Chapter 11: Two-Handed Input in Human-Computer Interaction

Introduction

A student turns a page of a book while taking notes. A driver changes gears while steering a car. A recording engineer fades out the drums while bringing in the strings.

What each of these tasks has in common is that they are bimanual activities. In fact, most human activities involve the use of two hands. While, on reflection, this may seem an obvious and somewhat trivial observation to make, it has significant implications for human-computer interaction. Almost without exception (the keyboard being the most notable), computer input techniques are based on the use of one hand. This means that the everyday skills we have acquired both through evolution and through a lifetime of learning, for the most part simply cannot be used to interact with computers.

When one considers the rich repertoire of two-handed skills that we have at our disposal, this points to the need for a more systematic examination of the possibilities for two-handed input. In this paper we will attempt to lay the groundwork for such an examination. In doing so we will show that two-handed input techniques can push the boundaries for human-computer interface design (a fact that researchers in HCI are slowly but surely coming to realize only in recent years, cite refs here for recent papers). Indeed, such techniques suggest whole classes of innovative new ways of interaction for a wide spectrum of applications, from the most advanced kinds of virtual reality systems, right through to more mundane applications such as word processing tools.

However we must be clear that in promoting a deeper exploration of the design space of two-handed interaction, we are not blindly assuming that two hands are better than one. We will argue that two hands *can* be a more efficient and effective approach to interaction both in terms of the time it takes to articulate and execute motor actions, and in the way tasks are cognitively processed. However, we will also show that there are many circumstances under which two-handed techniques can be *worse* than one-handed techniques. In other words, it is not necessarily the case that the haphazard assignment of one subtask to the right hand, and another subtask to the left hand will impart any benefits; indeed the result can be a more awkward and effortful interaction than with the current one-handed technique.

What we are working toward here are appropriate forms of interaction based on an understanding of human action. What we hope to provide is a theoretical framework within which one can begin to answer the following key questions:

- How do we determine which tasks are suited to two-handed input techniques?
- How do we assign roles to hands?
- Which input devices will be appropriate and how do we design the techniques to maximize their benefits?

In order to map out this design space, we will begin by describing two-handed interaction at the very simplest levels: first in terms of the basic classes of action of the two hands, and then as a sequence of actions over time. We then turn to the Kinematic Chain Model, a model of human bimanual action that provides the theoretical foundation to ground these kinds of classifications more firmly. In the final part of this paper, we will show that this model can help in guiding the design of innovative two-handed techniques, and can also help in the assessment of existing techniques.

Describing Two Handed Interaction

Motion vs. Action: The Level of Analysis Problem

Attempts at modeling input in human-computer interaction have generally overlooked the possibility of two-handed action (e.g., Card et al., 1991). We can find technical reasons why, until recently, only one-handed devices such as the mouse, the trackball or the pen-plus-tablet have been made available to users, but there is a conceptual issue here. Now that –more than a decade after Buxton and Myer's (1986) first demonstrations– there is a respectable body of evidence that bimanual input can substantially improve human-computer interaction, one may wonder why it took so long in the field to begin to recognize that single-handed input techniques suffer problems.

The answer has to do with the state of the art in basic research on human motor behavior. Since Woodworth (1899), the first investigator who was able to demonstrate a speed-accuracy tradeoff in aiming movement, progress has only been possible at the cost of a drastic minimization of DOFs, both in task space and in the anatomical space of effectors. For example, Fitts' (1954) paradigm most popular for the study of aimed movement has only two parameters, target distance and target width, and performance is taken to boil down to the time needed to complete the movement. To experiments on Fitts' law, researchers have typically used a single hand – in fact, more often than not, just one DOF of a single joint of the hand (e.g., a wrist pronation-supination, as in Meyer, Smith, Kornblum, Abrams, & Wright, 1990).

Here we have the problem that the so-called ´ hand ª movements of interest in HCI are actually extremely complex from the point of view of anatomy. In sharp contrast to the 1-DOF movement studied by Meyer et al. (1990), the simple act of moving a mouse involves perhaps a dozen bodily DOFs with a possible participation of virtually all the joints of the upper limb –from the finger phalanxes to the shoulder (and possibly beyond). In the face of such a complexity, one cannot localize action in the intrinsic geometry of the musculo-skelettal system and, therefore, one might be tempted to conclude that the hand term should be banned to designate an effector because it is structurally ill defined.

We need the hand concept, however, to describe human motor behaviour functionally, at the level of action. Motion in the sense of classical mechanics can indeed be observed about a single joint, but it is only at the level of assemblies of DOFs that behaviourally meaningful *gestures* can take place (Kugler, Kelso, & Turvey, 1980); and the effectors that can perform gestures are the hands, not the joints. As argued by Reed (1982) –who outlined a theory of action systems in an ecological, Gibsonian perspective–, coordinative structures are changeable, reversible coalitions of individual DOFs –with no reason to expect any particular subset to be constant throughout the execution of a gesture. The structural identity of the hand as an effector being so elusive, so we must be content with the fact that the effector we designate as a hand is in fact some (unknown) part of the left or right upper limb. In short, the only firm knowledge we have with regard to the anatomical characterization of the hand effector is its side.

Note that recourse to an abstract concept of a hand does not preclude the possibility of grasping firm patterns. Fitts' law again will serve to illustrate this point, as this law holds quite independently of the effector involved. Meyer et al. (1990) preferred to have their subjects move a pointer with a 1-DOF manipulandum, but in no way was this restriction a necessary: Recall that Fitts (1954) established his law in a stylus-tapping task that involved a highly variable set of DOFs, depending on between-target distance. Even though Fitts' law can be observed at the joint level, it represents structure at the level of action, structure in task space rather than bodily space. There is a shortage of those macroscopic concepts we need to try to recompose human motor behavior both functionally (think of the phrasing problem of Buxton, 1986) and in terms of the anatomical effectors (think of the bimanual input problem).

To begin with, however, we can describe the actions of the two hands in very simple terms, without considering the specifics of the interplay, or the nature of the dependencies, between the right and left hand. We will refer to this level of description as the “basic action language” of one hand versus the other. We will then move progressively closer to an understanding of how the two hands interact. First, we will sketch out the possibilities for right and left handed action within a temporal framework in order to consider the potential costs and benefits of two-handed techniques in performing compound, computer-based tasks. Finally, we will ground these descriptions in a model, which describes the nature of the relationship between right and left-handed action by viewing bimanual activity as a cooperative system.

Basic Action Language

One way to discuss bimanual interaction is in terms of the type of actions articulated by each hand. The nature of the action “language” is closely associated with, and constrained by, the input transducers available. Ideally, the action language desired should determine the transducers used. More typically, (but unfortunately), the transducers are given, and dictate the limits of the interaction language by their affordances.

At the simplest level, one can describe two basic classes of action: *discrete* and *continuous* (also often referred to as *analogue*).

Discrete actions are actions that involve the discrete triggering of events, typically through the action of pressing a button, such as on a keyboard. Examples are typing on a QWERTY keyboard, the use of function keys, or numerical keypads. As will be discussed in more detail below, these can also include actions triggered by depressing the buttons on a continuous device, such as a mouse.

Continuous actions are actions that involve continuous control over one or more degrees of freedom. This would include transactions seen in common GUI's, such as pointing and dragging. These are actions that are typically articulated using a device such as a mouse, trackball or joystick.

Note that here we are referring to the nature of the action itself and not necessarily the action of the thing that is being controlled. So, for example, in some computer games the movement of characters or objects is “continuously” varied using discrete actions on the keyboard. Conversely, one can generate examples where a continuous action device such as a mouse is used to enter data typically considered "discrete". Entering alphabetic characters with a stylus, especially using the popular Graffiti is one such example.

So, as a start, if we use this distinction as a means of categorizing various forms of bimanual action found in computer systems, we can construct the following, simple table. (Here we use *NDH* to stand for "non dominant hand" and *DH* to stand for "dominant hand"):

Table 1

NDH	DH	Example
Discrete	Discrete	Touch typing on a QWERTY keyboard
Discrete	Continuous	Using a GUI with a mouse in the DH and function keys in the NDH
Continuous	Continuous	Stretching a rubber-band line from both ends, using a trackball in the NDH and mouse in the DH

We can refine things by creating a third category of action, "Compound", which enables us to distinguish purely continuous actions from those that also include a discrete action using the same device. Selection by point and click, as seen in most GUI's is an example of a compound task. In the examples given, and in general, the distinction between continuous and compound is a function of making State 0-1 transitions (see ref) while performing a continuous action using the same hand. Using this new class of action, we can construct an expanded version of the previous table:

Table 2.

NDH	DH	Example
Discrete	Discrete	Touch typing on a QWERTY keyboard
Discrete	Continuous	Cursor positioning with joystick in DH while using function keys in NDH, as with IBM laptop
Discrete	Compound	Point and click selecting with mouse in DH, and function keys in NDH
Continuous	Continuous	Scrolling page with trackball in NDH while cursor tracking mouse in DH
Continuous	Compound	Scrolling page with trackball in NDH; Point + Click select with mouse in DH
Compound	Compound	Dragging the page with one mouse in the NDH while drawing with another mouse in the DH. As in T3 (Fitzmaurice et al, 1997).

While this method of classifying two-handed actions is extremely simple, it does help to begin to map out the range of possible two-handed interaction techniques using conventional input devices. In fact, most existing techniques fall easily into these different categories. Typing on QWERTY keyboard is the prototypical discrete+discrete two-handed task. Adding a mouse, however, opens up a new realm of two-handed possibilities. For example, Engelbart and English (1968) developed a user interface in which one hand operated a chord keyboard (see X) while the other controlled a three-button mouse. Hence, continuous two degree of freedom spatial tasks could be done with the mouse hand, while discrete tasks could be undertaken with the hand on the chord keyboard, and/or the mouse buttons.

The same basic configuration was used on a number of early systems developed at Xerox PARC in the 1970's, such as Bravo and Gypsy. The Gypsy System, a variant of Bravo, was a word processor having modeless UI. Besides employing an ancestor of dialogue boxes, it also utilized the Engelbart chord keyboard in one hand, and a three-button mouse in the other. The semantics of the chord keyboard for this system were as follows:

Cut:	thumb	
paste:	middle	
copy:	thumb+middle	(chord)
scroll up:	index:	
scroll down:	ring	
scroll faster:	index **|** ring + baby	

This basic approach of assigning one hand for discrete tasks and the other for continuous spatial tasks was carried over to the user interface of the first commercial system to grow out of the Xerox PARC research, the Xerox "Star" workstation (add ref: in Baecker & Buxton). This system retained the three-button mouse; however, rather than use the Engelbart chord keyboard, it had a set of (non-chording) function keys placed in a column down the left side of the keyboard. Each key represented one of the application independent, or "universal operations" of the system. These were:

Move
Copy
Show Properties
..??? .. to be completed.

While the Xerox Star provided the foundation for today's GUI, it is interesting to note that this fundamental part of its user interface was not made a feature in subsequent systems. In the Star, the use of the function keys by the non-mouse hand was an explicit and fundamental aspect of the UI, which contrasts with the UI of the Macintosh or Windows, for example. Nevertheless, virtually all GUIs use this approach as a secondary, or alternative, mode of interaction. This is seen in the use of "accelerator" or "hot" keys. With the Macintosh computer, for example, copying something to the "clipboard" can be done by selecting an object with the mouse, and then invoking the "copy" operation by pushing the "c" and "command" keys simultaneously. This approach of selecting the operand (noun) with the pointing hand and the operator (verb) with a keyboard is typically much faster than doing both through selection with the pointing hand. As stated above, the Star made this the fundamental mode of interaction for the most common operations.

Temporal Properties

Another way in which one can describe two-handed activity is to use a temporal framework. Such a framework is useful because it provides a way of conceptualizing and mapping out the potential costs and benefits of one-handed versus two-handed action, as we will show.

Consider first that most computer tasks are compound in the sense that they can be characterized as consisting of a number of subtasks. Consider, for example, the task of painting something in MacPaint on the Macintosh, and suppose one wanted to paint on a part of a page not currently visible on the screen. There are, therefore, two tasks involved: the primary task of painting (which we will call task A), and the secondary task, navigation (task B). One can envision a number of different ways in which such subtasks could be assigned with respect to the right and left hands:

Conventional one-handed approach

Using the usual Macintosh setup, that is, a mouse in one hand, the user draws (A) using the paintbrush tool, and then has to acquire the navigation tool (the “hand” tool) by selecting it from the palette, or move the scrollbars to perform the scrolling task. Changing back to the painting task again requires more switching time.

Note that switching time here can be further broken down into different components. Consider the time it takes to switch from navigation back to painting. This switching time involves: the “cognitive” switching time or mental effort involved in switching from one task to another, the time to redirect visual attention to a new part of the screen (i.e., the palette), the time to move to acquire the painting tool, and the time to move back to the page to begin painting.

This sort of approach is shown in Figure 1. Note that subtasks A and B need not refer to painting and navigating, but could as easily refer to scrolling and selecting tasks as in text editing, scaling and positioning tasks as in graphics packages, and so on.

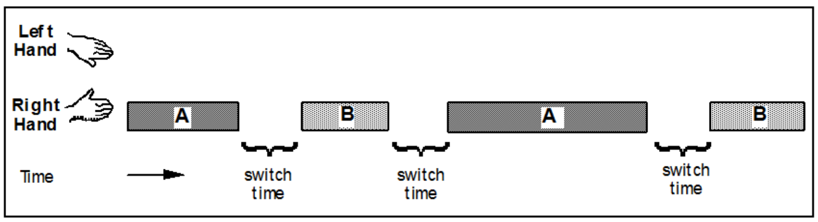

Figure 1. Performing subtask A and subtask B using a conventional one-handed approach. “Switch time” is made up of several components, including cognitive switching time, visual redirection or reassimilation time, and device acquisition time.

Two-handed approaches

Consider now that one might have a separate device for each task, and one device assigned to each hand. Because each hand now has the appropriate tool, and can be in “home position” for its respective task (i.e., over the scroll bar with one hand and over the page with the other), this approach eliminates the movement times associated with device acquisition, and also the time associated with visually having to redirect attention to acquire the device. Hence, even if the two hands are used in a strictly sequential manner (perhaps because of the technical limits of the system), and even if there is still some cognitive switching time incurred, there is still a significant improvement in performance over the status quo (Figure 2).

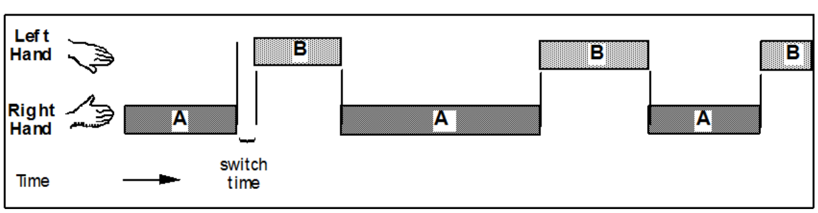

Figure 2. Performing subtask A and subtask B in a serial manner using a two-handed approach. Note that switch time, if it does occur, now is only due to cognitive effort, and does not include device aquisition time or visual reassimilation time.

This was shown experimentally in the selection navigation study by Buxton and Myers (1986). In this study, one hand was used to scroll a document using a touch pad, while the other was used to select text with a mouse. In this case, novices using the two-handed technique matched the performance of experts who were using the conventional GUI technique where the same hand had to use the mouse to both select text and navigate (using the scroll bars). Interestingly, of the 12 subjects using the two-handed group, while parallel activity was possible, only 2 of the subjects engaged in any, yet the benefits of using two hands were still seen.

Also significant and perhaps unsurprising here, however, is the fact that the two subjects who did carry out parallel actions were the fastest. Obviously, if the actions of two hands can also be done in parallel, then the time savings for two-handed techniques go beyond the elimination of the time required to acquire and re-acquire devices. In the ideal case, parallelism is maximized (Figure 3). For example in a two-handed technique we have experimentally evaluated, the "Toolglass" technique (Kabbash et al), we have found parallel activity an average of 83% of the time.

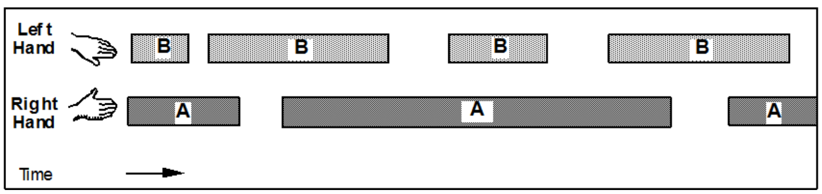

Figure 3 Performing two subtasks, A and B, in a cooperative, parallel manner using a two-handed approach.

However, some tasks are obviously less easily done in parallel than others. Even worse, carrying out two subtasks at once may incur such a high cognitive cost that the two-handed technique is even slower than a one-handed technique. Kabbash et al. (1994) found not that a two-handed technique which required the hands to carry out two independent subtasks caused subjects to take significantly longer to plan their actions than in a comparable one-handed technique. In other words, this technique imposed such a high degree of cognitive effort, the result was very long switching times. This cost was such that it negated any of the benefits of using two hands (i.e., the time savings in terms of the parallel activity that occurred, and the elimination of device acquisition and visual reassimilation times). In comparison to the conventional one-handed technique we used, this two-handed technique was, overall, slower. This example therefore shows that some subtasks inherently conflict with one another, which either results in little parallel activity, high cognitive costs, or both (as in Figure 4).

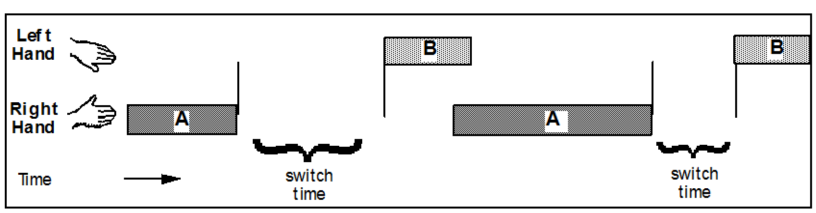

Figure 4. Performing subtask A and subtask B in a competitive manner using a two-handed approach. Parellelism is infrequent and switch times are large.

The Assignment of "Tasks" to Hands

Describing the actions of the two hands either by classifying them according their basic action language, or mapping them out along temporal dimensions may help us to understand the range of interactional possibilities, but it does not provide answers to some key questions, namely: Which subtasks can be carried out concurrently, and which cannot? What factors influence the degree to which left and right-handed actions can be combined or carried out simultaneously? For two-handed action, what role should be assigned to the left hand and what role to the right?

Some tasks are more tightly integrated than others: background/foreground tasks discussed in the MacPaint example, above, and more tightly integrated (associated?) tasks, such as two-handed stretching of a rectangle, or threading a needle.

Here is also where we want to discuss chunking and phrasing.

Role of skill through practice is to help bind actions together that would otherwise be difficult to perform concurrently.

Need to then point out that we need to turn to theory in order to more deeply understand bimanual action: to describe the underlying principles which govern bimanual skill, and to explicate its properties and characteristics.]

A Model of Human Bimanual Skill

In turning to the psychological literature for guidance on two-handed skill, we find that most basic research has traditionally revolved about the idea of lateral dominance. Psychologists seem to have quite persistently adhered to the view that the most important psychological fact about the bilaterally symmetrical organs of the human body (whether the hands, the feet, the eyes, or the cerebral hemispheres) is that one side is more sophisticated and functionally more important to the other. The strong emphasis placed on the measurement of hand preference and hand superiority implies a competitive approach to the left/right relationship.

The kinematic chain (KC) model we will introduce in this section is based on a quite different approach (for more detailed presentations of the model, see Guiard, 1987, 1988, and Guiard & Ferrand, 1996). From the outset, we claim that in real life our two hands cooperate with each other in the service of action. From the moment it is assumed that the two hands form a cooperative system, their comparative values become a somewhat secondary concern. What we carefully consider is which hand does what. Our major aim is to identify, across the diversity of manual activities, the higher-order, task-invariant logic of division of labour between the two hands. The KC model, we believe, suggests one promising avenue for such an enquiry.

Cooperation Within a Kinematic Chain

Cooperation may be defined as the style of interaction that takes place among a system's components when these components concur to solve a problem posed at the level of the system. The insight that lies at the core of the kinematic chain (KC) model is that the cooperation that takes place between the two hands in human real-life activity is quite reminiscent of that which takes place between two contiguous components of an arm (e.g., the elbow and the wrist, or the wrist and the finger). The suggestion, in other words, is to liken a between-limb (left-right) relationship to a within-limb (proximal-distal) relationship, capitalizing on the fact that the latter is better understood than the former.

The term “kinematic chain” (KC), which originates from an old sub-domain of mechanics (Reuleaux, 1877), denotes generically any structure formed by the serial assembly of a number of rigid links. Taking the human arm as our exemplary case, note, to begin with, that a KC is a hierarchical system, using the simple mathematical definition of a hierarchy as a transitive asymmetric relation. An arm is an oriented structure with a free distal extremity and a grounded proximal extremity, so all its components may be ranked from the proximal to the distal. In the following we will first consider three interesting properties of KCs, and then show how these properties translate into the left-right domain of two-handed action.

(1) Distal-to-proximal frame of reference

One consequence of the monotonic increase of inertia in the proximal direction in a KC is that whenever a rotation takes place about some joint, it takes the form of motion of the distal link relative to the proximal link — i.e., the latter always provides the frame of reference. Try the simple experiment of producing single-joint angular motion, say, at the wrist while keeping your arm unsupported. What you will see is motion of the hand relative to an almost immobile forearm and this is simply because, for the wrist just as well as each single joint of the arm, inertia is disproportionately large on the proximal side of the joint in comparison to the distal side (Guiard, in press). Therefore, insofar as angular joint motion is considered, an arm may be characterized as a multi-level hierarchy of reference frames.

(2) Scale hierarchy

The more distal a joint, the finer the granularity of its contribution to the arm’s gesture (Lacquaniti & Soechting, 1982). Think of a pointing movement with the arm over a distance of 50 cm or so. All the joints of the arm will more or less concur to move the fingertip to its new position, but clearly the control exerted by the finger joints on the displacement of the fingertip will be quite fine-scaled or micrometric in comparison with that exerted by the elbow or the shoulder. A joint can only perform rotations and link length plays the role of a gain factor; the longer this length — the joint’s radius of gyration, equal for an extended limb to the summed length of all the links distal to that joint — the larger the gain.

The distal and the proximal correspond to different compromises in the face of the magnitude vs. resolution dilemma (Weber’s law). The specific contribution of macrometric proximal joints like the elbow or shoulder is to allow the arm to cover relatively large distances, but this is at the cost of a low resolution. The opposite is true of the micrometric distal joints like those of the fingers. While these joints contribute quite small amounts of motion, they make it possible to control movement of the KC’s endpoint with a correspondingly high level of resolution. This hierarchy is spatio-temporal, not just spatial. Not only do the proximal components of a KC serve to cover larger distances than the distal components, their contribution tends to last longer.

[Add bit about temporal resolution but reduce]

(3) Proximal precedence

How are the contributions that emanate from the various components of an arm coordinated in time? The answer is that KC’s mobilize their components in a proximal to distal sequence, even though there may be considerable degrees of overlap between two successive recruitments. For example, kinematic analyses have shown that in reaching movements of the hand the contribution of the shoulder and elbow start and meet their peak of activity before those of the wrist and fingers (Jeannerod, 1981; Lacquaniti & Soechting, 1982). Quite interestingly, we know that the proximal precedence principle also holds true in the case of very rapid arm movements like throwing. In a good throw, the arm operates very much like a whip: Peaks of angular velocity at the joints appear successively in a proximal to distal sequence, with the missile receiving its ultimate thrust from the fingers (Bingham, 199?).

This principle of proximal precedence makes sense in view of the multi-scale characteristic of a KC: As the contribution of the proximal is macrometric in comparison with that of the distal, the only possibility is that the former operates first, in keeping with a ball-park or funnel principle. Proximal precedence, in other words, may be viewed as an instance of a more general macrometric (or global) precedence principle (seeXX, 1997, for a recent review of global precedence in perception).

(4) Terminal dominance

[omit this one?] So long as an arm is thought of from the structural viewpoint of anatomy, it will be readily recognized as a compound, multi-link structure. However, from the moment one thinks of its function, awareness of the whole cooperative structure tends to vanish and it extremity, the hand, remains alone on the scene. For example, even though the fact that an arm is made up of a large number of joints is trivial knowledge, it is a compelling feeling —revealed by everyday language— that one does not throw a ball with the whole arm, but *with the hand*. If one uses an implement to hit a ball, we will say one hits the ball with one's bat, stick, clubs, or racket —not one's arm.

So when emphasis is on the interaction between a KC and its environment, rather than the KC's internal structure, the micrometric terminal region of the KC typically becomes the representative of the whole cooperative structure. Presumably, the reason we designate a KC metonymically in terms of its terminal component is because this component constitutes the KC's critical region of encounter with the external environment.

Cooperation Between the Two Hands in the Light of The Kinematic Chain Analogy

We now wish to suggest that the left and right of the two-handed cooperative system may be likened to the proximal and distal components of a KC, respectively. Considering, in the same order as above, the issues of reference frame, metrical differentiation, precedence, and dominance, we will show that the translation of these issues into the left-right domain highlights four basic principles of human bimanual behavior [1]:

(1) Right to left hand reference

In a vast category of manipulations — including instances like unscrewing the lid of a jar, threading a needle, hammering a nail, rewinding a spring mechanism, or driving a screw — two hands are needed while the division of labor between them is markedly asymmetric. The left hand apparently serves a fixation function while the manipulation proper seems to be carried out by the right hand. There is little doubt that in movements of this sort the left hand does play an important fixation role, in the sense of preserving the position and orientation of an object in the face of perturbations induced by right hand activity. However, there seems to be an interesting aspect of the left hand role that a passive clamp metaphor fails to capture. As suggested by the KC model (see also MacNeilage, Studdert-Kennedy, & Lindblom, 1987), it is quite often the case in human bimanual

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[1] It should be noted that in this paper we exclusively consider the case of right-handers, the people who, according to the current definition, prefer to use their right hand in unimanual activities. So far we have resolved to defer the study of the left-handers to a future stage of research, in view of the fact that left-handers are known to exhibit less consistency at the population level (Peters, 1996). At the deliberate cost of temporarily ignoring between-individual variability, our research strategy is to focus on within-individual patterns as observable in the strong majority of right-handers.

activities that the left hand provides the reference frame within which the contribution of the right hand will insert itself.

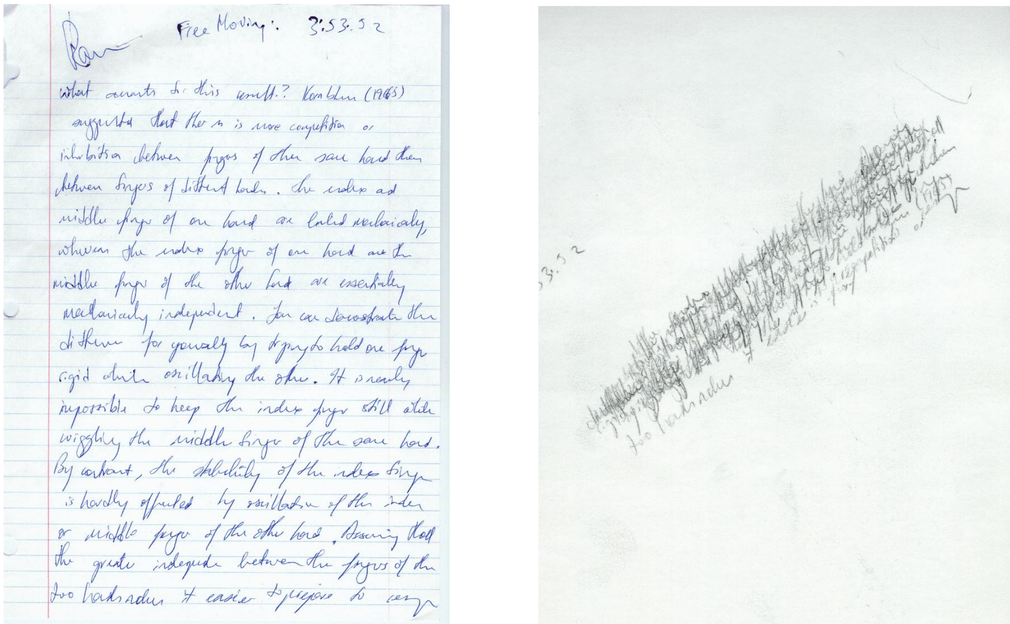

Figure 5 Two Views of the same handwritten text

The page on the left shows what the scribe wrote on the paper. The page on the left shows what appeared on the carbon copy placed under the blotter on which the scribe wrote the left hand page. The angle of the writing is a consequence of the scribe rotating the page while writing. The overlapping of the lines is a consequence of the scribe constantly repositioning the page as the writing progressed. (From Fitzmaurice, Balakrishnan, Kurtenbach & Buxton, 1998, after Guiard, 1987).

This can be readily illustrated with the example of handwriting. Contrary to the common belief, normal handwriting involves two hands, as demonstrated by Athenes (1983, 1984 verif) who found that the spontaneous speed of handwriting was slowed down by some XX% when instructions made it impossible for experimental participants to touch their sheet of paper with their left, non-preferred hand. The left and right hands operate basically at two levels of action corresponding (1) to the motion of the pen in the reference frame of the page and (2) to the motion of the sheet of paper in the larger reference frame of the writing table, as we have shown experimentally (Guiard, 1987). Our experiment showed that, as writing proceeds, skilled hand writers periodically reposition their sheet of paper with the left hand, so as to limit the vertical and, to a lesser extent, horizontal extension of right-hand movements over the table, thus avoiding jeopardizing their overall bodily balance (Athenes, 1984; Guiard & Athenes, 1985; Guiard & Millerat, 1984). (This is illustrated in Figure 5). The fact that the sheet of paper bears the appropriately laid out writing trace is clear evidence for a two-level description of handwriting performance: In handwriting — and more generally in graphic activities — the movements performed with the marking implement by the right hand are organized, not relative to any permanent and absolute frame of reference, but rather relative to the current position of the sheet of paper, another mobile object controlled by the left-hand.

In fact this right-to-left reference principle extends across a much broader spectrum of human two-handed activities than suggested in the preceding paragraphs... [give brief summary here...]

Thus the KC analogy helps recall that a frame of reference need not be stationary in any absolute sense. For the left hand to provide usable frames of reference, its motion just has to take place at a larger spatio-temporal scale. We will now see that this is exactly what happens in the two-handed cooperative system.

(2) Macro- vs. micrometric functional differentiation of the hands

In the light of the KC model, the left and right hands are looked on as two complementary organs, one macrometric and the other micrometric, that cooperate with each other. At first sight, the concept of a micro-macro contrast does not seem to add very much to the common observation that movements of the right hand are generally finer than those of the left. In fact, to say that the left and right hands are specialized for macro and micrometric roles like a proximal and a distal component of a KC is definitely more accurate than saying the right hand is specialized for "finer" movements.[2]

Consider again the case of handwriting. Here the KC model helps us to understand the utility of having our two hands work at two different levels of scale. The model suggests that it is advantageous to have our two hands take charge quite separately of two sub-tasks, namely, that of producing graphic forms in the page and that of manipulating the sheet of paper as a component of the desktop workspace. We may say that while the right hand has a monopoly on the page, a structure made up of words, lines, and paragraphs, the major role of the left hand is to interact with the sheet of paper.

Not only do these two components of the handwriting task differ in terms of the degree of abstractness — the page is an abstract entity in comparison to the sheet of paper—obviously they correspond to different levels of scale. In terms of spatial scale, the right hand produces small, high resolution shapes in the page, while the left copes with problems, such as bodily balance, that arise at the level of the interaction between the whole body and the desk. In temporal terms, handwriting movements are known to involve quite rapid pen oscillations (in the 3-7 Hz frequency band; Michel and Laviron, 1972) whereas seconds will typically elapse between two successive interventions of the left hand on the sheet of paper.

[Say briefly how this generalizes to other classes of task...]

(3) Left-hand precedence or right-hand lag

The fact that when using an optical microscope one has first to operate the macrometric knob and then the micrometric knob just seems to stand to reason, because a micrometric device does not fit the constraints of movement initiation and because a macrometric one is quite unsuitable to movement termination. For a reaching movement with an arm, likewise, there seem to be no sensible solution other than starting with the macrometric joints of the shoulder and elbow to bring the hand to the vicinity of the target, and then capitalizing on the wrist and finger joints to complete the final micro-adjustments. The KC model suggests that this principle should hold also in the context of two-handed movement, and this indeed is the case. Whenever the left hand serves some stabilizing function, it must intervene before the right hand —for example, the nail must obviously be held in the right place and with the right orientation when the collision with the hammer occurs. Also, from the moment it is recognized that in handwriting the left hand provides

[2] The problem with this traditional view is that the term "fineness", which has a strong positive connotation (the finer, the better), tends to mix up two variables, level of scale and level of skill. Notwithstanding that the micrometric role attributed to the right hand often proves to be far more difficult to carry out (this is most notably true of graphic tasks), this need not be always the case, and it seems prudent to disentangle these two variables (Guiard, Ferrand, & Gautier, in preparation).

the frame of reference needed by the right hand, the only way of interpreting each manipulation of the sheet of paper by the left hand is as a preparation for the forthcoming handwriting phase.

[Say briefly how this generalizes to other classes of task...]

(4) Right-hand dominance

[omit this one?] Perhaps the most unexpected consequence of applying the KC model to human two-handed skill is that hand dominance, the core concept of the mainstream psychological literature on manual asymmetry, receives a new, radically different treatment. In the following we consider successively the two facets of hand dominance, right-hand preference and right-hand superiority.

Concerning hand preference, our main task is not to explain why right-handers prefer their right hand, in the sense of valuing it more than the left, as this fact, after all, reflects to a large extent the demonstrated superiority of the right hand for difficult tasks. The interestingly puzzle we have to solve is why the people, including the students of human manual laterality, invariably characterize right-handers (left-handers) as those who do things with their right (left) hand, thereby mistakenly supposing that human manual actions are generally unimanual. For example, how can it be that laypersons as well as researchers traditionally categorize handwriting as a one-handed activity, given that this implies an active, if not deliberate, occultation of the participation of the left hand?

This persistent misconception, in our view an integral part of the hand preference phenomenon, is intelligible in the light of the KC model, using the analogy of the terminal dominance principle: In the same way as arm movements are typically perceived and represented metonymically as movements of the hand —the arm's terminal organ— actions emanating from the bimanual cooperative system tend to be perceived and represented metonymically as actions of the right hand —the "terminal" hand according to the model. The reason the right hand receives more consideration is because it is the bimanual system's most conspicuous component, the component that is brought directly in contact with the environment and terminates actions typically initiated by its partner. Both hands, however, undoubtedly contribute to the action —according to a hierarchical principle of macro vs. micro division of labor which the model helps to identify— and so the model's final suggestion is that hand preference essentially amounts to a cognitive bias.

Let us turn to the hand superiority phenomenon, the other easier facet of hand dominance as it can be firmly assessed through comparative dexterity tests in the laboratory. [Do we need this bit?...]

[Need summarizing ppg here]

Figure 6: As with all rules there are exceptions. For a right handed person, the stronger right arm is used to carry the stack. Hence, the right arm frames the location of the action, and the action is left-to-right. The benefits of strength trump the rules. (Photo: Bill Buxton)

Application to Human-Computer Interaction

Guiard's model says *how* bimanual asymmetric tasks work, not *when* they work.

In other words, we need to know: what are the properties of the set of tasks that are better performed bimanually?

E.g., threading a needle – task hierarchy. Most tasks, as we refer to them in common English usage, are actually compound tasks in the sense that they are comprised of subtasks…

It is arguable that all two-handed tasks could actually be done one handed. However usually this will involve additional overhead (and some may even require technological assistance.)

One-handed activity is also the situation that existing computer interfaces actually force you into, thereby often causing the artificial decomposition of what would normally be two-handed activities into a series of one-handed sequential actions. The question here then becomes: how do we identify which of these clusters of one-handed actions would be good candidates for two-handed techniques?

A good place to start is to consider what everyday two-handed tasks would look like if they were broken down into one-handed activities. What would they look like, and what would be their common properties?

Consider the task of reviewing a paper (marking up with pen and paper) Break down into marking and navigating. In the one-handed world, this would look like an oscillation sequence of marking actions interleaved with navigation actions. Here what is interesting is that the action of marking is to some extent dependent on the navigation action. However the navigation is in some sense the secondary act. It becomes the action through which the spatial and visual frame of reference is changed.

This example points out some properties we might look for:

-Oscillation between repeated subtasks

-Dependency of one subtask on the other (one subtask is the frame of reference for the other)

As a further example, use sweeping example and show how may not only be oscillation and dependency, but also there may be corrective overhead involved. Here we have a) select top left corner b) select bottom right corner, and c) clear selection.

Also, another nice example might refer to mode changes with one hand as changing the frame of reference for the other hand. Points out that changing frame of reference need not be spatial.

Reminder: Not All Bimanual Tasks are Asymmetric

(Bills section here) E.g., typing, piano keyboard, faders

Different class of task. May require a lot of learning

Benefit here is being in home position, space multiplexed solution

Spreadsheet e.g., and animation e.g.

The model directs us to which kinds of tasks can be considered for the application of two-handed techniques; give direction as to what the assignment of roles to hands should be; and also suggests the ways in which those techniques should be designed.

List of existing two-handed techniques: Can we characterize them in terms of the roles of the two hands in each case? (i.e., left hand frame of reference, micro-macro distinction, and right hand lag?)

_____add discussion of:____________

- Kabbash et al.: Left-tearoff, Palette and Toolglass techniques.
- Bier et al. (1994) See-through tools
- Stone et all (1994) Lenses
- Buxton- Active Desk
- Buxton and Myers
- Various 3D techniques: Hinckley, Fitzmaurice
- Bill: Add
- Bolt and Herranz (1992)
- Chatty (1994)
- LeBlanc et al. (1991)
- Tanner (1987)
- The responsive workbench of Cutler, Frˆlich, and Hanrahan (1997)
- Zhai, S., Smith., B.A.(2000). Multi-Stream Input: An Experimental Study of Document Scrolling Methods, IBM Systems Journal, 38(4), 642-651.
- Zhai, S., Smith., B.A.& Selker, T. (1997a). Dual Stream Input for Pointing and Scrolling. Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI'97), 305 – 306.
- Zhai, S., Smith., B.A.& Selker, T. (1997b). Improving browsing performance: A study of four input devices for scrolling and pointing tasks, Proceedings of INTERACT97: The Sixth IFIP Conference on Human-Computer Interaction, Sydney Australia, 286-292.

From these examples, talk about what sorts of general subtasks fit these roles and why: e.g. panning + zooming, positioning + scaling, positioning + selecting, positioning + drawing, and so on. Talk about some symmetric tasks and why these don't work (maybe this is where we cite the two-handed Fitts data.)

Conclusion

To be added..

RANDOM NOTES

One hand two steps vs. two hands one step (Buxton). Idea of direct perception via direct manipulation. Perception action coupling. Haptics = the archetypal sense. Vision works like haptics, not vice versa. Flows of stimulation yes, communication signals no. VR (in the most interesting and general sense, which includes holograms, the pantograph, and the desktop) is the triumph of the concept of action-perception coupling

Do not blindly assign the difficult role to the right hand. Musical examples: the guitar (for the beginner), la vielle (striking). These are instances in which the right to left reference principle (acting on an object, the string) whose length is controlled by the left hand) conflicts with the superiority of the right hand. Think also of the Middle Age pipe and tabor, assigned to the left and right hand, respectively.

Do not confuse structure and function: If, functionally, the designer must allow the user to feel like he is working one-handedly, actually the interface structure must rely on the user's both hands and mobilize them in a complementary way.

Navigation in multi-scale electronic worlds (Furnas and Bederson). If virtual reality is accessible simultaneously at several scales, the suggestion from KC model would be to entrust the left hand with selections at the larger scale.

Tool Glass and Magic Lenses

Some theory about the size of the items on the toolglass sheet. Remember is that Fitts Law works in two ways:

- Normal: where you move a point-cursor over distance D to a target of width W
- Prince (named after the first company to make over-sized tennis rackets), were you move a cursor of with W over distance D to a point-target.

For any value of D and W, the task has the same index of difficulty, all other things being equal.

For the details, see either Fitts' original paper, and or

> Kabbash, P. & Buxton, W. (1995).The "Prince" Technique: Fitts' Law and Selection Using Area Cursors. *Proceedings of CHI'95*, 273-279.

This study is an example of how, after developing the notion of tool-glass, we then dove in to try and make sure that we understood the underlying components of the task.

Given the Prince technique, the design challenge is how to keep the size of the overall toolglass sheet down (potential visual interference as well as potentially longer visual search) while keeping the size of the tools on it larger. For me, one of the important aspects of the T3 interface had to do with how we managed this, namely,

- take real care about grouping of tools, so that the number of tools on any sheet could be low
- keep the semantic power of individual tools high, so as to reduce the overall number of tools and sheets
- have a very fast, low overhead way to switch from sheet to sheet

What worked really well (feeling, not seeing, is believing), was how we combined marking menus with the tool-glass sheet. We had a margin across the top of the toolglass sheet which was where you initiated the marking menu that let you choose/change sheets. Hence, the control was integrated with the toolglass, but used marking menus rather than click-through tools to make selection. This I believe was absolutely the right decision – separation of church and state, so to speak, as well as marked (so to speak) improvement in selection speed.

The lesson here is the reminder that the best design often (usually? always?) comes from a combination of techniques, rather than just one. T3 is not just about toolglass, although it relies heavily on the technique. Each of the techniques used is essential, but not sufficient.

In my experience, I see many designers leaping on the most visible “cool” technique that a new successful product uses (think multi-touch and iPhone) and blindly believing that if they incorporate that technique/technology into their design that they too will have a great UX. Good luck to them. What I love about this stuff is the subtle mixing and matching, where we use each type of tool and technique in the most idiomatic way – in full understanding and reflection of one of my most common mantras: everything is best for something and worst for something else. The trick is knowing how best to use each, and when not to use something, and why.

To integrate into chapter:

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Casala, D., Guiard, Y. & Beaudouin-Lafon, M. (1999). Evaluating two-handed input techniques: Rectangle editing and navigation. *Proceedings of CHI’99 Extended Abstracts,* 236-237.

Carson, R., Thomas, J., Summers, J., Walters, M. & Semjen, A. (1997). The Dynamics of bimanual circle drawing. *The Quarterly Journal of Experimental Psychology.* 50A(3), 664-683.

Fallot-Burghardt, W., Fjeld, M., Speirs , C, Ziegenspeck , S., Krueger, H. & Läubli, T. (2006). Touch&Type: A Novel Pointing Device for Notebook Computers. *Proceedings of the 4th Nordic Conference on Human-Computer Interaction (NordiCHI 2006)*, 465-468.[3]

Hinckley, K., Czerwinski, M. & Sinclair, M. (1998). Interaction and Modeling Techniques for Desktop Two-Handed Input. *Proceedings of UIST '98,* 49-58.

Mottet, D., Guiard, Y., Ferrand, T. & Bootsma, R. (2001). Two-Handed Performance of a Ryhthmical Fitts Task by Individuals and Dyads. *Journal of Experiemntal Psychology: Human Perception and Performance,* 27(6), 1275-1286.

Raisamo, R. & Raiha, K. (1996). Techniques for aligning objects in drawing programs. *Proceedings of UIST'96,* 157-164.

[3] Note to self: see my notes on this paper.