Symmetric Bimanual Interaction

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ABSTRACT

We present experimental work that explores the factors governing symmetric bimanual interaction in a two-handed task that requires the user to track a pair of targets, one target with each hand. A symmetric bimanual task is a two-handed task in which each hand is assigned an identical role. In this context, we explore three main experimental factors. We vary the *distance* between the pair of targets to track: as the targets become further apart, visual diversion increases, forcing the user to divide attention between the two targets. We also vary the demands of the task by using both a slow and a fast *tracking speed*. Finally, we explore *visual integration* of sub-tasks: in one condition, the two targets to track are connected by a line segment which visually links the targets, while in the other condition there is no connecting line. Our results indicate that all three experimental factors affect the degree of parallelism, which we quantify using a new metric of bimanual parallelism. However, differences in tracking error between the two hands are affected only by the visual integration factor.

Keywords

two-handed input, symmetric interaction, Guiard theory, input, interaction techniques,

INTRODUCTION

Several promising two-handed interaction techniques have been described in the interface design literature [2, 3, 4, 10, 27, 28]. A solid theoretical basis for the design of such systems exists in the form of Guiard's Kinematic Chain theory [7, 8] and experimental studies in the human-computer interaction literature [1, 10, 11, 14] that have explored Guiard's theory as well as additional factors influencing cooperation of the hands when each hand is assigned a different, *asymmetric* role.

However, the literature suggests that a number of tasks that can be facilitated by two-handed input, such as two-handed line drawing, positioning and sizing a rectangle [5, 17], and 2D or 3D navigation [9, 16, 28] can be performed effectively with a *symmetric* assignment of roles to the hands. Unlike asymmetric two-handed interaction, which is well explained by the KC model, factors governing this second class of symmetric bimanual tasks have not been articulated as well in the research literature. Without better empirical data, there is little scientific knowledge to guide the design of interfaces that incorporate symmetric interaction techniques.

In this paper, we investigate how factors such as attention, task difficulty, and visual integration affect performance in a symmetric bimanual task. Of particular interest is whether symmetric bimanual tasks are fundamentally different from asymmetric bimanual tasks. At this point, it is important to note the difference between *task assignment* and *task performance*. Even if the task *assigned* to each hand is identical (i.e., symmetric), it is plausible that the combined task will not be *performed* in a symmetric and/or parallel manner. Under some conditions, it may be natural to perform a symmetric bimanual task in a sequential manner, moving one hand followed by the other, rather than moving both at the same time. The task could also be performed asymmetrically in the sense that one hand's performance could result in greater errors or poorer temporal performance than the other.

Note that we distinguish between symmetric and parallel performance. It is possible for bimanual performance to be sequential in nature, but nonetheless symmetric in the terms of error rate and/or time taken to perform each hand's subtask. Conversely, performance could be parallel (occur simultaneously) and yet asymmetric in terms of error and time measures. This raises the question of whether humans always perform symmetric tasks in a symmetric, parallel manner regardless of task difficulty, attentional demands, or visual integration of the sub-tasks assigned to each hand. Do users switch to a more sequential and/or asymmetric interaction style as these factors change?

Our results suggest that even when users are given a task with identical, symmetric role assignments for each hand, they do not always perform the task in a parallel, symmetric manner. We show that the lack of visual integration causes performance to become asymmetric in that root-mean square (RMS) error increases at a greater extent for the left

Published in Proceedings of 2000 ACM Conference on Human Factors in Computing Systems (CHI'2000), pp 33-40

hand[1]. Also, divided attention, task difficulty, and the lack of visual integration can all affect the degree of parallelism exhibited when performing the symmetric bimanual task. These results suggest that under some conditions, existing models of bimanual interaction [7, 21] may apply to tasks with a symmetric assignment of roles to the hands.

PREVIOUS WORK

There are several examples of symmetric two-handed interaction techniques in the literature. These include two-handed map manipulation [9], a two-handed “bulldozer” metaphor for 3D navigation [28], and symmetric rectangle and line editing [5, 17]. Furthermore, in the workflow of some two-handed input systems (e.g. Kurtenbach et. al. [16]) one can observe fluid transitions between asymmetric and symmetric two-handed actions, such as using a ToolGlass [3].

Leganchuk et. al. [17] used a rectangle editing task to reason about cognitive benefits of bimanual interaction. They showed that two different bimanual rectangle editing techniques resulted in superior performance to a unimanual technique. However, they found no difference between the bimanual technique that consistently assigned identical tasks to each hand (i.e., symmetric task assignment) and another technique that fluidly switched between asymmetric and symmetric task assignment.

Casalta and Guiard [5] found that in a rectangle editing task, symmetric task assignment resulted in better performance, as well as increased bimanual parallelism, than an asymmetric task assignment. This result suggests that for some tasks, a symmetric assignment of roles to the hands can result in better performance than an asymmetric role assignment.

Hinckley et. al. [9] describe a technique for two-handed manipulation (panning, zooming, and rotation) of maps. Their mapping of the degrees-of-freedom results in a technique that supports both symmetric and asymmetric use of the hands. For example, the user may zoom on a particular location by “pinning down” that location with one hand and “stretching” the map with the other hand; or conversely, the user may perform a more coarse zooming operation by moving both hands in opposite directions.

Balakrishnan and Kurtenbach [2] explore bimanual camera control and object manipulation. They report that in a 3D object docking task, subjects invariably adopt a symmetric style of interaction even though they could have adopted a asymmetric style of interaction to reduce the number of degrees-of-freedom that need to be controlled at once.

A number of bimanual tasks with a symmetric assignment of roles to the hands have been studied in the psychology and motor behavior literatures, including bimanual pointing to separate targets [15, 18, 25], bimanual tapping of rhythms [21, 26], circle drawing [24], and bimanual steering [22, 23].

Kelso, Southard, and Goodman [15] explore a two handed tapping task with targets of disparate difficulty for each hand (i.e., the task assignment is symmetric in that each hand performs a tapping task, but asymmetric in that the difficulty of each hand's task is different). They find that while the hands move at different speeds to different points in space, times to peak velocity and acceleration are highly synchronized. Thus, in a sense, performance is symmetric and parallel even though the task assignment is not completely symmetric.

Marteniuk, MacKenzie, and Baba [18] describe a similar experiment to Kelso et. al. [15]. From both their own data and a reanalysis of Kelso et. al.'s [15] data, they report some evidence for a left-right asymmetry between the two hands. In a more recent study, Jackson, Jackson, and Kritikos [12] find that in more complicated "reach and grasp" bimanual task, kinematic measures of performance are unaffected when each hand performs movements of identical or different levels of difficulty. They find that movements of both hands are scaled to a common time duration, whereas movement velocity and grip aperture are scaled independently. Hence, their data seems to support the findings of Kelso et. al. [15].

In a symmetric circle drawing task, Swinnen, Jardin, and Meulenbroek [24] report a distinct asymmetry in performance. Interestingly, they find that the dominant hand leads the non-dominant hand during the task. This is in contrast with Guiard's KC model, which postulates that the non-dominant hand precedes the dominant hand in the performance of asymmetric tasks. They also report that attentional cueing affects the size of the asymmetry: the amount of asymmetry (phase offset between the limbs) increases when subjects are told to monitor the dominant hand, and decreases when subjects are told to monitor the non-dominant hand.

Preilowski [22, 23] explored a two-handed steering task using hand cranks, each of which controls one degree-of-freedom of a cursor. After practice, normal subjects can steer the cursor (i.e., both hands are performing somewhat symmetrically and in parallel) without visual feedback, whereas patients with damage to the anterior commissure cannot. His focus however, was not on the symmetry/asymmetry and parallel/sequential issues per se.

In short, there appear to be many unresolved issues regarding symmetric bimanual tasks and exactly how these differ from, or when they may be preferable to, asymmetric assignments of roles to the hands. Prior studies have not quantified potential factors that may drive symmetric bimanual performance. The psychology and motor control literature are also inconclusive as to how bimanual tasks that assign essentially symmetric roles to each hand are performed. Some evidence [12, 15, 22, 23] suggests that

[1] For convenience, since the current experiment used only right-handed participants, we always refer to the preferred hand as the right hand and the nonpreferred hand as the left hand. For left-handers, these hand roles would be reversed.

performance is mostly symmetric, whereas others [18, 24] indicate asymmetric performance with attention being a contributing factor. The literature therefore suggests that this is an area in need of further experimental study.

EXPERIMENT

Task and Stimuli

We chose a bimanual target tracking task for two main reasons. First, the standard target docking or selection task that is widely used in motor behavior studies is unsuitable for our purposes because the only way to vary the difficulty of the task is to change the size of the target and its distance from the starting point. A large part of the task is therefore simply getting to the vicinity of the target; only at the last phase of the task does the size of the target affect performance. Hence, task difficulty does not apply uniformly throughout the task. In contrast, the task difficulty in a tracking task can be made to apply uniformly throughout the task (since the user must always attempt to stay on target), providing us with a rich set of data. Second, to the best of our knowledge, apart from Preilowski [22, 23], bimanual target tracking has not been studied in the literature. Thus, the present study contributes to the literature in the task aspect as well. Note that this tracking task is not intended to necessarily be representative of any particular symmetric bimanual user interface. Rather, we use this task as an experimental instrument to explore factors that can influence bimanual performance.

Participants tracked targets with both hands. There were two main conditions that varied the level of integration of the visual stimuli:

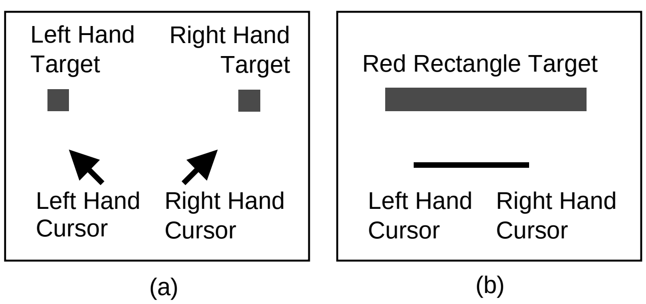

Figure 1. Experiment Stimuli. (a) Stimuli for the *Separated* condition. The Left and Right hand cursors are used to track the Left and Right hand targets, respectively. The distance between the centers of the targets are kept constant for a trial at either 100 or 840 pixels. (b) Stimuli for the *Integrated* condition. The Left and Right cursors control the position, orientation, and length of the line. The cursors themselves are not shown. The user tracks the red rectangle with the line. The length of the red rectangle is kept constant for a trial at either 100 or 840 pixels. None of the text in this diagram is displayed during the experiment.

Separated targets - Two red square (20x20 pixel) targets appeared at a given distance to the left and right of the center of the screen (Figure 1a). Participants controlled a white colored cursor with each hand. The left hand cursor always pointed towards the left side of the screen, the right hand cursor pointed towards the right. Participants were told to track the left square with the left cursor, and the right square with the right cursor. The two targets moved around the screen in a pseudorandom fashion, with the constraint that the movements of both targets were symmetric in the sense that they each moved the same amount in a given direction at a given time. The distance between the targets, and amount of movement at each time step (i.e., speed), were kept constant for a given trial (distance and speed were manipulated as experimental conditions). The background color of the screen was black throughout the experiment.

Integrated target - A single red rectangular (size: 20 pixels wide x *distance* pixels long) target appeared centered on the screen (Figure 1b). Instead of two cursors, a straight white line was drawn between the positions of the left hand and right hand cursors (the cursors were not shown). Participants were told to match the position, orientation, and length of the white line with that of the red rectangle. The rectangle moved around the screen in the same pseudorandom manner as the targets in the *Separated* condition. Essentially, the end points of the red rectangle were the same as the center points of the two targets in the *Separated* condition; henceforth we will refer to these as the "target points".

From the motor domain perspective, both *Separated* and *Integrated* conditions are identical in that the same motor actions are required to track the target(s). In the visual domain, however, they differ in that the *Separated* condition could be perceived as being two separate tasks whereas the *Integrated* condition could be perceived as being a single, integrated task [6].

The attentional demands of the task were manipulated by varying the distance between the target points. Two distances were used: 100 and 840 pixels. In the 100 pixel or *Singular Attention* condition, both target points (i.e., both targets in the *Separated* condition and the entire target in the *Integrated* condition) were visible in the participant's focal visual field. Thus, the participant only had to attend to a single area of on the screen at any one time. In the 840 pixel or *Divided Attention* condition, it was impossible to attend to both target points at the same time. This resulted in the participant having to divide attention between two areas of the screen.

The difficulty of the task was manipulated by varying the speed at which the target(s) moved. Two speeds were used: *Slow* (1 pixel/frame – the target moved 1 pixel in each of the x and y directions per frame update), and *Fast* (2 pixels/frame). The frame rate was kept constant at 60Hz

Apparatus

The experiment was conducted on a graphics accelerated two-processor workstation running Windows NT, with a 21-inch, 1280x1024 resolution, color display. Two pens on a Wacom Intuos 12x18 inch digitizing tablet were used as the input devices. The tablet was sampled at a constant rate of 60Hz, and the graphics update rate was also kept constant at 60Hz.

Participants

Eight right-handed volunteers participated in the experiment.

Design

A within-subjects repeated measures design was used. All participants performed the experiment for both the *Separated* and *Integrated* conditions. The presentation order of these two conditions was counterbalanced across the participants (Participants #1,3,5,7 did the *Separated* condition followed by the *Integrated* condition. Participants #2,4,6,8 did the *Integrated* condition followed by the *Separated* condition). For each condition, participants performed 7 blocks of trials. The first block of trials was considered to be practice trials and was excluded from the data analysis. Therefore, a total of 6 blocks of trials were used in the analysis. Each block consisted of 1 trial for each of the four combinations of attention and speed conditions. The presentation of these four trials within each block was randomized. Each trial lasted for 45 seconds. Participants were allowed breaks between trials. The experiment consisted of 384 total non-practice trials, as follows:

8 participants x
2 visual integration conditions (*Separated, Integrated*) x
6 blocks of trials for each integration condition x
2 attention conditions (*Singular, Divided*) per block x
2 speed conditions (*Slow, Fast*) per block
= 384 total trials of 45 seconds each.

For each participant, the experiment was conducted in one sitting and lasted about one hour.

Participants initiated a trial by positioning the two cursors over the two targets (in the *Separated* condition. In the *Integrated* condition, they matched the position, orientation, and length of the white line with the red rectangle). No button presses were required. The target(s) then begin to move in a pseudorandom fashion for 45 seconds at the speed fixed for that trial. At the end of 45 seconds, the screen went blank for 2 seconds, and the next trial's stimuli were presented. The movement trajectories were precomputed and the same set of four trajectories (one for each attention x speed condition) was used for all the blocks in both the *Separated* and *Integrated* conditions. The use of a fixed set of trajectories allowed for a fair comparison between the conditions.

Hypotheses

We expect to find the following effects in our experimental data:

H1. The *Integrated* visual stimuli conditions will result in more accurate tracking than the *Separated* conditions.

H2. The *Singular Attention* conditions will result in more accurate tracking than the *Divided Attention* conditions.

H3. The *Slow* speed conditions will result in more accurate tracking than the *Fast* speed.

While accuracy is an important measure of performance in tracking tasks, the primary goal of this study is not to evaluate tracking performance per se. Rather, we are interested in how the experimental manipulations of visual integration, attentional demands, and task difficulty affect the level of parallelism and symmetry exhibited by the user when performing a symmetric bimanual task where each hand is assigned identical functional roles.

Two-handed performance can be considered to occur symmetrically, or in parallel, or possibly both (or neither). In the present discussion, we say that the two hands exhibit *symmetric* performance if the average root mean square (RMS) tracking error exhibited by the hands over the course of a trial have equal values – that is, if the difference in tracking error between the left hand and the right hand is statistically indistinguishable. Note, however, that this measure of symmetry ignores bimanual performance in the *time* dimension: the user might exhibit performance which, for example, adjusts only the right hand, and then only the left hand.

By contrast, our measure of *parallel* bimanual performance does consider time, by quantifying the *simultaneous magnitude and direction of movement* of each hand, using a new metric that is discussed later in this paper. By distinguishing symmetrical performance from parallel performance, our analyses take into account two different interpretations of bimanual performance, allowing us to produce a more complete characterization of our experimental results.

Accordingly, we further hypothesize that:

H4. The *Integrated* visual stimuli conditions will be performed more symmetrically than the *Separated* conditions.

H5. The *Singular Attention* conditions will be performed more symmetrically than the *Divided Attention* conditions.

H6. The *Slow* speed conditions will be performed more symmetrically than the *Fast* speed conditions.

H7. The *Integrated* visual stimuli conditions will be performed with greater parallelism than the *Separated* conditions.

H8. The *Singular Attention* conditions will be performed with greater parallelism than the *Divided Attention* conditions.

H9. The *Slow* speed conditions will be performed with greater parallelism than the *Fast* speed conditions.

Results

Overall Tracking Performance

Our first measure of tracking performance was the root mean square (RMS) error between each cursor position and the corresponding target point at each time step ($1/60^{th}$ of a second) during the trial. The average RMS error for each hand per trial was computed, resulting in two RMS error metrics: RMS_{rh} for the right hand average RMS error, and RMS_{lh} for the left hand average RMS error. In addition a compound metric, $RMS_{tot} = RMS_{lh} + RMS_{rh}$, was computed to represent the total RMS error per trial.

The overall mean RMS_{tot} for our experimental conditions is shown in Figure 2. Repeated measures analysis of variance with RMS_{tot} as the dependent variable was conducted on the data. Overall, there was no significant difference between the two visual integration (*Separated, Integrated*) techniques ($F_{1,6} = 4.8$, p=0.06). Thus, using RMS_{tot} as the performance measure, hypothesis H1 is not confirmed. There was a significant effect for the attentional (*Singular* vs. *Divided Attention*) factors ($F_{1,6} = 109$, $p<0.01$), with *Singular Attention* resulting in superior performance, thus confirming hypothesis H2. A significant effect was found for the speed (*Slow* vs. *Fast*) factors ($F_{1,6} = 87$, $p<0.01$), with *Slow* speed resulting in superior performance, thus confirming hypothesis H3. The only other significant effect was an *Attention* x *Speed* interaction ($F_{1,6} = 6.62$, $p<0.05$), indicating that when tracking at the faster speed, divided attention has a greater effect.

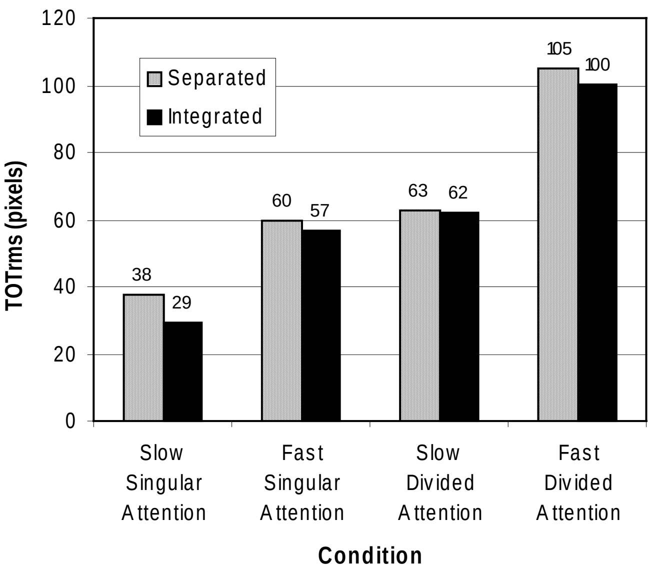

Figure 2. Overall tracking performance as measured by *RMStot*, broken down by the experimental factors. Data for all trials from all 8 participants.

Symmetry Analysis

Looking at the differences in performance between the two hands (Fig. 3), we find that the overall difference between performance of the right hand (RMS_{rh}) and the left hand (RMS_{lh}) was 8%, indicating that there was a slight asymmetry between the hands overall, although this result was not significant (p=0.07). Repeated measures analysis of variance conducted with the difference between RMS_{rh} and

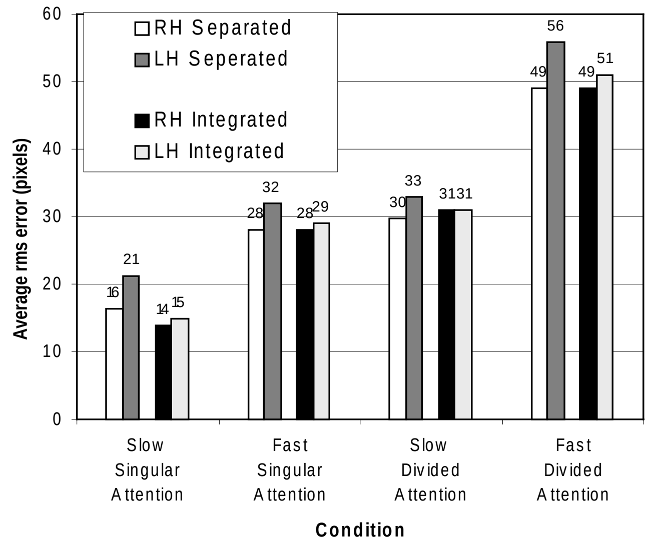

Figure 3. Tracking performance for each hand, broken down by experimental factors. Data for all trials from all 8 participants.

RMS_{lh} as the dependent variable showed a significant difference between the two visual integration conditions ($F_{1,6} = 7.6$, $p<0.05$). As the slopes in Figure 4(a) show, the RMS_{lh} measure was significantly higher than the RMS_{rh} measure for the *Separated* conditions, but did not differ significantly for the *Integrated* conditions. This result indicates that poor visual integration causes performance to become asymmetric, confirming hypothesis H4. There was no significant effect for the attention factor ($F_{1,6} = 3.14$, $p>0.05$) or the speed factor ($F_{1,6} = 0.94$, $p>0.05$), as illustrated by the identical slopes in Figures 4b and 4c). Thus, hypotheses H5 and H6 were not confirmed.

Parallelism Analysis

In order to analyze the level of parallelism exhibited by the two hands, we need an appropriate measure of parallelism. One such measure is the "Integrality" metric introduced by Jacob et. al. [13]. They proposed a means of quantifying parallelism (we use the term "parallel" instead of "integral" as originally proposed) in the time domain, based on whether movements in the dimensions of interest occurred simultaneously at each time step. This measure, however, classifies a set of movements as parallel as long as they moved by any amount during a time period. The relative magnitude and direction of movement in each dimension of interest is not taken into account.

Masliah [19] has proposed the m-metric to quantify coordination in multi-degree-of-freedom docking tasks. The m-metric takes into account the magnitude and direction of movement of each dimension of interest when computing simultaneity. The metric as originally proposed is only applicable to docking tasks. Here, we adapt it to measure parallelism in a tracking task. The basic idea behind this measure is to first compute how much the error between the

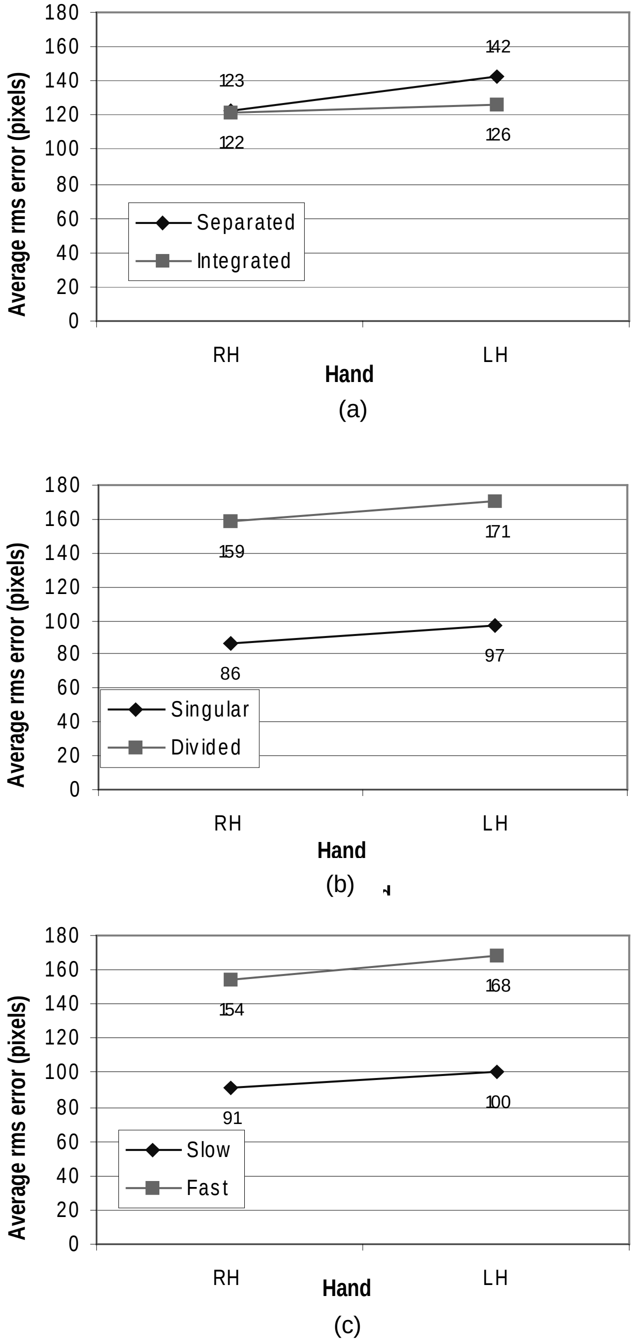

Figure 4. Tracking performance for each hand for (a) the two visual integration conditions, (b) the two attention factors, (c) the two speed factors.

current position and the target position is reduced at each time step. This percentage error reduction per time step is computed for each hand as follows:

$$\%ER = \frac{\text{actual magnitude of movement towards target}}{\text{movement required to reduce error to 0}}$$

This results in a number between 0 and 1, where 1 means the cursor is perfectly tracking the target and 0 means the cursor is not following the target at all.

The amount of parallelism at each time step is then calculated by taking the ratio of the two hand's %ER values, with the larger value taken as the denominator:

$$\text{Parallelism} = \frac{\text{Right Hand's \%ER}}{\text{Left Hand's \%ER}}$$

The average of all Parallelism measures over the duration of a trial thus results in a bounded measure between 0 and 1. Values closer to 1 indicate that both hands are simultaneously reducing their errors by the same amount (i.e., highly parallel, identical, movements), whereas values closer to 0 indicate that the hands are working in a sequential manner.

This metric not only considers if motion of the two hands is simultaneous, but also takes into account the magnitude and direction of any simultaneous motion. Thus, movements that occur at the same time but which do not contribute towards the accurate completion of the task are given much less weight in the metric. We feel that this results in a more meaningful measure of bimanual parallelism.

We analyzed our experimental data using this new parallelism metric. Figure 5 shows the mean parallelism values for each condition.

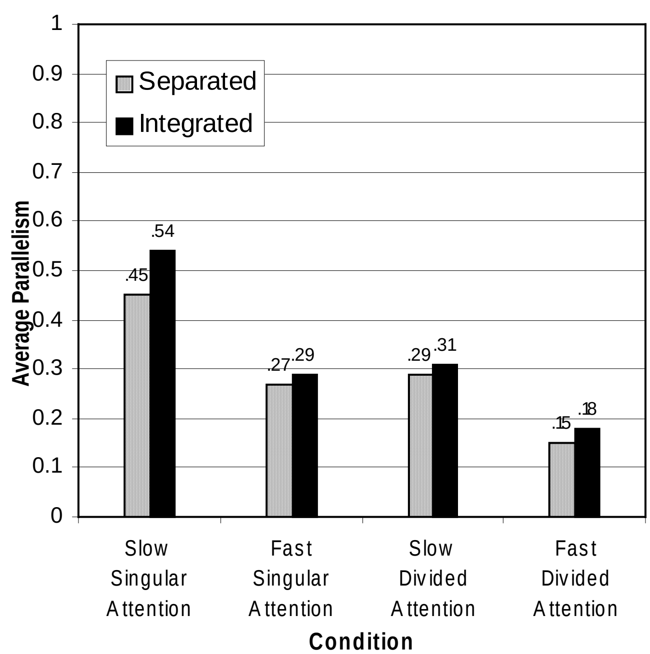

Figure 5. Parallelism between the two hands, broken down by experimental factors. Values close to zero indicate little parallelism, values close to 1 indicate a high degree of parallelism. Data for all trials from all 8 participants.

Overall, parallelism was not very high, at 0.31 units. There was a significant effect for the two visual integration conditions ($F_{1,6}$ = 7.28, p<0.05), with the *Integrated* conditions exhibiting 12% more parallelism than the *Separated* conditions, thus confirming hypothesis H7.

Hypothesis H8 was also confirmed by a strong significant effect for the two attentional factors ($F_{1,6}$ = 108, p<0.01), with *Singular Attention* conditions showing more parallelism than the *Divided Attention* conditions.

Hypothesis H9 was confirmed by a significant effect for the two speed factors ($F_{1,6}$ = 46, p<0.01), with *Slow* conditions showing more parallelism than the *Fast* conditions.

CONCLUSIONS AND FUTURE WORK

We have presented experimental work that explores issues surrounding symmetric bimanual action. We also introduced a new metric, adapted from the coordination metric of Masliah [19], which quantifies the extent to which movements of the hands occur in parallel. The analysis of our data using this parallelism metric showed that increasing task difficulty, divided attention, and lack of visual integration can all cause the user to adopt a more sequential style of interaction.

Overall, our data showed a slight asymmetry (albeit not statistically significant at the 5% confidence level) with respect to RMS tracking error, with the left hand having 8% higher error than the right hand. We also found that a lack of visual integration results in significant asymmetry between the hands. Attentional demands and task difficulty, however, did not affect the level of symmetry in performance (i.e., both hands exhibited similar RMS tracking error rates).

Taking the symmetry and parallelism analyses as a whole, we see that decreased parallelism does not (except when visual integration is lacking) cause performance as measured by RMS tracking error to become more asymmetric. In other words, parallelism is not a requirement for performance to be symmetric.

From a practical viewpoint, although we used a bimanual tracking task as an experimental instrument to explore issues that can affect bimanual performance, and not necessarily to be representative of any particular symmetric bimanual user interface, the results can nonetheless yield design insights for symmetric bimanual interfaces. For example, our finding that lack of visual integration does not lend itself to symmetric interaction suggests that for a symmetric task like two-handed rectangle editing [5, 17] it would be not be good design to merely display the corners of the rectangle (as is sometimes done in the interest of not obscuring underlying geometry).

Also, our finding that dividing attention results in highly sequential performance suggests that symmetric tasks where the two hands are not operating nearby in the focal visual field should be avoided. This may be one reason that symmetric bimanual interaction lends itself to navigation tasks [9, 16, 28]. In a navigation task such as steering through a 3D environment [28], visual flow occurs across the entire display window in response to two-handed movements, so the focal visual field can provide sufficient feedback. A problem might arise in a bimanual interface using two cursors that may become widely separated, unless some secondary feedback in the focal visual field can be provided. For example, the map navigation example of [9] employs separate cursors for each hand, but the continuous visual flow of real-time feedback from the map moving, expanding, or shrinking provides sufficient feedback. If only two separate cursors were provided, our results suggest that the user's ability to control symmetric bimanual actions could be compromised.

From a theoretical perspective, given that our results show a slight general asymmetry in the performance of symmetric bimanual tasks, it is possible that existing theoretical models of asymmetric bimanual interaction [7, 21] could apply to symmetric bimanual tasks as well. However, since we also found that the level of symmetry does not easily degrade when task difficulty is increased or attention is divided, it is likely that performance in symmetric tasks also differ fundamentally in some aspects from asymmetric tasks. For example, our data clearly indicates that for symmetric tasks there is no tendency for the human motor system to devote more resources to the dominant hand when attention is divided.

By contrast, previous work by Peters [20] shows that when independent, asymmetric tasks are assigned to each hand, there is a tendency to devote more resources to the dominant hand. To the best of our understanding, the effect of task difficulty and visual integration on the performance of asymmetric bimanual tasks has not been explored. As such, we cannot draw any conclusions as to whether symmetric and asymmetric tasks differ along these factors. Clearly, more research is needed to quantify these differences and thus build better models that account for both symmetric and asymmetric bimanual tasks. The work presented in this paper is a step towards a more comprehensive understanding of symmetric (as well as asymmetric) two-handed interaction, including a better understanding of under what conditions symmetric, parallel action of the hands is possible.

ACKNOWLEDGEMENTS

We thank Bill Buxton, George Fitzmaurice, Gordon Kurtenbach, Russell Owen, and Jade Rubick for advice and assistance in various forms throughout the course of this work. We also thank all those who participated in our experiment, and Alias|wavefront and Microsoft for supporting this collaborative research study.

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