred hand, allowing users to restrict necessary hand motion to a small working volume.

Our system implementation embodies this design principle by mapping the input degrees of freedom from the two hands such that all motion of the plane or stylus (held in the user’s preferred hand) is interpreted as relative to the doll’s head (held in the user’s nonpreferred hand). For right handers, the left hand specifies a base frame of reference relative to which the right hand expresses a second active frame of reference.

This design principle can lead to some apparent contradictions of conventional design wisdom. First, a commonly accepted user interface design principle is that the mapping of motion of objects on the screen should directly correspond to the motion of the user. We claim that a direct 1:1 motion mapping does not necessarily satisfy the design principle that the nonpreferred hand acts as the base frame-of-reference. Our system exhibits a non-corresponding motion artifact which contradicts the “1:1 motion mapping” principle, yet nonetheless leads to an interaction technique which seems natural to users.

Second, in the existing literature on virtual manipulation, it is often assumed that the system must provide a means of “clutching” objects. Clutching allows users to leave objects frozen at a particular position and orientation; see Hinchley et al. [1994b] for a discussion of some design issues influencing clutching and recalibration mechanisms. We claim that, while clutching is often useful, this is not always true: bimanual manipulation seems to work best when there is no clutch for the base frame of reference formed by the nonpreferred hand.

4.1.1 Non-Corresponding Motion Artifact

As mentioned earlier (in section 3.3.3, Viewing Patient Data with a Head Prop), the doll’s head provides just four degrees of freedom of motion because the polygonal brain is constrained to appear at the center of the screen. The brain is the natural central object of the manipulation and exploration supported by the interface. This design decision interacts with two-handed control and leads to an interaction technique which does not strictly copy physical reality, yet nonetheless seems quite natural.

Users do expect the real-world spatial relationship between the doll’s head and the cutting-plane prop to be mirrored by their on-screen graphical representations. Simplifying control of the polygonal brain by centering it on the screen, however, requires a software mapping of its real-world position to its centered

---

1 Britton et al. [1978] propose the kinesthetic correspondence principle, which states that “when the user’s hand moves a device, the image controlled by the device should move in the same direction.” Similarly, when discussing input mappings, the textbook Readings in Computer-Human Interaction: Towards the Year 2000 suggests that “Mappings describe the relationships between controls and their effects on a system. For example, moving a control to the left should move a corresponding display object left” (Baekcker et al. 1995, page 1).

2 For example, Liang and Green [1993] report that “since [a 6DOF tracker] is an absolute locator, a clutch mechanism is necessary for re-mapping its physical location into a logical location.”

3 For clarity, throughout this section we discuss our interaction techniques as they apply to the cutting-plane prop, but note that the same input mappings also apply to the trajectory selection prop.
position by constraining the left-to-right (X axis) and up-down (Y axis) translations (note that no such mapping is required for the orientation of the prop). Define the position of the head prop in the real world as \((H_{RX}, H_{RY}, H_{RZ})\). If the center point of the screen is defined as \((C_x, C_y)\), then the virtual constrained head position is given by the following:\(^8\)

\[
(H_{VX}, H_{VY}, H_{VZ}) = (C_x, C_y, H_{RZ})
\]

When the user moves the cutting plane prop relative to the doll’s head, the user expects to see this relative motion mirrored on the screen. This implies that the virtual representation of the cutting plane prop is drawn relative to the virtual position of the head prop. That is, the virtual position of the plane is equal to the virtual position of the head plus the real-world offset \((\Delta_x, \Delta_y, \Delta_z)\) between the head prop and the cutting plane prop. Define the position of the cutting plane prop in the real world as \((P_{RX}, P_{RY}, P_{RZ})\). The offset \((\Delta_x, \Delta_y, \Delta_z)\) is then given by:

\[
(\Delta_{xx}, \Delta_{yy}, \Delta_{zz}) = (H_{RX}, H_{RY}, H_{RZ}) - (P_{RX}, P_{RY}, P_{RZ})
\]

and the virtual position of the plane is given by:

\[
(P_{VX}, P_{VY}, P_{VZ}) = (H_{VX}, H_{VY}, H_{VZ}) + (\Delta_{xx}, \Delta_{yy}, \Delta_{zz})
\]

This mapping results in the following non-correspondence artifact: if the user holds the cutting-plane prop still and translates only the head prop, the polygonal brain will remain centered (because its x, y coordinates are still constrained to the center of the screen) and the virtual plane will move in the opposite direction. This violates the generally accepted 1:1 motion mapping principle, but it adheres to the design principle that the object in the nonpreferred hand (the doll’s head) should form the base frame of reference. In hundreds of informal user trials, we have found that users almost never discover this non-corresponding motion artifact, because they typically hold and orient the doll’s head in a relatively stable location while moving the cutting plane prop relative to it. In this case, motion corresponds to the user’s actions, and the net result is that the interaction behaves exactly as users expect it would.

This input mapping has another subtle effect on user behavior: since the nonpreferred hand now defines a dynamic frame of reference relative to which all manipulation occurs, this means that the user is not forced to work relative to the screen itself or relative to some center point within the environment, as required by one-handed desktop VR interfaces that employ free-space input devices [Deering 1992; Liang and Green 1993]. Users are at liberty to shift their body posture, to hold their hands at a comfortable position on the desk surface, or even to hold them in their lap. There is also no need for a “homing” or re-centering command to move the center point, since the nonpreferred hand automatically and continuously performs this function just by holding the doll’s head.

4.1.2 No Clutch for the Base Frame of Reference

The design principle that the interface should preserve the mobile, dynamic role of the nonpreferred hand as a base frame of reference appears once again in the design of the clutching interface. We initially expected that our interface design would require a mechanism to tell the computer to "stop watching" a particular prop, thereby allowing the user to freeze the image in a desired configuration and put down the props. And as mentioned previously (in section 3.3.4, Slicing the Patient Data with a Cutting-Plane Prop), the cutting-plane prop does have a thumb button which allows the user to leave the plane embedded within the polygonal brain.

In our original interface design, we also included a footpedal which allowed the user to "clutch" the doll’s head, causing the polygonal brain to remain fixed in place. Nonetheless, extensive user testing has suggested that the interface is easiest to use when there is no clutch for the doll’s head.

Freezing (or “clutching”) the polygonal brain in place initially seemed like a useful thing to do, but we found that if the doll’s head was clutched, it was no longer useful as a reference. We have watched many users clutch the head and then become confused as they subconsciously begin to move their nonpreferred

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\(^8\) The system actually performs a log transformation on the zoom factor. Thus \(H_{VZ}\) is mapped to a function of \(\log(H_{RZ})\). As long as a corresponding log transform is also applied to the Z coordinate of the cutting plane, \(P_{RZ}\), this log transform does not affect the mapping described in this section.
hand to aid the action of the preferred hand, only to have no effect. If the footpedal is used to freeze the polygonal brain, the user is again forced to move relative to a fixed point in the environment, rather than relative to the reference frame specified by the nonpreferred hand. After gaining some experience with the interface, users generally tended to constantly hold down the footpedal for the doll’s head anyway, thereby constantly enabling motion. This questions whether the head clutch serves any real purpose other than to initially confuse users.

Threading a needle provides an interesting parallel example from the real world: logic tells us that it should be easier to thread a needle if it is held motionless in a clamp, while the preferred hand holds the thread to guide it through the eye of the needle. Holding the needle in the nonpreferred hand introduces a second moving thing and should make the task more difficult. But using both hands instead makes the task easier: when faced with a stationary needle, the first instinct is to grab it with the nonpreferred hand. The nonpreferred hand acts as a dynamic and mobile clamp which can skillfully coordinate its action with the requirements of the preferred hand.

In our current interface design, the polygonal brain is always allowed to move. The interface does provide the ability to grab a still image “snapshot” in a separate window of the GUI by touching a button on the touchscreen (while the other hand holds the doll’s head). Thus, this design does not have the side-effect of interfering with further manipulation because the moving polygonal brain is always available. With this capability, there is no apparent need for a head clutch that freezes the polygonal brain itself, except in unusual circumstances, such as when a user without the ability to use both hands wishes to operate the interface. For such situations, it is still possible to use a footpedal for clutching the doll's head, but this behavior is not enabled by default.

4.1.3 Connection with Guiard Work: Behavioral Principles Inform Design

Guiard’s analysis of human skilled bimanual action [1987] provides an insightful theoretical framework for classifying and understanding the roles of the hands. Guiard has proposed the Kinematic Chain as a general model of skilled asymmetric 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 Kinematic Chain model hypothesizes that the preferred and nonpreferred hands make up a functional kinematic chain: for right-handers, the distal right hand moves relative to the output of the proximal left hand. Based on this theory and observations of people performing bimanual tasks, Guiard proposes three high-order principles governing the asymmetry of human bimanual gestures, which can be summarized as follows (assuming a right-handed subject):

1. **Right-to-left reference**: Motion of the right hand typically finds its spatial references in the results of motion of the left hand. For example, when writing, the nonpreferred hand controls the position and orientation of the page, while the preferred hand performs the actual writing by moving the pen relative to the nonpreferred hand.

2. **Asymmetric scales of motion**: The right and left hands are involved in asymmetric temporal-spatial scales of motion. The right hand specializes in rapid, small scale movements; the left, in slower, larger-scale movements. During handwriting, for example, the movements of the left hand adjusting the page are infrequent and coarse in comparison to the high-frequency, detailed work done by the right hand.

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

Looking beyond the hands, one might also apply the Kinematic Chain model to reason about multiple effector systems ranging from the hands and voice (playing a piano and singing [Guiard 1989]), the hands and feet (operating a car’s clutch and stick shift), or the multiple fingers of the hand (grasping a pen).

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* For a left-handed subject, the roles of the right and left hands would be reversed for each of these principles.
It is quite compelling that the behavioral principles proposed by Guiard (in particular, the first principle of right-to-left reference) closely parallel our proposed design principle (of the nonpreferred hand as a dynamic frame of reference) as well as the input mappings described earlier. Although our initial implementation of the interface preceded our exposure to Guiard, Guiard's work has been instrumental in helping us to understand why the design worked, and to formulate our subsequent experimental work. We believe this is an example of a more general synergy between behavioral principles, often proposed by the psychology community, and design principles, sought after by the human-computer interaction community. Behavioral science has direct application to design: human-computer interaction can profit from increased collaboration with perceptual psychologists, cognitive psychologists, and motor behavior researchers.

4.2 Experiment 1: The Structure of Two-Handed Manipulation

Experiment 1 is a test of Guiard's right-to-left reference principle, which essentially states that there is a hierarchical structure to bimanual manipulation. In the original work where Guiard proposes this principle [Guiard 1987], he discusses a series of everyday actions (such as handwriting, sewing, and swinging a golf club) and provides a convincing qualitative argument that the actions assigned to each hand follow the right-to-left reference principle. Guiard also describes a tapping experiment (Fitts' task) with a bimanually held rod [Guiard 1995], which demonstrates an asymmetric partition of labor between the two hands, but does not directly address the hypothesis of right-to-left reference.

Beyond the above-mentioned studies by Guiard, most previous behavioral studies of bimanual movements have studied the two hands performing relatively independent subtasks [Annett et al. 1979; Cremer and Ashton 1981; Honda 1982; Marteniuk et al. 1984; Peters 1985; Provins and Glencross 1968; Wing 1982; Wolff et al. 1977]. While such experiments can yield many insights, they do not necessarily reveal effects which involve the hands working together to achieve a common goal.

To test the hypothesis that there is a structure to two-handed manipulation, we employ a cooperative pointing task where the subject manipulates a tool in one hand and a target in the other hand (Figure 9) [Hinckley et al. 1997b]. Both hands are free to move, and a symmetric or parallel style of motion is therefore left as a possibility (assuming the null hypothesis that there is no structure to bimanual manipulation).

![Figure 9](image)

A subject performing the experimental task.

The experimental task can be thought of as a two-handed version of Milton-Bradley's game "Operation." The subject tries to move the tool such that it touches a small gold-colored target area at the bottom of a slot on the target object; if the subject misses, an annoying buzzer signals an error. The target area itself is also wired to a circuit that sounds a pleasant beep when the subject succeeds. The target area is only slightly larger than the tool, so the task requires dexterity to perform successfully. Subjects are instructed that avoiding errors is more important than completing the task quickly.
4.2.1 Experimental Design

The experiment looks at two factors of interest, the Grip and the Difficulty. Each subject performed the experiment 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). Each subject also performed two versions of the task, an Easy task and a Hard task. The Hard task requires hitting a small gold-colored target area on the target object, as described above. 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 is turned off and no “errors” are possible. In this case, we instructed the subject to optimize strictly for speed. We used a fully crossed latin square design to counterbalance for order of presentation effects, resulting in four experimental conditions: Preferred-Hard, Preferred-Easy, Reversed-Hard, and Reversed-Easy.

We included only right-handed subjects in the study, because hand usage patterns in left-handers tend to be somewhat more chaotic than those in right-handers. Also, the general issues posed by handedness are surprisingly complicated (Guiard 1995; Halpern 1992), and without a clear understanding of two-handed manipulation in right-handers, it seems premature to address the behavioral strategies used by left-handers. Nonetheless, we expect left-handers should exhibit a similar (but less consistent) pattern of findings to those reported here.

We performed this experiment using instrumented physical objects, rather than virtual objects. Since the purpose of the experiment is to look at basic aspects of bimanual motor control, we felt that by using physical objects we could be certain that we were measuring the human. Virtual 3D manipulation introduces a number of potential confounds, including artifacts caused by the particular depth cues employed, the display frame rate, the input device precision, and input device latency, to name a few. Nonetheless, we expect it would be possible to extend this experiment to a virtual 3D manipulation task, and we would like to explore this issue in a future study.

We also used two different tools (a plate and a stylus) and three different target objects (a puck, a triangle, and a cube). Using multiple objects helped to guarantee that our findings would not be idiosyncratic to one particular implement, and the multiple objects also helped to give users something to think about during the experiment other than what they were doing with their hands.

![Figure 10](image)

*Left:* experiment configuration. The monitor seen at the far end of the table displays the stimuli for each trial.

*Right:* sample screen showing experimental stimuli.

For the Hard task, the dependent variables are time and errors (a pass / fail variable). For the Easy task, since no errors are possible, only time is measured. Time is measured from when the tool is removed from the platform (*seen in Figure 10*) until the tool touches the target area; this measure does not include the time to initially grasp the tool or to return the tool to the platform when done with the task.

Sixteen unpaid subjects (8 males, 8 females) from our psychology department’s undergraduate student subject pool participated in the experiment. All subjects were strongly right-handed. 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, with a short break between conditions.
4.2.2 Experimental Hypotheses

The main hypotheses for this experiment were as follows:

**H1:** The Hard task is asymmetric and the hands are not interchangeable.

**H2:** The importance of the structure of bimanual manipulation increases as the task becomes more difficult.

Taken together, these hypotheses imply that there will be less difference between the Reversed and Preferred grips for the Easy task.

4.2.3 Limitations of the Experiment

There are several factors which limit the sensitivity of this experiment. First, we would like to have a range of experimentally controlled difficulties analogous to the Index of Difficulty (ID) for Fitts' Law. 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 pass/fail outcome. Thus, we have no data for the magnitude of the errors made when 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.

4.2.4 Results

We performed a 2 (Tool: plate or stylus) X 3 (Object: cube, puck, or triangle) X 2 (Task: easy or hard) X 2 (Grip: preferred or reversed) analysis of variance with repeated measures on the completion time outcome measure. Overall, the preferred Grip was significantly faster than the reversed Grip ($p < .0001$) and the easy Task was significantly faster than the hard Task ($p < .0001$). But, as predicted, the significance of the Grip factor varied with the experimental Task (Figure 11). For the hard Task, the preferred and reversed grips differed significantly ($p < .0001$) but for the easy task they did not ($p < .10$, not significant). The resulting Grip X Task interaction was also highly significant ($p < .0005$).

![Figure 11](image)

The difference between the preferred and reversed grips varies with the difficulty of the task.

The above pattern of results strongly support both of our main experimental hypotheses. The hands are clearly not interchangeable for the Hard task, but for the easy task reversing the roles of the hands has no
reliable effect. The resulting Grip X Task interaction effect strongly supports our hypothesis that the importance of the structure of bimanual manipulation varies with task difficulty. Another way of saying this is that the effect on completion time of making the task harder is greater with the Reversed Grip assignment than with the Preferred Grip assignment.

Table 1 shows a summary of the overall performance data. Note that the difference in times reported for the Hard conditions was not due to a time / accuracy trade-off, as 14/16 subjects made fewer or the same number of errors in the Preferred-Hard condition versus the Reversed-Hard condition. In the Hard conditions, the relatively high error rates shown below resulted from the difficulty of the task, rather than a lack of effort. We instructed subjects that "avoiding errors is more important than speed," a point which we carefully emphasized several times.

<table>
<thead>
<tr>
<th></th>
<th>Easy</th>
<th></th>
<th>Hard</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard</td>
<td>Error Rate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(seconds)</td>
<td>Deviation</td>
<td></td>
<td>(seconds)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Standard</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Deviation</td>
</tr>
<tr>
<td>Preferred</td>
<td>0.76</td>
<td>0.15</td>
<td>0%</td>
<td>2.33</td>
</tr>
<tr>
<td>Reversed</td>
<td>0.83</td>
<td>0.19</td>
<td>0%</td>
<td>3.09</td>
</tr>
</tbody>
</table>

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

We also investigated the possibility of bias in the results due to unintended effects. Neither Order of presentation nor Error vs. Non-error trials were significant factors. The Tool and Object factors were significant (p<.05) but neither factor influenced our main findings. Gender was a significant factor (p<.05), with female subjects performing slightly faster than male subjects for the hard task only. Separate analysis of male and female subjects confirmed that our main findings were all significant for both groups.

Overall, these results strongly support Guiard's proposed right-to-left reference principle, suggesting that there is a structure to bimanual manipulation, with optimum performance occurring when the preferred hand works relative to the frame of reference specified by the nonpreferred hand. The results do not support the hypothesis that the hands can be modeled as independent input streams working in parallel. Finally, our results show that the referential division of labor between the hands has the greatest performance advantage in the case of dexterous and precise manipulation.

4.3 Two Hands are Not Just Faster Than One Hand

In our introductory discussion of two-handed manipulation (section 4), our second major claim was that two hands are not just faster than one hand. We cited two reasons for this claim: first, using both hands can influence how users think about a task; and second, using the two hands together can provide information that one hand alone cannot. We now return to this claim, discuss its implications for two-handed interface design, and present a second study which investigates these behavioral issues.

Our first point here is that providing a two-handed interface can change the syntax of the user's interaction with a system, and the syntax of manual interactions directly structures how the user thinks about a task. Using our interface props, a user can express complex spatial relations (such as a cut relative to a particular brain orientation) in a single two-handed action. Not only does this make the interaction concurrent (as opposed to being sequentially moded), but it also results in an interface which more directly matches the task that the user has in mind. Thus, two-handed manipulation can potentially change how users think about a task. This viewpoint has been advocated by Buxton, who in previous work has claimed that "the physical articulation of a task can influence cognitive aspects of performance" [Buxton 1990; Leganchuk 1995].

A second important point is that users know where their hands are. Users can effortlessly move their hands relative to one another, but it requires a conscious effort to move a single hand relative to an abstract 3D space. Commenting on the design of the 3Draw system, Sachs has claimed that "the simultaneous use of two [3D input] sensors takes advantage of people's innate ability—knowing precisely where their hands are relative to each other" and that "users require far less concentration to manipulate objects relative to each

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10 Recall that no errors were possible in the Easy task. Thus, the "error rate" was 0% by definition. We have included error rate in this table to remind the reader of this point.
other than if one object were fixed absolutely in space while a single input sensor controlled the other” [Sachs et al. 1991]. The crux of this distinction is the difference between body-relative versus environment-relative motions, and the impact this can have on the user’s visual attention and his or her dependence on visual feedback.

4.3.1 Two-Handed Input Can Change How Users Think About a Task

One might argue that using two hands to operate an interface only adds complexity and makes an interface harder, not easier, to use—after all, it is difficult to "rub your head and pat your stomach at the same time." There are many compound tasks, however, such as navigation and selection in a text document or positioning and scaling a rectangle, which users perceive as integral attributes [Jacob et al. 1994] that are aspects of a single cognitive chunk [Buxton 1986]. When designed appropriately, a two-hand interface for integral compound tasks does not necessarily impose a cognitive burden, and can help users to reason about their tasks.

Figure 12 illustrates how our neurosurgical visualization interface simplifies the compound task of selecting a cutting-plane relative to a specific view of the polygonal brain. Cutting relative to a view consists of two sub-tasks: viewing and cutting. Viewing can further be subdivided into orienting the brain and specifying a zoom factor, and so forth. At the lowest level, there are ten separate control parameters (yaw, pitch, roll, and zoom for the view; x, y, z, yaw, pitch, and roll for the cutting tool) that can be specified. In a sliders or knob-box implementation of this interface, the user would have to perform ten separate one-dimensional tasks to position the cutting plane relative to a view, resulting in a user interface which is nearly impossible to use. Using the props with both hands, however, reduces this entire hierarchy into a single transaction (cognitive chunk) which directly corresponds to the task that the user has in mind. As a result, the user perceives the interface as being much easier to use.

![Task hierarchy for selecting a cut relative to a specific view.](image)

This framework, suggested by Buxton’s work on chunking and phrasing [Buxton 1986], is useful for reasoning about the differences between one and two-handed interfaces. With a one-handed interface, View and Cut would always have to be performed as purely sequential subtasks. There is also the need to switch back and forth between viewing and cutting, so this implies a third sub-task, that of changing modes. Changing modes might involve acquiring another input device, speaking a voice command, or moving the mouse to another region of the screen, but all of these mode switching techniques take a non-zero amount of time. This process can be modeled as a simple state diagram (Figure 13).

![State diagram](image)
A two-handed interface changes the syntax for this task. Under bimanual control, a new meta-task with a single *Cut Relative to View* state becomes possible. The simultaneous *Cut Relative to View* task is not the same thing as the serial combination of the sub-tasks. The simultaneous task allows for hierarchical specialization of the hands, and there is no cost (or need) to switch between *View* and *Cut* subtasks. Since the *View* and *Cut* subtasks can be integrated without cost, this encourages exploration of the task solution space. And since the user never has to engage in a *Change Modes* sub-task, there is no possibility for this extraneous sub-task to interfere with the user's primary goal of viewing and cutting. Thus, by altering the structure of physical transactions with the interface, two-handed input can also impact the user's performance at the cognitive level.

### 4.3.2 Users Know Where Their Hands Are

In the real world, we typically have haptic feedback (contact with physical objects) to guide our actions. But in computer-generated worlds, this is rarely the case. Manipulation in virtual environments often depends heavily on visual feedback techniques. For example, in the case of selecting a virtual object using a glove, the user must visually attend to the object (watch for it to become highlighted) before selecting it. This is often acceptable, but can potentially lead to problems of split attention: for example, what if the user is monitoring an animation while trying to pick up a tool?

Two-handed interaction offers one form of *passive haptic feedback* that can help to address this type of problem. We use the term passive haptic feedback to describe the information which the user's own manual movements provide for feedback during manipulation. This includes *proprioception*, which is the reception of stimuli produced within the body, and *kinesthesia*, which is the natural sense of bodily movements and tensions, as well as the haptic feedback provided as the user grips or manipulates the input devices themselves. This feedback is passive only in the sense that the computer can't directly control or alter these sensations. But the design of user interfaces can and should take passive haptic issues into account to provide a human-computer dialogue which is natural and which takes full advantage of these human capabilities and sensations.

Using both hands can help users to ground themselves in the interaction space by encouraging movement in a body-relative space, as opposed to an abstract environment-relative space. A comparison of a 3D sculpting interface [Galyean and Hughes 1991] and the Worlds-in-Miniature technique [Stoakley et al. 1995] highlights this point. In Galyean and Hughes's 3D sculpting interface, the user deforms a 3D model by positioning a single tracker in an absolute, fixed volume in front of a monitor. This sounds intuitive, but Galyean and Hughes report that "controlling the tool position is not easy. Even though the [3D input] pointer is held in a well-defined region, it is often difficult to correlate the position of the pointer in space with the position of the tool on the screen." The user must consciously attend to the visual display of the pointer position to accomplish his or her tasks.

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11 An ecological psychologist (one who studies perception in the natural environment, emphasizing the moving, actively engaged observer) would think of these as "active" feedback sensations, because the user seeks out and explores the stimuli rather than passively receiving them [Gibson 1962]. From the standpoint of feedback which is under direct control of the computer, however, the information is static or passive, even if the user is active in exploring a passive stimulus.
The Worlds-in-Miniature (WIM) interface metaphor [Stoakley et al. 1995] provides a virtual reality user with a hand-held miniature representation of an immersive life-size world (Figure 14). Users interact with the WIM using both hands. The user's nonpreferred hand holds a clipboard ("the WIM") while the preferred hand holds a ball instrumented with some buttons. Reaching into the WIM with the ball allows manipulation of objects. Compared to the fixed volume used by Galyean and Hughes [1991], users have quite a different interaction with the WIM; they can very quickly develop a sense of the space they are working in, since they are repeatedly manipulating miniature objects in the space defined by the nonpreferred hand holding the clipboard. We have observed users manipulating objects in the WIM without even looking at it (that is, users have manipulated objects while holding the clipboard below the field-of-view seen in the immersive display). This is possible because users have a keen sense of where their hands are relative to one another.

Our discussion so far has focused on 3D and immersive input techniques, but the same issue arises for 2D input when implementing two-handed interactions with relative input devices (such as a pair of mice [Zeleznik et al. 1997], or a mouse and a trackball [Bier et al. 1993]) versus absolute input devices (such as a multi-sensor tablet [Kurtenbach et al. 1997]). With a tablet, the user knows where one cursor is relative to the other without ever looking at the screen, because the user's own hands are the cursors. With relative input devices, however, the real-world spatial relationship between the two hands does not correspond to the visual feedback of the on-screen cursors, and as a result two-handed coordination may be more difficult using the relative devices [Zeleznik et al. 1997]. Tablets can potentially simplify between-hand coordination, but multi-sensor tablets do present their own quirks, such as the possibility for multiple input devices to collide with one another [Kurtenbach et al. 1997]. The issue of two-handed input with absolute versus relative devices (or possibly a combination of absolute and relative devices) is an interesting topic for future study.

4.4 Experiment 2: The Bimanual Frame-of-Reference

Experiment 2 explores the hypothesis that users have a precise sense of where one hand is relative to the other when performing a six degree-of-freedom placement task. We call this sense the bimanual frame-of-reference because the information from the hands alone is enough to specify a centered and oriented reference frame for the user. This frame-of-reference is particularly interesting because it does not depend heavily on visual feedback: as an intuitive example, it is easy to touch the tips of your index fingers together behind your head, a movement which clearly is not guided by visual feedback.

This study investigates the following specific hypotheses:

H3: The two hands together provide sufficient perceptual cues to form a frame of reference which is independent of visual feedback.
**H4:** When using just one hand, subjects can employ other body-relative cues (sense of joint angles, sense of torso midline) to estimate a remembered hand position, but these cues are less precise. Thus, unimanual control is more dependent on visual feedback.

**H5:** The physical articulation of a task can influence cognitive aspects of performance, in terms of the task strategy used. Using two hands together encourages exploration of the task solution space, and this will allow subjects to develop a superior strategy for the experimental task.

### 4.4.1 Cognitive Aspects of Performance

Working with Buxton, Leganchuk [1995] has explored H5 in previous work, providing preliminary evidence which suggests that "representation of the task in the bimanual case reduces cognitive load." Leganchuk’s experiment studied an "area sweeping" task in which subjects selected an area encompassing a target. This is similar to sweeping out a rectangle to select a set of targets in a graphics editing application. Using both hands allowed subjects to complete the task significantly faster than using just one hand. Furthermore, the difference in times could not be attributed to the increased time-motion efficiency alone. This was interpreted as evidence that the bimanual technique "reduces cognitive load."

Another way to investigate the hypothesis that bimanual control can influence cognitive aspects of performance is to take direct measures of cognition, such as quantifiable metrics of learning, memory, or transfer of skill. Leganchuk’s strategy of taking differences between one and two-handed techniques relies on the assumption that differences beyond those clearly accounted for by increased time-motion efficiency can be attributed to differences in cognitive load. But if one can demonstrate a direct metric of cognition, this assumption does not have to be introduced.

### 4.4.2 Task and Experimental Design

The task consisted of two phases. In the primary phase, users attempted to align two virtual objects. The purpose of this phase was to engage the user in an initial task which would require moving and placing the hand(s) in the environment. The second phase consisted of a "memory test" where users tried to reproduce the placement of their dominant hand without any visual feedback. We used the doll’s head and cutting-plane input devices from our neurosurgical visualization system for this study.

For the primary task, users were instructed to align and intersect the target object (an extruded triangle, controlled by the doll’s head) and the plane (controlled by the plate tool) so that they were coplanar (Figure 15). The triangle would highlight in yellow when the plane was aligned with it (the triangle appeared at a new random orientation for each trial). A footpedal was used as a clutch for the plate tool. When subjects held the pedal down, the plane could move freely relative to the target object. When the pedal was released, the plane would stay embedded in the target object. If the two were aligned when the pedal was released, this ended the primary task.

![Figure 15](image_url)  
**Figure 15** Stimuli for the Primary task. The triangular target is shown at the left. Users tried to move the plane so that it was roughly coplanar with the target object, causing it to highlight (right).
At the end of the primary task, the computer recorded the position and orientation of the preferred hand (which was always holding the plate tool). A dialog then appeared telling the subject to "Get Ready for Memory Test!" (Figure 16a). For the memory test, subjects were instructed to put their preferred hand down on a mouse pad at the side of the work space, to close their eyes, and then to attempt to exactly reproduce the position and orientation of the plate tool without any visual feedback (Figure 16, b and c).

The experiment compared two conditions, a bimanual condition and a unimanual condition. In the bimanual condition, simultaneous motion of both input devices was possible. The doll's head was held in the nonpreferred hand, the plate in the preferred hand. Since the distance between the two objects does not affect the alignment required for the primary task, it is always possible for the doll's head and the plate tool to make physical contact when completing the task. Subjects were instructed to use this technique in the bimanual condition, since we wanted to test how well subjects could use the nonpreferred hand as a reference. The bimanual condition is shown in Figure 16 above.

In the unimanual condition, subjects were instructed to always keep their nonpreferred hand in their lap. Subjects were only allowed to grasp one device at a time, using only their preferred hand. There was a definite device acquisition time required when switching input devices, but subjects were instructed that time to complete the task was not important: only their accuracy on the memory test mattered. For the memory test, the unimanual condition was identical to the bimanual condition, except that the nonpreferred hand was no longer available as a reference.

Clearly, both conditions utilized a space-multiplexed design, with a separate input device for each function, as opposed to a time-multiplexed design, where a single device controls multiple functions by changing modes. Brooks [1988] reports that overloading a device with multiple functions can often cause confusion. Thus, we chose a space-multiplexed design for the unimanual condition because we did not want the possible issue of users becoming confused over which "mode" they were in to interfere with the experiment itself.

For the unimanual condition only, a second clutch footpedal was needed to allow subjects to rotate the doll's head and leave it "parked" at a particular orientation, thus allowing them to put down the doll's head
and pick up the plate tool. Users had no difficulty in using the two pedals: there were no experimental trials where a user clicked the wrong pedal in the unimanual condition. Originally we had planned to use two footpedals in the bimanual condition as well, but as explained in section 4.1.2 above (No Clutch for the Base Frame of Reference) we found that clutching the target object was problematic.

A within-subjects latin square design was used. Seventeen unpaid subjects (13 female, 4 male) were recruited from our psychology department's subject pool. One subject (male) was left-handed. No subjects had experience with 3D input devices or two-handed computer interfaces. Eight subjects (six female, two male) performed the unimanual condition first and nine subjects (seven female, two male) performed the bimanual condition first. Subjects performed 12 experimental trials for each condition.

4.4.3 Results

Accuracy on the memory test was the only dependent measure. Accuracy was measured in terms of angle (shortest-arc rotation to align the remembered reference frame with the ideal reference frame) and distance (Euclidean distance between the reference frames). We performed an analysis of variance on the Condition factor (unimanual or bimanual) with repeated measures on the angle and distance outcome measures. The overall means for each condition are shown in Table 2. Overall, Condition was highly significant for distance ($p<.0001$), with performance in the bimanual condition approximately two times more accurate than in the unimanual condition. This evidence strongly supports both hypothesis H3 and H4, suggesting that subjects were able to utilize the perceptual cues provided by the nonpreferred hand to reproduce their six-degree-of-freedom posture independent of visual feedback. The angle outcome measure did not reliably differ across conditions.

Thus, users maintain a fairly precise, hand-relative-to hand representation of the space they are working in which does not depend on visual feedback. Users also maintain an environment-relative representation, but this representation is less precise in the sense that it depends more heavily on visual feedback. This suggests that two hands and split attention may go well together: when using two hands, the user's attention does not have to constantly monitor the manipulation itself.

<table>
<thead>
<tr>
<th></th>
<th>Angle (degrees)</th>
<th>Distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bimanual</td>
<td>11.2</td>
<td>16.6</td>
</tr>
<tr>
<td>Unimanual</td>
<td>10.4</td>
<td>32.6</td>
</tr>
</tbody>
</table>

Table 2: Overall means of angle and distance outcome measures for each experimental condition.

We also analyzed the effects of the Order of presentation. This revealed a significant Condition X Order interaction for Distance ($p<.01$), indicating a one way transfer of skill [Poulton and Freeman 1966] from the Bimanual condition to the Unimanual condition. The means for each condition grouped by Order show this transfer effect (Figure 17). Subjects who performed the Bimanual condition first performed 28% better on the subsequent Unimanual condition compared to those subjects that performed the Unimanual condition first. There was no reliable transfer of skill in the other direction: when performing the Unimanual condition first, Bimanual performance only improved by some 7%. This suggests that subjects learned a more effective task strategy in the bimanual condition, and were able to transfer some of this skill to the unimanual condition. This evidence supports H5, suggesting that bimanual control can affect performance at the cognitive level by influencing a subject's task-solving strategy.
Figure 17  Transfer of Skill: For the Unimanual-First subjects, exposure to the unimanual condition had no significant effect on subsequent bimanual performance. But for the Bimanual-First subjects, exposure to the bimanual condition dramatically improved subsequent unimanual performance by 28%. This suggests a one-way transfer of skill from the bimanual condition to the unimanual condition.

Our qualitative observations also supported this position. When performing the unimanual condition first, subjects had a tendency to avoid using the doll's head: only 2 out of 8 of these subjects consistently reoriented the target object with the doll's head. Subjects would instead adapt the plate tool to the initial (randomly generated) orientation of the target object. Subjects were aware that they could move the doll's head because we made sure that every subject tried doing this during practice trials for the unimanual condition. By contrast, for 8 out of the 9 subjects who tried the bimanual condition first, during the unimanual condition they would re-orient the doll's head on essentially every trial. As one subject explained, during the bimanual condition she had learned that "instead of accepting what it gave me, I did better when I moved [the doll's head]."

The input devices used in this study were rich in tactile orientation cues and this certainly helped subjects to perform the experimental task more precisely. If we had used featureless spheres as input devices, for example, subjects probably would have had a less acute sense of the orientation of each device [Hinckley et al. 1997c]. Because smooth, featureless spheres are commonly used as 3D input devices, future work should further explore this issue.

We also believe that allowing contact between the two hands was a factor in the experiment, but not the only factor. When using two hands, subjects could often come quite close to the original position even before contact was established. Further study is necessary to determine if this differs significantly from moving a single hand relative to the environment. To quantify this, a future study would need to explore a bimanual condition in which no physical contact is allowed.

A future study might also look at the accuracy of relative placement in a bimanual condition where the user had to rest both hands prior to the memory test. It is not clear if performance would be better or worse than one-handed placement in this case. The present study also does not compare the effectiveness of the nonpreferred hand as a reference to other possible non-visual means of providing reference information, such as providing an audio tone that changes pitch or gets louder as the subject approaches the target orientation.
5 CONCLUSION

The WIMP (Windows, Icons, Menus, and Pointer) interface metaphor was designed to match the computing capabilities available in the late 1970's and early 1980's. Computers are no longer limited to small black-and-white displays and meager central processors with an impoverished input bandwidth. A variety of factors make the limitations of the WIMP interface paradigm increasingly apparent: continued vigorous growth in processor power and memory capacity; technological innovations such as large flat-screen color displays, real-time interactive 3D graphics, and high degree-of-freedom input devices; and the demands of highly skilled end users (such as neurosurgeons, animators, and artists) with specialized and difficult computer-aided tasks to perform.

A host of devices, displays, and interaction techniques have been proposed and demonstrated as candidates for the post-WIMP interface. Yet demonstrations of new interaction techniques may not be enough to fully take advantage of a technique. To understand why interaction techniques do or do not work, and to suggest possibilities for new interaction techniques, the interface designer needs to understand and quantify principles which govern human action-perception mechanisms and the resulting user behavior.

The present research contributes a neurosurgical visualization system which has undergone extensive informal usability testing in the context of real domain experts doing real work, but it also presents the results of experimental evaluations which illustrate general behavioral principles for two-handed interfaces. The selection of experimental evaluations has been tempered by design experience, so there is some assurance that these experiments apply to design in a meaningful way. It is our hope that these approaches, taken as a whole, can make a decisive statement that involving both hands in multiple degree-of-freedom manipulative tasks can offer user interface designers a means to take what seems to be complex, high-degree-of-freedom tasks and present them to users in a way that permits natural, efficient, and highly dexterous manipulation.

We have argued that the common-sense view of “two hands save time by working in parallel” is not always sufficient to solve the interface design problems that can arise in two-handed manipulation. First, two hands do not necessarily work in parallel because there is a hierarchical structure to dexterous bimanual manipulation, with the preferred hand articulating its motion relative to the dynamic frame of reference specified by the nonpreferred hand. This directly influences the type of input mappings that are appropriate for two-handed virtual manipulation. We have demonstrated one such mapping, and shown that although it exhibits a non-corresponding motion artifact which apparently contradicts the “1:1 motion mapping” principle, most users never realize that such an artifact exists, precisely because our input mapping reflects the natural structure of bimanual manipulation. This style of manipulation is furthermore most effective when the interface preserves the dynamic role of the nonpreferred hand, for example by resisting the temptation to provide a clutching mechanism for the base frame of reference. Finally, we have experimentally investigated the hierarchical structure of bimanual manipulation suggested by Guiard’s right-to-left reference principle [Guiard 1987], providing evidence for a cooperative pointing task which refutes the hypothesis that the hands are parallel and independent input streams, especially for the case of precise manipulation.

Second, two hands do more than just save time over one hand. Users have a keen sense of where their hands are relative to one another and this can be used to develop interaction techniques which are potentially less demanding of visual attention. Using both hands helps users to ground themselves in a body-relative interaction space, as opposed to requiring consciously calculated action in an abstract environment-relative space. Furthermore, a two-handed compound task is not the same thing as the serial combination of the one-handed subtasks. Using both hands alters the syntax of the manual tasks which must be performed, which influences a user’s problem solving behavior and therefore has a direct influence on how users think about a task. We have investigated these issues in an experimental study of the bimanual frame-of-reference, demonstrating that two-handed performance is twice as accurate as one-handed performance for the task of reproducing a remembered posture without visual feedback. This study also illustrated a transfer of skill effect, suggestive of a change in problem solving strategy resulting from exposure to the two-handed condition.

We advance multiple degree-of-freedom input with two hands as a candidate for one style of post-WIMP interface. Our research results are by no means a complete study of human two-handedness, but they do significantly advance our understanding of important issues that arise in two-handed interface design.
Taken as a whole, our examples, analyses, and experimental studies answer questions of when and why two-handed techniques may be useful for virtual manipulation, address concerns of how to implement such interaction techniques, and provide design principles which can be applied to the design of new two-handed interfaces.

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I would like to dedicate this work to the memory of my wife, Kerrie Exely Hinckley. This work would not have been possible without Kerrie's love and support. Kerrie can be seen demonstrating the experiment in Figure 16.

REFERENCES


