

S. Riek · J. R. Tresilian · M. Mon-Williams ·
V. L. Coppard · R. G. Carson

Bimanual aiming and overt attention: one law for two hands

Received: 8 December 2002 / Accepted: 25 June 2003 / Published online: 16 August 2003
© Springer-Verlag 2003

Abstract Reaching to interact with an object requires a compromise between the speed of the limb movement and the required end-point accuracy. The time it takes one hand to move to a target in a simple aiming task can be predicted reliably from Fitts' law, which states that movement time is a function of a combined measure of amplitude and accuracy constraints (the index of difficulty, ID). It has been assumed previously that Fitts' law is violated in bimanual aiming movements to targets of unequal ID. We present data from two experiments to show that this assumption is incorrect: if the attention demands of a bimanual aiming task are constant then the movements are well described by a Fitts' law relationship. Movement time therefore depends not only on ID but on other task conditions, which is a basic feature of Fitts' law. In a third experiment we show that eye movements are an important determinant of the attention demands in a bimanual aiming task. The results from the third experiment extend the findings of the first two experiments and show that bimanual aiming often relies on the strategic co-ordination of separate actions into a seamless behaviour. A number of the task specific strategies employed by the adult human nervous system were elucidated in the third experiment. The general strategic pattern observed in the hand trajectories was reflected by the pattern of eye movements recorded during the experiment. The results from all three experiments demonstrate that eye movements must be considered as an important constraint in bimanual aiming tasks.

Keywords Movement · Planning · Preparation · Prehension

Introduction

Many skills rely on the two hands moving to separate locations but arriving at their respective destinations almost simultaneously or in a precise temporal order. Some of these skills require similar movements from the two limbs (symmetrical) whilst others demand different movements from the two limbs (asymmetrical). The movements can either be executed simultaneously (synchronous) or in a sequential or staggered order (asynchronous). A body of evidence supports the idea that bimanual synchronous movements can share a common timing in their respective control signals for both symmetrical and asymmetrical movements of the two limbs (Hering 1868/1977; Kelso et al. 1979a, 1979b; Kelso and Schöner 1988; Sugden and Utley 1995; Corbetta and Thelen 1996; Steenbergen et al. 1996). This suggests that the nervous system prefers to place temporal constraints upon the two limbs in order that they 'act together as a single unit' (Hering 1868/1977; Kelso et al. 1979a, 1979b). How does the nervous system temporally coordinate the actions of the two hands when they are required to make movements of dissimilar amplitude? To address this question, a number of researchers have used a manual aiming paradigm in which the two hands are required to move from rest to spatial targets (e.g., Kelso et al. 1979a, 1979b; Marteniuk et al. 1984; Fowler et al. 1991).

Unimanual, target-directed aiming tasks in which the size and distance of the target are independent variables and movement parameters such as movement time (MT) and speed are dependent measures, lead to performance that is well described by Fitts' law (Fitts and Peterson 1964). This law describes the empirical relationship between the dependent and independent variables and may be written as follows:

S. Riek (✉) · J. R. Tresilian · V. L. Coppard · R. G. Carson
School of Human Movement Studies,
University of Queensland,
4072 St. Lucia, Queensland, Australia
e-mail: sriek@hms.uq.edu.au
Tel.: +61-7-33656107
Fax: +61-7-33656877

M. Mon-Williams
School of Psychology Mathematics and Computing,
University of Aberdeen,
Old Aberdeen, AB24 2UB Aberdeen, Aberdeenshire, Scotland

$$MT = a + b \log_2(2A/W) \quad (1)$$

where a and b are constants which depend upon the individual and the task, A is the movement amplitude and W is a measure of target size. $\log_2(2A/W)$ is referred to as the index of difficulty (ID). Kelso et al. (1979a, 1979b) reported that the two hands show almost perfect temporal synchrony when making simultaneous movements to targets of different width or disparate amplitude. On the basis of this observation, Kelso et al. drew the following conclusions: (i) asymmetrical limb movements share common temporal control; (ii) Fitts' law is violated.

While the basic finding of bimanual synchrony in asymmetric movement has been replicated (Marteniuk et al. 1984; Fowler et al. 1991), except in conditions with a high degree of task difference (Corcos 1984), there remains considerable discussion over the degree of synchrony. In addition, no opposition to the notion that Fitts' law is violated in such movements has arisen (e.g., Kelso et al. 1979a, 1979b; Marteniuk et al. 1981; Fowler et al. 1991). The claim that Fitts' law is violated is based upon the following line of reasoning (see, e.g., Schmidt 1988, p. 259, for a textbook exposition). If the right hand, for example, aims for a target with a low ID the movement time will be shorter than the time of a movement aimed at a high ID target, as described by Fitts' law. The same result holds if the left hand is used. When the two hands aim simultaneously at these targets—the right hand to the low ID target and the left to the high ID target, for example—the MTs of the two hands are almost the same and not “markedly different as Fitts' law (and common sense) would predict” (Schmidt 1988, p. 259), with the hand moving to the low ID typically displaying a marked increase in movement time compared with unimanual movement to the same ID. This argument is based on an implicit assumption that has been shown empirically to be false.

The argument claims that Fitts' law predicts that MTs of the two limbs in a bimanual aiming task with targets of different ID should be “markedly different”. This prediction is based on MTs observed in a unimanual task. The implicit assumption is that Fitts' law type relationships observed in one task (unimanual aiming) should describe performance in another task (bimanual aiming). This assumption is typically found to be false: when Eq. 1 is fit to data from different types of aiming task the values of the constants a and b vary between tasks. To emphasise this fact, Fitts' law might be expressed as follows:

$$MT = a(T) + b(T)ID \quad (2)$$

where $a(T)$ and $b(T)$ are variables which depend upon the task T . Thus, a Fitts' law relationship with particular values for the constants a and b (Eq. 1) will fit data obtained within a specific task context but not data from other task contexts. There is no reason to suppose that aiming one hand at a target when the other is not moving is the same task as aiming the hand at the target when the other hand is itself aiming at a target. Indeed, these two tasks are clearly different and it would not be expected

that the Fitts' law relationship found for one would be the same as that found for the other. Thus, synchrony in bimanual aiming movements when the hands reach to targets of different ID does not, in itself, disconfirm Fitts' law.

In this paper we present results from three experiments designed to investigate speed and accuracy relationships in bimanual aiming tasks. In the first two experiments we examine whether Fitts' law holds in bimanual aiming tasks and under what conditions. It is shown that Fitts' law holds very well for the aiming movement of one of the two limbs when the task conditions for that limb can be considered to be more or less constant. In the third experiment, we explore the allocation of overt attention in bimanual aiming by observing eye-movements during performance.

Experiment 1

Materials and methods

Six right-handed adults (three males and three females with good eyesight and no movement problems) aged between 22 and 30 years volunteered to participate in the experiment for no reward. Participants gave their informed consent prior to their inclusion and all experiments and procedures conformed to the Declaration of Helsinki and were approved by the University of Queensland's Medical Ethics Committee. The experimental task required participants to sit at a table and move styli held in the right hand, left hand or both hands from a starting position through the air to various targets located further away from their body in the sagittal plane. The starting point was always 6 cm from the edge of the table: the targets varied in both amplitude and size. Two target amplitudes were used: one target position was 6 cm and the other 24 cm from the starting point. There were two sizes of target: one was 1 cm and the other was 4 cm in diameter. These different parameters were calculated using Eq. 1, so that the small and large targets could have an equal index of difficulty (ID) according to the distance that they were placed at. Consequently, when the smallest diameter target was placed in the near position (6 cm), the ID was the same as when the large diameter target was 24 cm away. The starting points for the right and left hand were separated by 12 cm in the coronal plane. Participants were seated with the midline of their body centered between the starting positions. The stylus on the right was always used to switch off targets on the right and the stylus on the left was always used to switch off targets on the left (i.e., the styli never crossed the midline). All possible combinations of amplitude, size and hand (right, left and bimanual) were used, giving a total of 24 conditions (8 unimanual and 16 bimanual). Each participant completed five trials for each condition: the order of presentation was randomised.

All of the targets were located on a box (8×5 cm): hitting the target switched off a small light emitting diode located on the box and stopped the box emitting a loud 'buzz'. The experimenter would activate one box (unimanual conditions) or two boxes (one for the right and one for the left hand activated simultaneously) so that the light(s) on the activated box(es) would be illuminated and the box(es) would begin to emit a noise. The activation time was taken as the beginning of the recording and the time that the target was depressed was taken as the end of the movement. The boxes (two for the right hand and two for the left) were attached temporarily to the desktop to allow for smooth and efficient re-positioning during the experimental session. All four boxes were in position during the experiment and the participants were not precued as to which targets they would be required to move to (limiting the potential for pre-planning the movement). In all conditions the participants held the styli in a 'pencil-grip' and

depressed the button with the tips of the styli. The participants were always asked to move as quickly and as accurately as possible to switch off the light/noise. No instructions were ever given to the participants to move both hands simultaneously. If the target was missed, the trial was excluded and repeated at a later stage in the experiment (less than 2% of trials). Five familiarisation trials were completed before recording took place.

The kinematics of the hand trajectories were measured in 3D using an Optotrak movement recording system. This system measures the position of small infra-red light emitting diodes (IREDs) and is factory pre-calibrated with a positional resolution of within 0.1 mm. The IREDs on the styli were positioned 2 cm from the tip which was used to depress the targets. Data were collected at 200 Hz and stored on computer. The data analysis was conducted using custom programs written in a Labview software application (version 3.1, National Instruments). IRED data were filtered using a dual-pass Butterworth second order digital filter with a 12 Hz cut-off (equivalent to a fourth order filter with no phase lag and a cut-off of 9.63 Hz). The transport component of each hand was analysed by calculating the tangential speed (square root of the sum of square of the numerical derivatives of the x , y , and z coordinates of the IREDs). The movement onset was calculated using an automatic movement parsing algorithm (Teasdale et al. 1993; algorithm B). Movement offset was calculated using the same algorithm which was working in reverse. Both onsets and offsets were verified by visual inspection by the experimenter; any error was corrected.

Results

Two components of the data were considered: reaction time (determined from the tangential speed profile) and the movement time (time from movement onset to movement offset determined by depression of the target button). The means across the six participants were obtained from the median of the five trials for each participant in each condition. The upper plots of Fig. 1 (panels A and B) show the relationship between index of difficulty and the movement time for the right and left hand in the unimanual conditions. The high coefficient of determination (R^2) indicates that Fitts' law adequately describes the MT data for the right limb as its target ID is varied. A repeated measures analysis of variance on the medians showed a reliable effect for condition, $F_{(3,20)}=3.652$, $p<0.05$, and hand, $F_{(1,20)}=13.68$, $p<0.05$, indicating that: (i) movement time increases as a function of task difficulty and (ii) the left hand moves more slowly than the right. While it is expected that, with all else being equal, the dominant and non-dominant hands would display differences, planned comparisons between the movement times to targets of equal index of difficulty showed no reliable differences for either the right or the left hand.

The middle two plots in Fig. 1 (panels C and D) show the relationship between MTs of the right and left limbs and their target IDs for those trials in which the other limb moved 6 cm (to the short target). The correlation coefficient indicates that the movement time of a particular hand was predictable from the target ID consistent with Fitts' law. It is important to note that each participant's data were also examined and that the relationships we report across participants were consistent for individuals (apart from one condition highlighted

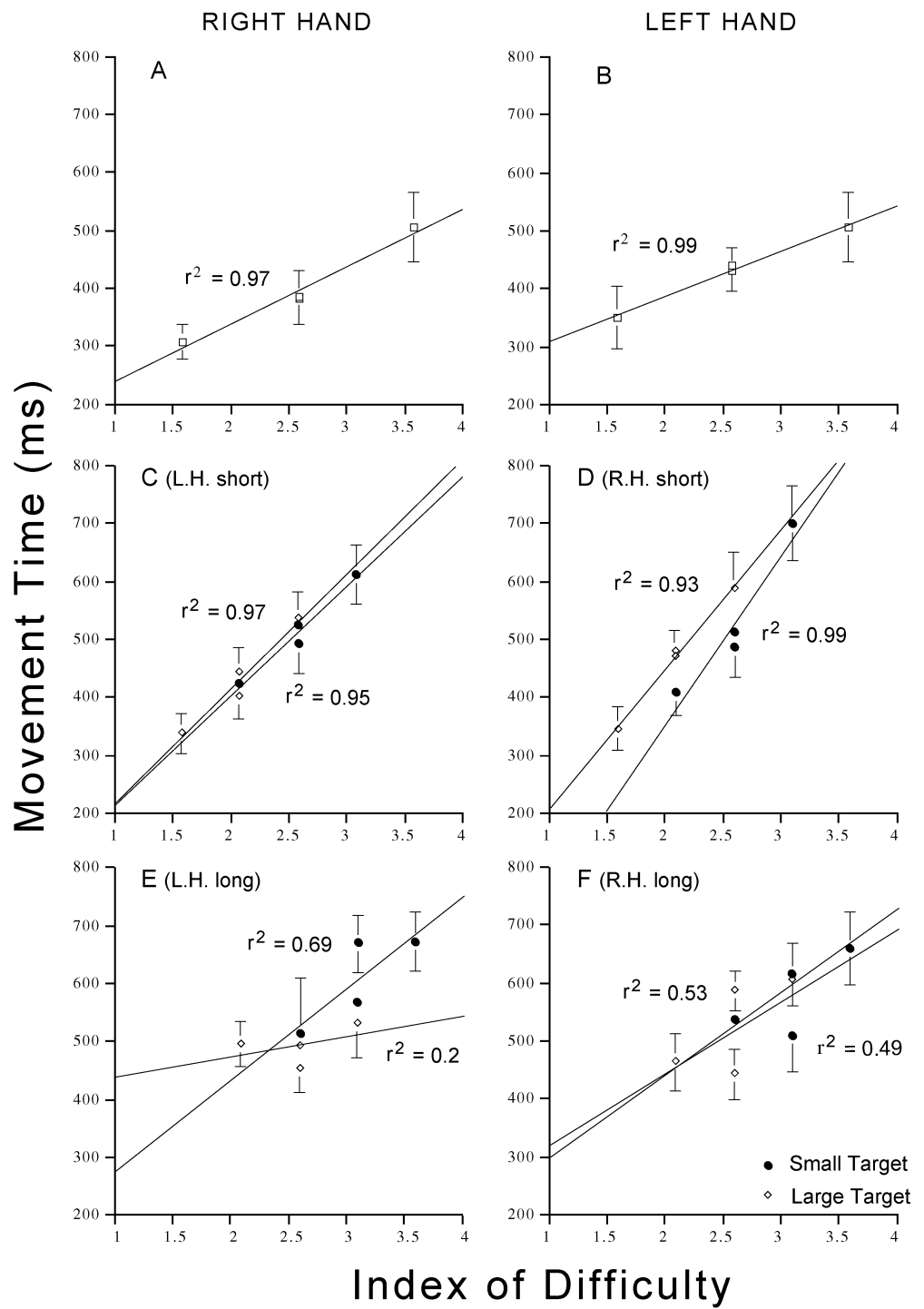
below). The differences between the unimanual and bimanual correlation coefficients were not statistically reliable (Fisher's transformation).

The lower plots of Fig. 1 (panels E and F) show the relationship between MTs of the right and left limbs and their target IDs for those trials in which the other limb moved 24 cm (to the long target): the relationship weakens in these conditions. In the data from the left hand, the lower coefficient of determination for both target sizes (0.53 for the small and 0.49 for the large) is due to a decrease in MT when the right hand moves to the large target far away. These data suggest that facilitation between limbs occurs when moving through a longer distance (as suggested by Kelso et al. 1979a, 1979b). A similar facilitation effect appears to occur when the right hand moves to a large target far away whilst the left hand moves the same distance to the same sized target. It should be noted that this was the only condition in which the individual data and the group data did not correspond: the mean coefficient of determination across individual participants was 0.53 (SE=0.09). The coefficient (0.69) found when the left hand moved towards the small target far away is due to an increased MT when the right hand moved to the small close target.

The bimanual data were also studied in relation to reaction times of the movement. The bimanual data could be split into three groups: one group consisting of four conditions where both targets were at 6 cm, one group consisting of four conditions where the targets were at 24 cm and the other group containing eight conditions where the targets were at unequal distances. A repeated measures analysis of variance on the means of each group showed a reliable effect for condition, $F_{(2,13)}=8.46$, $p<0.05$, but not for hand. It was expected that reaction time would increase as a function of task difficulty as initially shown by Fitts and Peterson (1964). Planned comparisons revealed that the unequal bimanual movements had the longest reaction time while the equal amplitude 24 cm movements had a greater reaction time than the equal amplitude 6 cm movements (Fig. 2A). The reaction time data were also examined to determine whether the hands initiated the movement at the same time. The absolute (unsigned) asynchrony of the equal and unequal amplitude data was compared using Dunn's procedure. The unequal amplitude conditions resulted in a reliably greater degree of asynchrony, $t_{(7)}=2.37$, $p<0.05$, than the equal amplitude conditions (Fig. 2B). The eight conditions that resulted in greater asynchrony at the beginning of the movement were split into two pools: one pool of four where the left hand moved 24 cm while the right moved 6 cm (left long/right short) and a second pool where the right hand moved 24 cm and the left 6 cm (right long/left short). Figure 2C shows that it was the hand moving towards the long target that reliably initiated movement first, $t_{(3)}=5.72$, $p<0.01$.

In most cases the hands completed the task at the same time. The relative (signed) asynchrony at the end of the task was determined by subtracting movement time for the right hand from the movement time for the left. A

Fig. 1A–F *Upper plots* The relationship between the targets' index of difficulty and the movement time for the right and left hand in the unimanual conditions. The high coefficient of determination (r^2) indicates that Fitts' law adequately describes the MT data for the right limb as its target ID is varied. *Middle plots* The relationship between the average ID for the two limbs whilst one limb moved 6 cm to either the large or small target (e.g. when the task conditions were constant). *Lower plots* The relationship between the average ID for the two limbs when one limb always moved 24 cm



negative value indicates that the right hand finished before the left. The conditions were split into two groups; the first consisted of the four conditions in which the hands were moving to targets of equal size and equal amplitude and the other consisted of the remaining conditions where size and/or amplitude differed. Analysis of variance indicated that the two groups were reliably different in their degree of synchrony in movement termination ($F_{(1,14)}=4.95$, $p<0.05$) with the equal size and

amplitude conditions resulting in near synchronous movement termination (3 ms, $SE=1.58$) and the unequal conditions showing a bias toward the right hand terminating first (-23.3 ms, $SE=8.25$).

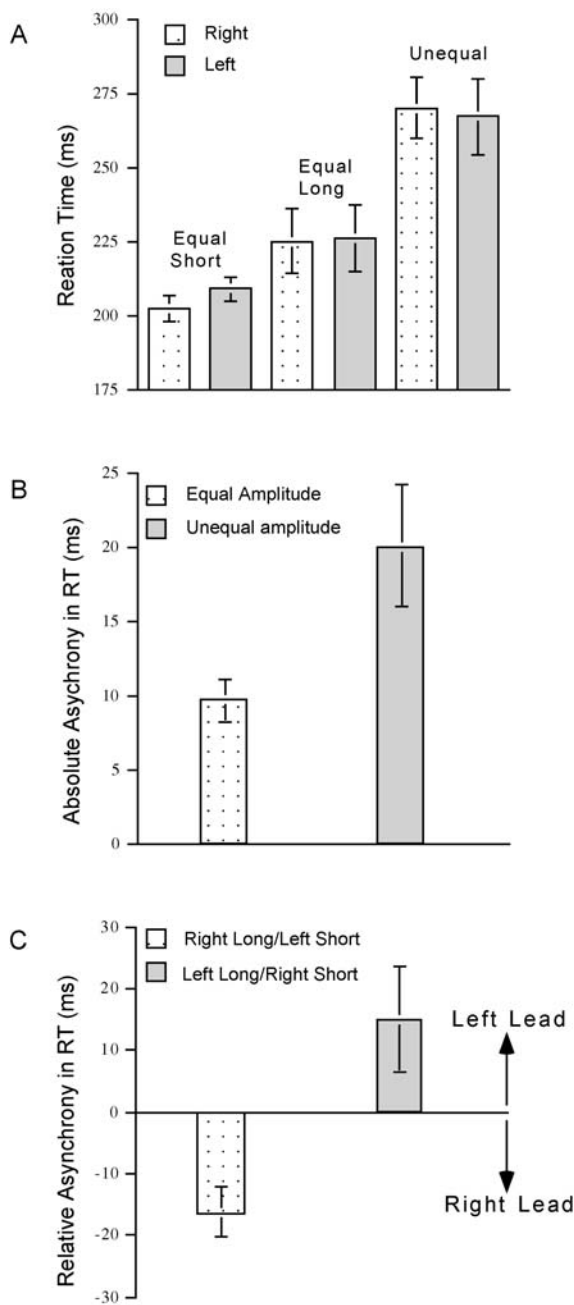


Fig. 2A–C *Upper plot* Movement onset time as a function of target amplitude (both targets short, both long or unequal amplitude). The unequal bimanual movements caused the longest onset time whilst the equal amplitude 24 cm movements caused a greater onset time than the equal amplitude 6 cm movements. *Middle plot* The relationship between the absolute asynchrony at onset and the target amplitude (both targets at the same distance versus the targets at different distances). The unequal amplitude conditions were found to cause a greater degree of asynchrony than the equal amplitude conditions. *Lower plot* The eight unequal amplitude conditions were split into two groups: one group of four where the left hand moved 24 cm whilst the right moved 6 cm and another group where the right hand moved 24 cm and the left 6 cm. It was found that the hand moving towards the target at 24 cm would reliably begin to move first

Discussion

The results demonstrate that the values of a and b obtained when Eq. 1 was fit to aiming data for one limb depended upon what the other limb was doing, thus confirming, for the case of bimanual aiming movements, the general finding that the coefficients a and b depend upon the nature of the aiming task being performed.

In the conditions where one limb consistently moved a long distance (24 cm), the fit of Eq. 4 to the data was rather poor. The poor fit was due largely to the fact that MT was strongly dependent upon whether or not the hands moved equal distances or not: MT was shorter for movements of equal amplitude independent of target size (and hence of ID). It appears that moving the two limbs by the same amplitude allows participants to move faster than when the amplitudes differ. The reason for this is likely to be related to attention: equal amplitude movements in the experimental configuration may have allowed attention either to be simultaneously directed to the two targets or permitted rapid switches of attention between the two targets which may not be the case for targets in the unequal amplitude conditions. The fact that the unequal and equal amplitude conditions impose different constraints on attention processes means that the task conditions are not equivalent. Different task conditions would be expected to lead to different values for the constants, a and b , in Fitts' law; that is, a single pair of values would not be expected to describe accurately the data over different task conditions.

In summary, the results of this experiment are partly consistent with the hypothesis that Fitts' law can describe the relationship between MTs and IDs in bimanual aiming (see also Robinson and Kavinsky 1976) but that particular values of the constants in the Fitts' law relationships only apply to specific task context. In the analysis provided, task context for one limb was defined by what the other limb was doing. We suggest that the results are consistent with the idea that Eq. 1, with specific values for a and b , adequately describes the relationship between MT and ID for a particular limb—the right limb, for example—when the task context provided by the left limb was equivalent across variations in the right limb's target ID. It appears that it is not sufficient for the task of one limb to be identical (e.g., reach the same distance to the same target) in order for it to provide an equivalent task context for all movements of the second limb. It is possible, for example, that the attention demands of the bimanual task vary as the difference between the tasks for the two limbs varies and the constants a and b vary. In this case, the attention demands of the task are not necessarily constant if one limb always performs the same task whilst the task of the other limb changes. In other words, it is likely that the movement tasks of each limb interact to determine the task context for each limb. Experiments 2 and 3 examined aspects of this hypothesis in greater detail.

Experiment 2

The results of Experiment 1 suggest that provided the task context for a particular hand was approximately constant across changes in the target ID for that hand, Fitts' law provides a good description of the relationship between average MT and ID. If the task context varies over changes in the ID of a target, then Fitts' law is unable to adequately describe the MT-ID relationship. As noted in the "Introduction", a constant task context is a prerequisite for the applicability of Fitts' law.

The task context for one limb in bimanual aiming is set, in part, by what the other limb is doing. Of course, this is not to say that if one limb (say the left) always makes a movement to the same target, then the task context is constant for the right limb. The results of Experiment 1 suggest that the demands of the movement tasks being executed by the two limbs interact in determining the task contexts for each limb. We speculate that the attention demands of the task play a significant role. For example, if the target for the left limb is small and distant, it is necessary to overtly attend to (fixate) the target to effectively guide the hand there. This requirement for fixating the left hand's target conflicts to a varying extent to the fixation/attention demands of targets being aimed at by the right hand: if the right hand's target is close to the left hand's target, the conflict is less than if the target is more distant and requires a large eye-head movement to fixate it.

The purpose of the second experiment was to investigate further whether a constant relationship (and presumably, a constant demand on visual attention) between the two limbs provides a constant task context in bimanual aiming, and, therefore, a strong Fitts' law relationship.

Materials and methods

The apparatus and general procedures in the second experiment were identical to the first but the experimental task was changed as detailed: first, only the relevant targets were present at the beginning of the trial (e.g. participants had advance information on the required limb movements). Second, all the targets were 1 cm in diameter so that only movement amplitude was varied. Third, two starting positions for each hand, separated by 6 cm in the sagittal plane, were used. This arrangement resulted in seven bimanual conditions in which the hands could move equal (i, vi, vii) or unequal (ii, iii, iv, v) amplitudes and start or end at the same or different distances away. The conditions were selected to enhance the likelihood that participants would need to make eye movements to acquire the target. The conditions were as follows:

- (i) Both hands started and finished at the same egocentric distance
- (ii) The right hand's starting position was further away than the left by 6 cm but the movements ended at the same egocentric distance
- (iii) The left hand's starting position was further away than the right by 6 cm but the movements ended at the same egocentric distance
- (iv) Both hands had the same starting distance but the right hand's movement ended 6 cm further than the left
- (v) Both hands had the same starting distance but the left hand's movement ended 6 cm further than the right

- (vi) The left hand's starting and finishing position was further away than the right by 6 cm
- (vii) The right hand's starting and finishing position was further away than the left by 6 cm

In conditions (ii) and (iii) the targets are at the same egocentric distance, but the hands moved different distances to get there. In conditions (iv) and (v) both hands started at the same egocentric distance but moved to targets at different distances. In conditions (vi) and (vii) both hands moved the same distance but the starting and target positions were different. Thus, within each pair of conditions, the relative demand on visual attention is constant. The targets were placed from the starting positions in 6 cm steps up to a maximum distance (from the start) of 30 cm. This meant that there were five target configurations for the bimanual trials in which the hands ended at the same distance (conditions i–iii) and same demand on attention, and four configurations in all other conditions. We also explored the unimanual movement times as a function of ID (to five target distances). Each of 6 participants completed five trials for each condition resulting in a total of 205 trials presented in a randomised order. The data were analysed in an identical manner to those from the first experiment.

Results and discussion

The different conditions in this experiment all resulted in good Fitts' law relationships. Table 1 reports the results of regressing group mean movement times on ID for the two limbs across the conditions. The coefficients of determination clearly show that the mean movement time of a particular hand was predictable from the target ID alone. Each participant's data were examined and the relationships reported across participants were consistent at an individual level. There was no systematic indication in the individual data that any one condition tended to result in a worse Fitts' law relationship than any other condition. We conducted statistical tests on the coefficients (converted to *Z* scores) but were unable to find any statistically reliable differences between conditions. Thus, if any

Table 1 Movement time data as a function of average index of difficulty (ID) for the two hands in Experiment 2. The group mean movement time was plotted against average ID for each condition and straight lines were fitted to the data using linear regression analysis. The equations for the fits are provided in the table (bias and gain) and their coefficient of determination (r^2) values

Condition	Bias	Gain	r^2
Unimanual (right)	79.8	79.3	0.98
Unimanual (left)	27.6	106.7	0.97
Condition (i) right hand	180.8	96.2	0.97
Condition (i) left hand	224.2	88.8	0.97
Condition (ii) right hand	170.5	93.8	0.96
Condition (ii) left hand	21.5	115.1	0.96
Condition (iii) right hand	60.5	114.8	0.89
Condition (iii) left hand	73.2	116.9	0.93
Condition (iv) right hand	185.7	92.7	0.91
Condition (iv) left hand	73.8	116.3	0.93
Condition (v) right hand	5.0	128.3	0.94
Condition (v) left hand	46.8	118.5	0.89
Condition (vi) right hand	-16.3	129.7	0.94
Condition (vi) left hand	-26.6	127.2	0.97
Condition (vii) right hand	87.4	109.5	0.86
Condition (vii) left hand	91.4	116.1	0.92

differences were present in the ability of Fitts' law to describe the data from different conditions, these differences were rather small (cf. Table 1). The results therefore confirm that Fitts' law is not violated in bimanual movement and that keeping the relationship between the two limbs constant over variation in ID provides a relatively constant task context: constant enough to yield Fitts' type relationships as good as those reported in studies of unimanual aiming. As predicted, different relationships between what the two limbs are doing lead to different Fitts' law coefficients. Movement time in bimanual aiming therefore depends not only on ID but on other task conditions.

The results of Experiments 1 and 2 suggest that movement times for the two limbs may be predicted from the ID of two targets in bimanual aiming tasks with constant task contexts: showing that Fitts' law is not violated in bimanual aiming tasks. We suggested that a constant task context might be achieved when the attention demands are relatively constant. In a task requiring discrete manual aiming movement, it has been demonstrated that the eyes normally fixate the target before the limb begins movement (Carlton 1981). We supposed that this foveation (ensuring that the target image is located at the fovea of the retinae) would be the major attention constraint within the experiments (which involved small targets in the sagittal plane). The experimental arrangement used here meant that targets placed at equal distances away could be attended to simultaneously (or overt attention could rapidly shift between targets) whereas targets at unequal amplitudes would require overt changes in attention (e.g. movement of the eyes). We conducted a third experiment in order to address this issue further.

Experiment 3

When a person is asked to make a discrete manual aiming movement to a stationary target, their eyes normally fixate the target before the movement is prepared (Carlton 1981), providing the motor control system with visual information about the position of the target, and later about the path of the hand as it moves toward the target (Elliott 1992). This is advantageous as it places the eyes in a position to optimise the acquisition of information at a time when it is most needed for accurate aiming, by reducing spatial variability of the hand (Helsen et al. 2000). While some have suggested that the underlying similarity between eye and hand movement control suggests a common command is delivered to both systems (e.g. Bizzi et al. 1971), more recent evidence examining positional data suggests the contrary (Helsen et al. 2000). In terms of the coordination between hand and eye movements, it seems well established that the eyes need only get to a position in the general vicinity of the target area to provide the manual system with sufficient information about the relative positions of the hand's target (Binsted et al. 2001; Helsen et al. 2000) with eye-

hand coupling linked to the termination of the movement on the target. The third experiment was conducted in order to explore further the allocation of overt attention in bimanual aiming by observing eye movements during performance in relation to a more detailed analysis of the movement trajectories.

Materials and methods

Apparatus and procedure

Six right-handed adults (two males and four females with no movement problems) participated in this study. The experimental design was similar to the first two experiments but this time the targets were arranged in the coronal plane. This arrangement was used to facilitate the measurement of eye movements: monitoring vengeance movements together with horizontal conjugate movements is technically difficult when compared to measuring conjugate movements alone. It should be noted that this arrangement increases the need for overt shifts in attention as the non-foveated targets are shifted towards the periphery of the retinae. There were three sizes of target: large (4 cm diameter), medium (2 cm diameter) and small (1 cm diameter) and two distances: long (12 cm) and short (6 cm).

Each participant completed two sessions, in one session the large and medium targets were used and placed either a short or long distance from the starting point. In the other condition the medium and small targets were used and placed either a short or long distance from the starting point. Each of the 16 combinations of target distance and target size was repeated five times for a total of 80 trials in each session. Trial order was randomised within each session and session order was counterbalanced across participants.

Eye movement kinematics

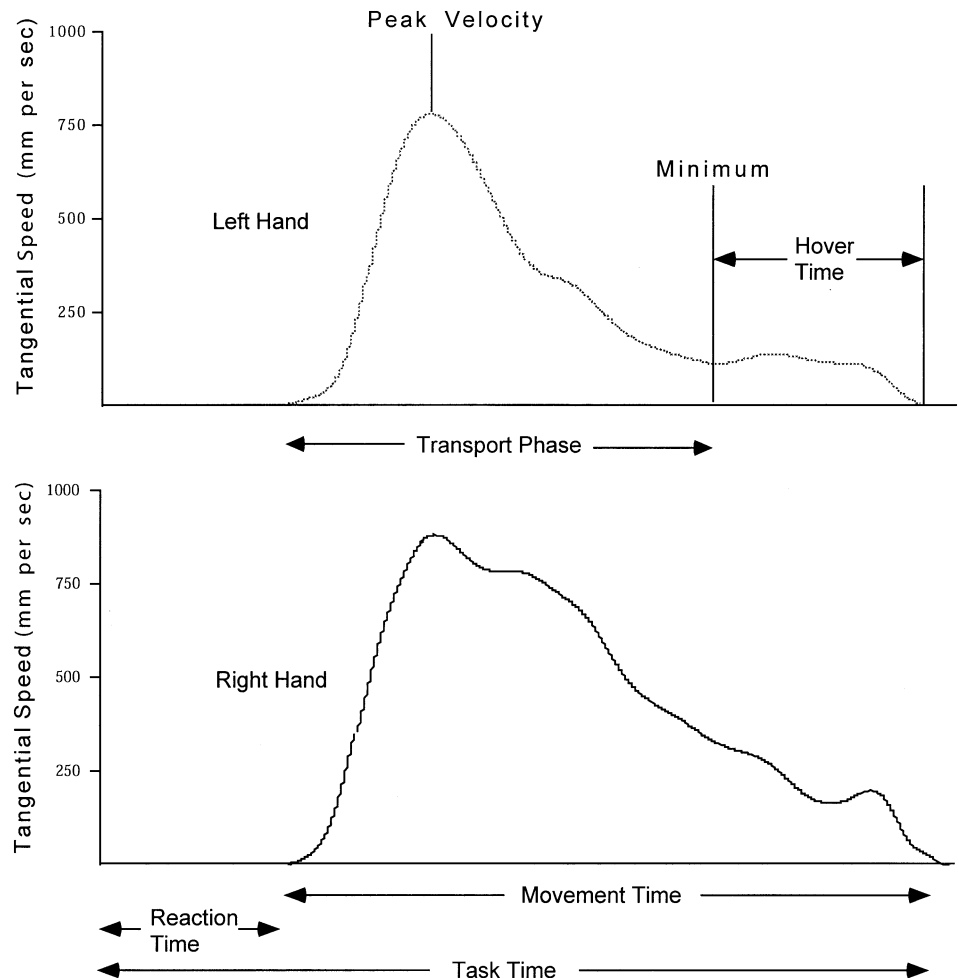
Horizontal eye position was monitored for both eyes by comparing diffuse infra-red light from the nasal and temporal limbi (Applied Science Laboratories Eye Tracker Model 210; Bedford, MA, USA). The eye movement sensor's two output channels had bandwidths of 180 Hz and were interfaced to the Optotrak system. The channels were not low pass filtered and eye movement data were digitised at 200 Hz and stored in computer memory. Noise in the system was equivalent to approximately 30 min of arc. The eye monitoring system was attached to a metal frame with a chin rest which was used to stabilise extraneous movements by strapping the participant's head in place. Horizontal eye position was calibrated at the beginning of each session using an 11 point calibration grid (± 15 degrees) placed over the targets.

Statistical analyses

The 16 combinations of target size (small-medium or medium-large) and target distance (short, long) in each session yielded six combinations in which the ID difference between the hands was zero and ten combinations in which there was an ID difference between the hands. The latter combinations could be further subdivided into those conditions in which the ID value of the right hand (RH) target was greater than that of the left hand (LH) target [ID difference=+1 (4 combinations) or ID difference=+2 (1 combination)], and those conditions in which the ID value of the LH target was greater than that of the RH target [ID difference=-1 (4 combinations), ID difference=-2 (1 combination)].

The target combinations in which the ID difference between the hands was zero could be further subdivided into those conditions in which the target size and target amplitude of each hand was identical and those conditions in which the target size and target amplitude of the RH was different from that of the LH (e.g. LH: long amplitude medium target; RH: short amplitude small target).

Fig. 3 Typical plot (selected at random) for a bimanual condition. Time is shown along the x-axis and tangential speed along the y-axis. The *top plot* shows the profile from the right hand and the *bottom plot* shows the left hand. The parameters explored within the current study are indicated (reaction time, first minima, task time, movement time, hover time)



In additional analyses restricted to equal ID combinations, we assessed whether differences existed between the degree of synchronicity present when aiming movements were made to identical targets and when the movements differed (in size of movement). As the inferential tests were of relatively low power ($n=6$), measures of effect size were calculated (Cohen 1969). The effect size index for ANOVA (f) is a dimensionless index which describes the degree of departure from no effect (i.e. the degree to which the phenomenon is manifested). A small effect size is indicated by an f of 0.1, a medium effect size by an f of 0.25, and a large effect size by an f of 0.4 (Cohen 1969).

Results

Movement trajectory

The movements appeared to exhibit an initial phase in which the limb was transported toward the target, followed by a hover phase in which the limb was held stationary above the target. Once both limbs were aligned the movement was then terminated by lowering the styli on to the targets. As illustrated in Fig. 3, the movement trajectories were described by reaction time (RT), movement offset time, time to peak tangential speed (t_{PkS}), time to end of the transport phase determined by the minimum tangential speed (t_{min}), and hover time,

defined as the time from the 1st minimum of the tangential speed (corresponding to a 'pause' in the movement) to the end of the movement. These variables were chosen to provide a more detailed description of the movement kinematics beyond simply reaction time and total movement time.

ID combinations

Reaction time (RT)

When the ID values for the left hand and right hand targets were equal, there was an overall tendency for movements of the right hand to be initiated more rapidly than movements of the left hand. As is evident from inspection of Fig. 4A, B, when the ID value of the left hand target was greater than that of the right hand target (ID difference -2 and -1), the magnitude of this asynchrony in RT was not reliably different from that present in the equal conditions (Small-Medium Targets: ID difference -2 vs. ID difference $=0$; $F_{(1,75)} < 1$, $p > 0.20$, $f = 0.04$; ID difference -1 vs. ID difference $=0$; $F_{(1,75)} < 1$, $p > 0.20$, $f = 0.08$; Medium-Large Targets: ID difference -2 vs. ID difference $=0$; $F_{(1,75)} = 1.92$, $p > 0.15$, $f = 0.27$; ID

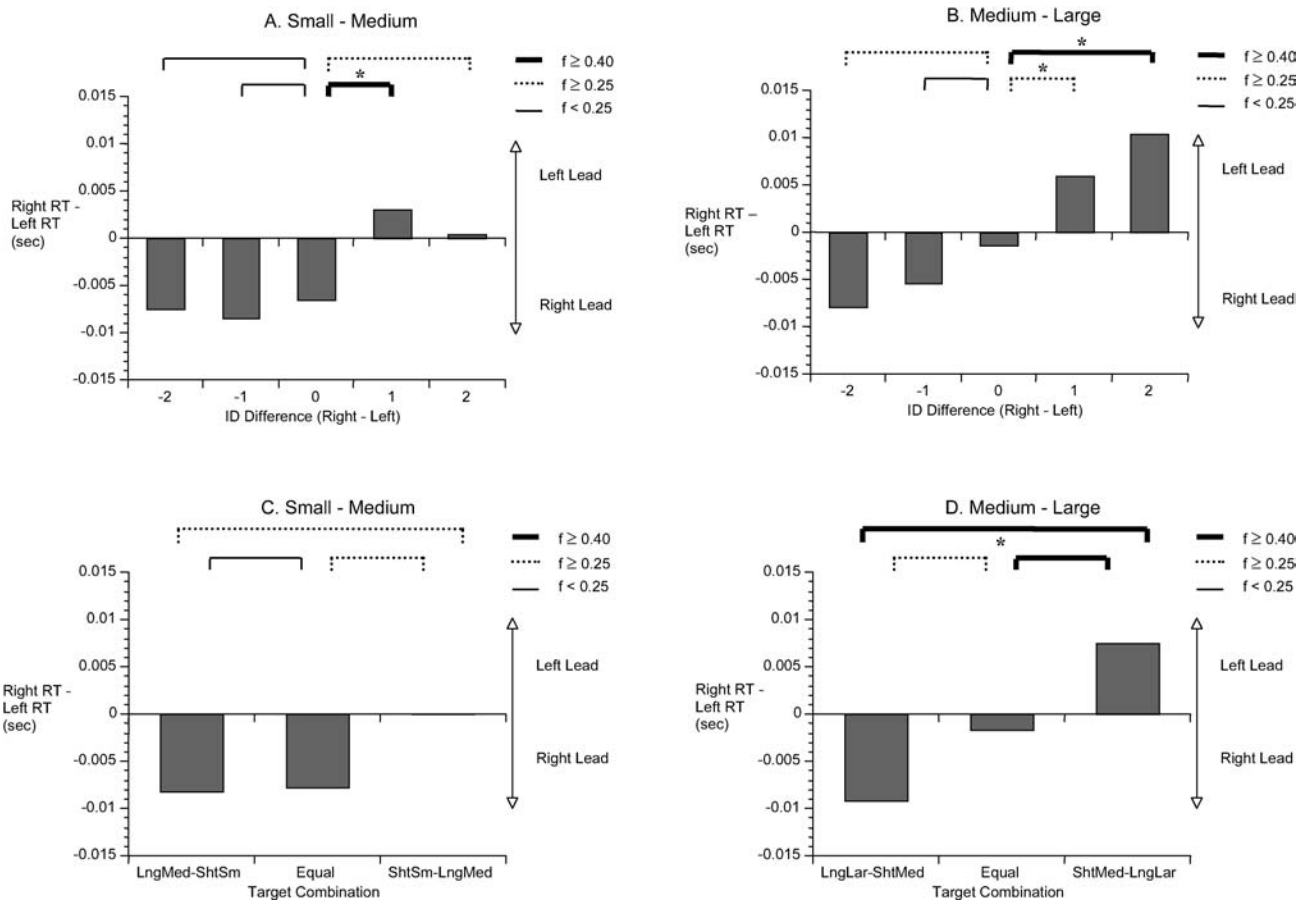


Fig. 4A–D Median reaction time (RT): asynchrony between the left hand (LH) and the right hand (RH). In panels **A** and **B**, the differences in reaction time (RH–LH) are plotted as a function of the difference in ID values between the LH and RH targets. In panels **C** and **D**, the differences in reaction time (RH–LH) are shown for those conditions in which the ID values for the LH and RH targets were equal. The data presented in panels **A** and **C**

correspond to movements directed to small (10 mm) and medium (25 mm) sized targets. The data presented in panels **B** and **D** correspond to movements directed to medium (25 mm) and large (40 mm) sized targets. The effect size index for ANOVA is denoted f . Statistically reliable differences ($p < 0.05$) are indicated by *asterisk*. In all comparisons the degrees of freedom are 1, 75

difference -1 vs. ID difference $=0$; $F_{(1,75)}=2.05$, $p > 0.15$, $f=0.17$). In contrast, when the ID value of the right hand target was greater than that of the left hand target (ID difference $+2$ and $+1$) the trend was reversed (Small-Medium Targets: ID difference $+2$ vs. ID difference $=0$; $F_{(1,75)}=1.77$, $p > 0.15$, $f=0.29$; ID difference $+1$ vs. ID difference $=0$; $F_{(1,75)}=9.38$, $p < 0.01$, $f=0.40$; Medium-Large Targets: ID difference $+2$ vs. ID difference $=0$; $F_{(1,75)}=6.28$, $p < 0.05$, $f=0.50$; ID difference $+1$ vs. ID difference $=0$; $F_{(1,75)}=6.97$, $p < 0.05$, $f=0.31$). Movements were initiated more rapidly by the left hand than by the right hand, when the right hand was directed to a more “difficult” target combination.

Movement offset

The difference in the times at which movements of the left hand and the right hand were terminated (offset) was not reliably influenced by the relative ID values of the left hand and the right hand targets (Fig. 5A, B; Small-

Medium Targets: ID difference -2 vs. ID difference $=0$; $F_{(1,75)} < 1$, $p > 0.20$, $f=0.10$; ID difference -1 vs. ID difference $=0$; $F_{(1,75)} < 1$, $p > 0.20$, $f=0.07$; ID difference $+2$ vs. ID difference $=0$; $F_{(1,75)} < 1$, $p > 0.20$, $f=0.19$; ID difference $+1$ vs. ID difference $=0$; $F_{(1,75)} < 1$, $p > 0.20$, $f=0.08$; Medium-Large Targets: ID difference -2 vs. ID difference $=0$; $F_{(1,75)}=1.89$, $p > 0.15$, $f=0.30$; ID difference -1 vs. ID difference $=0$; $F_{(1,75)} < 1$, $p > 0.20$, $f=0.12$; ID difference $+2$ vs. ID difference $=0$; $F_{(1,75)}=1.46$, $p > 0.20$, $f=0.27$; ID difference $+1$ vs. ID difference $=0$; $F_{(1,75)}=1.35$, $p > 0.20$, $f=0.15$).

Time to peak speed

When movements were directed to targets of small and medium size (Fig. 6A), the peak speed (tPKS) of the right hand was achieved more rapidly than that of the left hand in conditions where the ID value of the left hand target was greater than that of the right hand target (ID difference -2 and -1) when compared with those in the

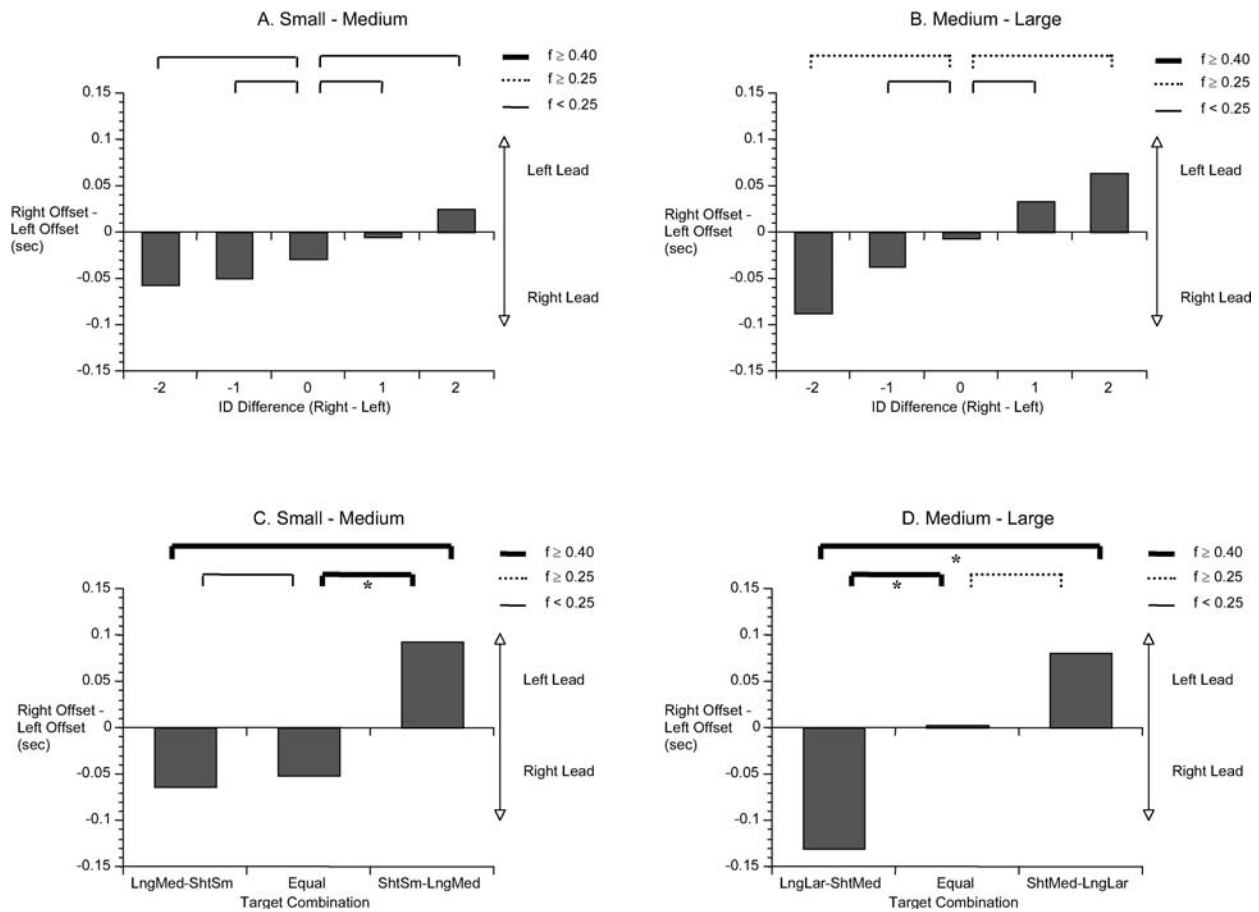


Fig. 5A–D Median movement offset time (*Offset*): asynchrony between the left hand (LH) and the right hand (RH). In panels **A** and **B**, the differences in movement offset times (RH–LH) are plotted as a function of the difference in ID values between the LH and RH targets. In panels **C** and **D**, the differences in movement offset times (RH–LH) are shown for those conditions in which the ID values for the LH and RH targets were equal. The data presented

in panels **A** and **C** correspond to movements directed to small (10 mm) and medium (25 mm) sized targets. The data presented in panels **B** and **D** correspond to movements directed to medium (25 mm) and large (40 mm) sized targets. The effect size index for ANOVA is denoted *f*. Statistically reliable differences ($p < 0.05$) are indicated by *asterisk*. In all comparisons the degrees of freedom are 1, 75

equal conditions (ID difference -2 vs. ID difference $=0$; $F_{(1,75)}=8.97$, $p < 0.01$, $f=0.66$; ID difference -1 vs. ID difference $=0$; $F_{(1,75)}=6.67$, $p < 0.05$, $f=0.34$). In conditions in which the ID value of the right hand target was greater than that of the left hand target (ID difference $+2$ and $+1$), asynchronies in time to peak speed were not distinguished from those obtained in the equal (ID difference $=0$) conditions (ID difference $+2$ vs. ID difference $=0$; $F_{(1,75)}=2.08$, $p > 0.15$, $f=0.32$; ID difference $+1$ vs. ID difference $=0$; $F_{(1,75)} < 1$, $p > 0.20$, $f=0.09$).

When movements were directed to targets of medium and large size (Fig. 6B), a slightly different pattern of results was obtained. When the ID value of the left hand target exceeded that of the right hand by a value of 2 (ID difference -2), the peak speed of the right hand was attained more rapidly than that of the left hand relative to conditions in which the ID difference was zero (ID difference -2 vs. ID difference $=0$; $F_{(1,75)}=6.03$, $p > 0.05$, $f=0.54$). In contrast, when the ID value of the right hand target exceeded that of the left hand target by a value of 2

(ID difference $+2$), the peak speed of the left hand was attained more rapidly than that of the right hand (ID difference $+2$ vs. ID difference $=0$; $F_{(1,75)}=4.97$, $p < 0.05$, $f=0.49$). There was no reliable effect when the ID difference was a value of 1 (ID difference -1 vs. ID difference $=0$; $F_{(1,75)}=1.95$, $p > 0.15$, $f=0.18$; ID difference $+1$ vs. ID difference $=0$; $F_{(1,75)}=2.18$, $p > 0.10$, $f=0.20$).

Time to end of transport phase (t_{-min})

When the ID values of the left and right hand targets were equal (ID difference $=0$), there was a tendency for the end of the transport phase to occur earlier for movements of the right hand than for movements of the left hand. This difference was most pronounced when movements were directed to targets of small and medium size. As is evident from inspection of Fig. 7A, B, when the ID value of the left hand target exceeded by two that of the right hand target (ID difference -2), the extent of this asynchrony

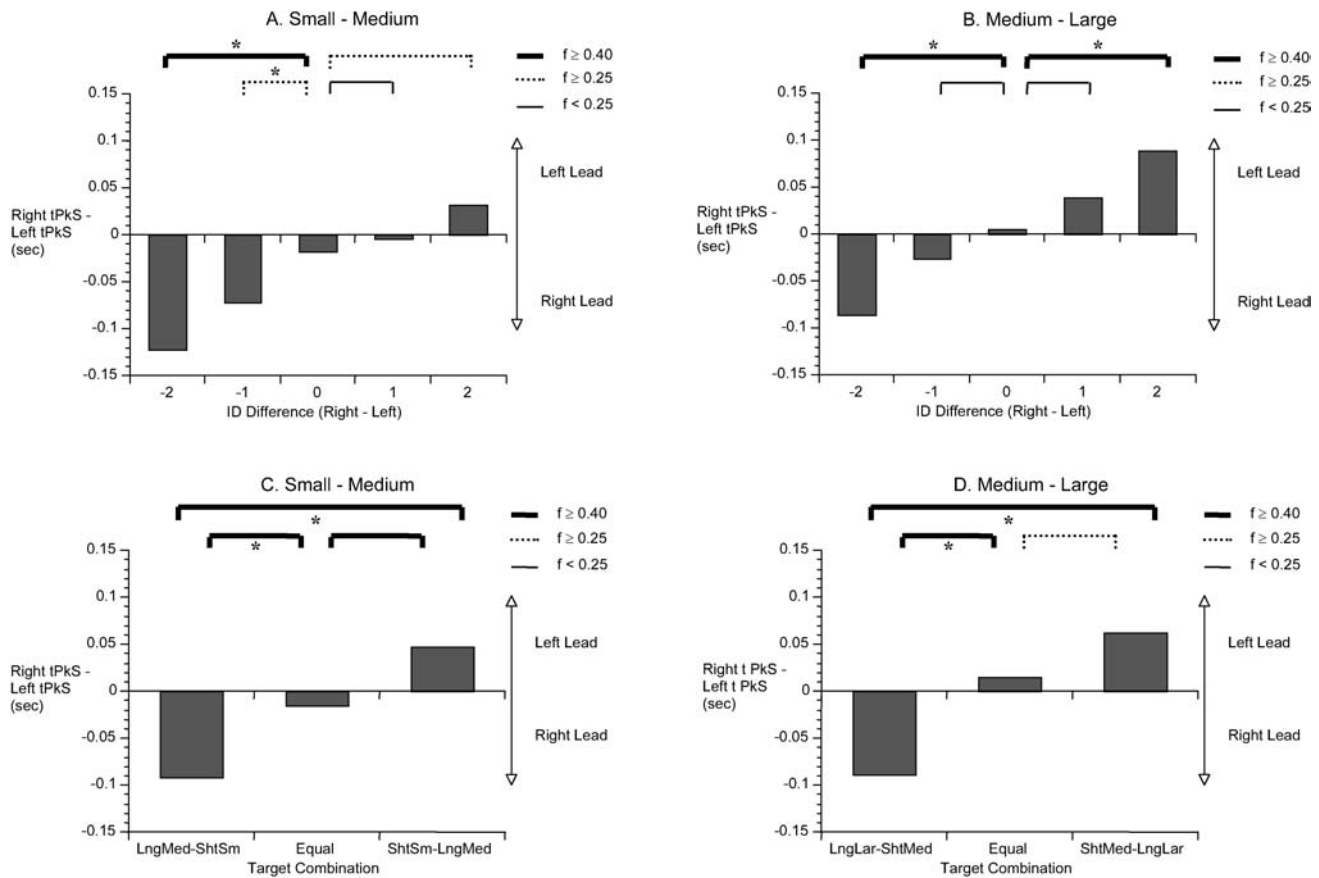


Fig. 6A–D Median time to peak speed (*tPKS*): asynchrony between the left hand (LH) and the right hand (RH). In panels **A** and **B**, the differences in the time to peak speed (RH–LH) are plotted as a function of the difference in ID values between the LH and RH targets. In panels **C** and **D**, the differences in the time to peak speed (RH–LH) are shown for those conditions in which the ID values for the LH and RH targets were equal. The data presented in panels **A**

and **C** correspond to movements directed to small (10 mm) and medium (25 mm) sized targets. The data presented in panels **B** and **D** correspond to movements directed to medium (25 mm) and large (40 mm) sized targets. The effect size index for ANOVA is denoted *f*. Statistically reliable differences ($p < 0.05$) are indicated by asterisk. In all comparisons the degrees of freedom are 1, 75

was more pronounced (ID difference -2 vs. ID difference $=0$; $F_{(1,75)}=4.66$, $p < 0.05$, $f=0.48$; ID difference -1 vs. ID difference $=0$; $F_{(1,75)}=2.7$, $p > 0.10$, $f=0.22$). In contrast, when the ID value of the right hand exceeded that of the left hand (ID difference $+2$ and $+1$), this asynchrony was reversed (ID difference $+2$ vs. ID difference $=0$; $F_{(1,75)}=6.14$, $p < 0.05$, $f=0.55$; ID difference $+1$ vs. ID difference $=0$; $F_{(1,75)}=5.52$, $p < 0.05$, $f=0.31$). In these instances, the end of the transport phase occurred earlier for movements of the left hand than for movements of the right hand.

Hover phase

The pattern of asynchronies present for the terminal 'hover' phase of the movements (Fig. 8A, B) was the reverse of the pattern of asynchronies evident during the initial phase of the movement. The net result of these complementary patterns was that the movements of the two hands terminated at almost the same time in most

conditions. When the ID values of the left hand and right hand targets were equal, there was a tendency for the duration of the hover phase to be slightly greater for movements of the right hand than for movements of the left hand. When movements were directed to targets of small and medium size (Fig. 8A), this difference was most pronounced when the ID value of the left hand target exceeded that of the right hand target (ID difference -2 vs. ID difference $=0$; $F_{(1,75)}=7.59$, $p < 0.01$, $f=0.61$; ID difference -1 vs. ID difference $=0$; $F_{(1,75)}=5.01$, $p < 0.05$, $f=0.29$). In contrast, this asynchrony was reversed when the ID value of the right hand exceeded that of the left hand (ID difference $+2$ vs. ID difference $=0$; $F_{(1,75)}=2.29$, $p > 0.10$, $f=0.33$; ID difference $+1$ vs. ID difference $=0$; $F_{(1,75)}=6.03$, $p < 0.05$, $f=0.32$). For movements directed to targets of medium and large size, the duration of the hover phase was greater for movements of the left hand than for movements of the right hand (Fig. 8B) when the ID value of the right hand exceeded that of the left hand (ID difference $+2$ vs. ID difference $=0$; $F_{(1,75)}=6.88$, $p < 0.05$, $f=0.58$; ID difference $+1$ vs. ID difference $=0$; $F_{(1,75)}=4.34$,

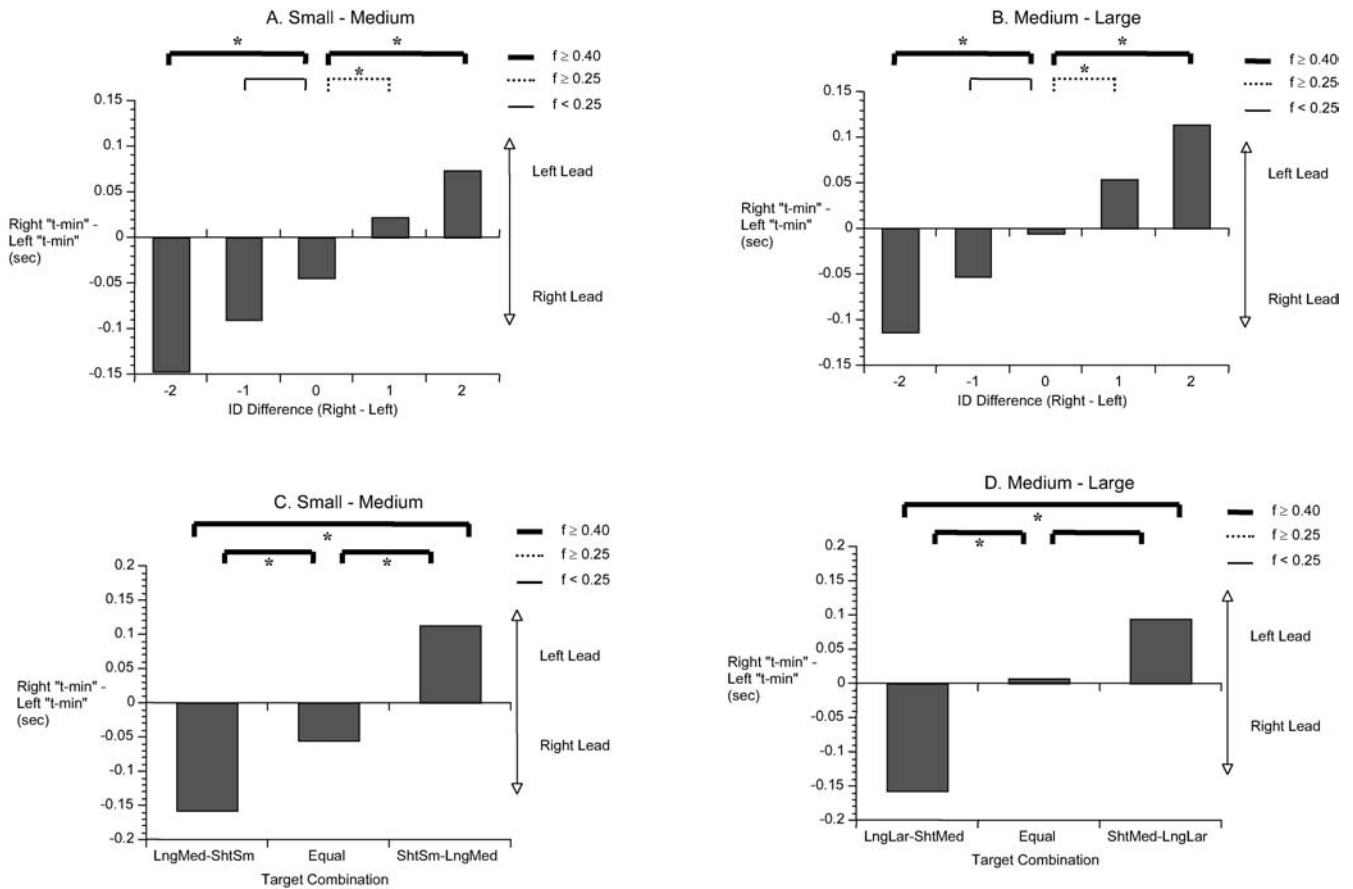


Fig. 7A–D Median time to the end of the transport phase (t_{-min}): asynchrony between the left hand (LH) and the right hand (RH). In panels **A** and **B**, the differences in the time to the end of the transport phase (RH–LH) are plotted as a function of the difference in ID values between the LH and RH targets. In panels **C** and **D**, the differences in the time to the end of the transport phase (RH–LH) are shown for those conditions in which the ID values for the LH

and RH targets were equal. The data presented in panels **A** and **C** correspond to movements directed to small (10 mm) and medium (25 mm) sized targets. The data presented in panels **B** and **D** correspond to movements directed to medium (25 mm) and large (40 mm) sized targets. The effect size index for ANOVA is denoted f . Statistically reliable differences ($p < 0.05$) are indicated by asterisk. In all comparisons the degrees of freedom are 1, 75

$p < 0.05$, $f = 0.27$). In conditions in which the ID value of the left hand target was greater than that of the right hand target (ID difference -2 and -1), asynchronies in duration of the hover phase were not distinguished from those obtained in the equal (ID difference $= 0$) conditions (ID difference -2 vs. ID difference $= 0$; $F_{(1,75)} < 1$, $p > 0.20$, $f = 0.13$; ID difference -1 vs. ID difference $= 0$; $F_{(1,75)} < 1$, $p > 0.20$, $f = 0.12$).

Equal ID combinations

Reaction time (RT)

When participants were aiming at targets that were of medium and large size, movements of short amplitude to medium targets were initiated more rapidly than movements of long amplitude to large targets—even though the ID values were equal for each hand (Fig. 4D; Long-Large (LH) Short-Medium (RH) (1) vs. equal; $F_{(1,75)} = 2.37$, $p > 0.10$, $f = 0.34$; Short-Medium (LH) Long-Large (RH) (2) vs. equal; $F_{(1,75)} = 3.53$, $p > 0.05$, $f = 0.42$; (1) vs. (2) $F_{(1,75)} = 7.30$, $p < 0.01$, $f = 0.76$). This tendency was not present when the movements were directed to targets of small and medium size (Fig. 4C; Long-Large (LH) Short-Medium (RH) (1) vs. equal; $F_{(1,75)} < 1$, $p > 0.20$, $f = 0.02$; Short-Medium (LH) Long-Large (RH) (2) vs. equal; $F_{(1,75)} = 2.00$, $p > 0.16$, $f = 0.32$; (1) vs. (2) $F_{(1,75)} = 1.41$, $p < 0.20$, $f = 0.34$).

Movement offset

The patterns evident in the time to movement initiation were also found in the movement offset times so that the movements of the right and left hands were not terminated in synchrony. When participants were aiming at targets that were of small and medium size (Fig. 5C), movements of the left hand of short amplitude to small targets were terminated in advance of movements of the right hand of long amplitude to medium targets (Short-Small (LH) Long-Medium (RH) (2) vs. equal;

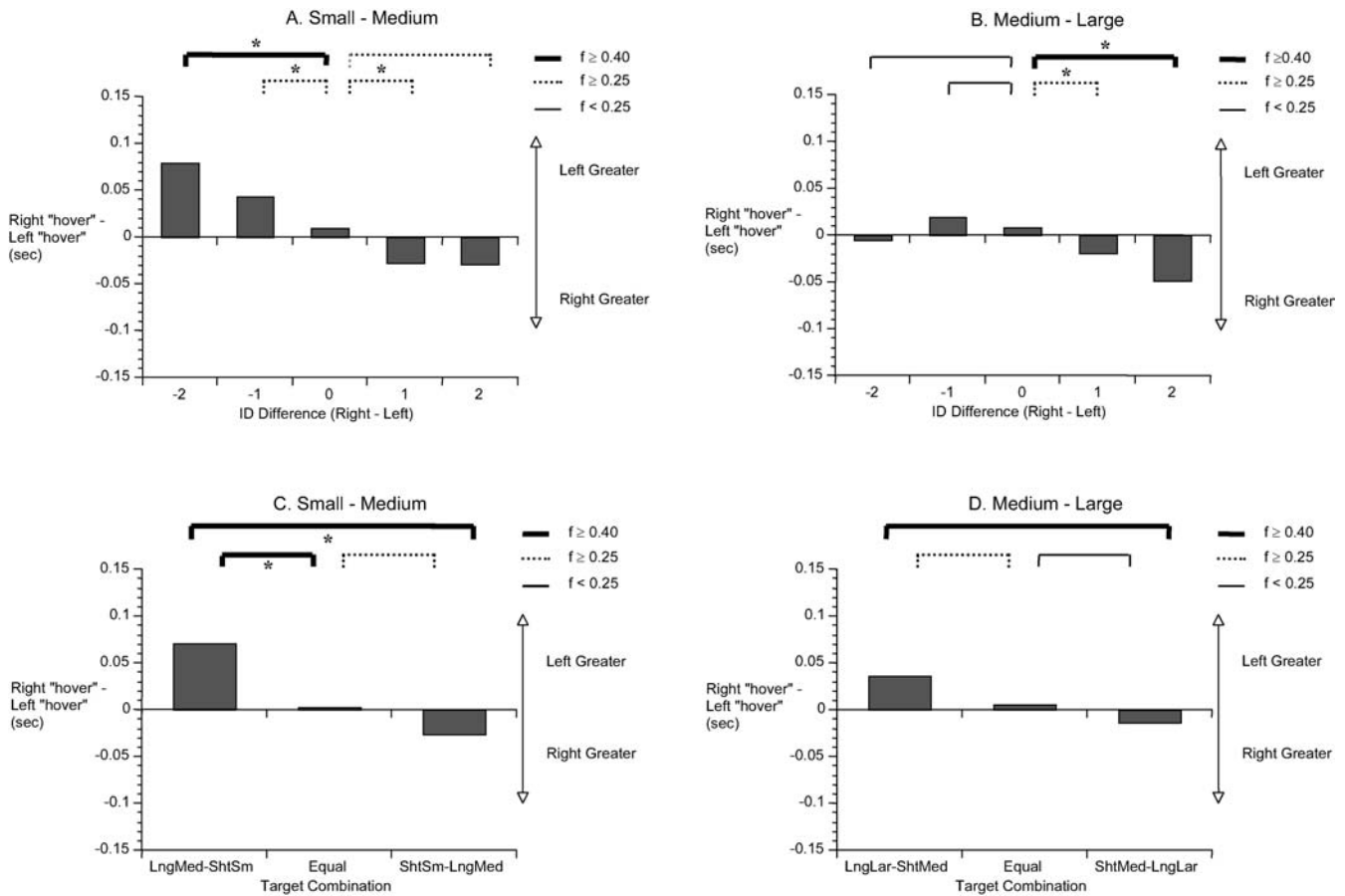


Fig. 8A–D Median time of the hover phase: asynchrony between the left hand (LH) and the right hand (RH). In panels **A** and **B**, the differences in the hover time (RH–LH) are plotted as a function of the difference in ID values between the LH and RH targets. In panels **C** and **D**, the differences in the hover time (RH–LH) are shown for those conditions in which the ID values for the LH and RH targets were equal. The data presented in panels **A** and **C**

correspond to movements directed to small (10 mm) and medium (25 mm) sized targets. The data presented in panels **B** and **D** correspond to movements directed to medium (25 mm) and large (40 mm) sized targets. The effect size index for ANOVA is denoted *f*. Statistically reliable differences ($p < 0.05$) are indicated by *asterisk*. In all comparisons the degrees of freedom are 1, 75

$F_{(1,75)}=5.16$, $p < 0.02$, $f=0.52$), but no effect was observed when the participants aimed at targets that were medium size and long amplitude for the left hand (Long-Medium (LH) Short-Small (RH) (1) vs. equal; $F_{(1,75)} < 1$, $p > 0.20$, $f=0.04$; (1) vs (2); $F_{(1,75)}=3.79$, $p=0.06$, $f=0.56$). Similarly, when participants were aiming at targets that were of medium and large size, short movements to medium targets for the right hand were terminated in advance of long movements to large targets for the left hand (Fig. 5D; Long-Large (LH) Short-Medium (RH) (1) vs. equal; $F_{(1,75)}=4.84$, $p < 0.05$, $f=0.50$).

Time to peak speed

These patterns were found to a greater degree in the time to peak speed (Fig. 6C, D). There was a marked asynchrony between the hands, even though the left and right hand targets were defined by equal ID values. When participants were aiming at targets that were of small and medium size, the peak speed of short movements to small

targets occurred earlier than long movements to medium targets (Long-Medium (LH) Short-Small (RH) (1) vs. equal, $F_{(1,75)}=4.47$, $p < 0.05$, $f=0.48$; Short-Small (LH) Long-Medium (RH) (2) $F_{(1,75)}=3.00$, $p > 0.05$, $f=0.40$; (1) vs. (2) $F_{(1,75)}=9.25$, $p < 0.01$, $f=0.88$). Similarly, when participants were aiming at targets that were of medium and large size, the peak speed of short movements to medium targets occurred earlier than in long movements to large targets (Long-Large (LH) Short-Medium (RH) (1) vs. equal, $F_{(1,75)}=7.22$, $p < 0.01$, $f=0.61$; Short-Medium (LH) Long-Large (RH) (2) $F_{(1,75)}=1.55$, $p > 0.20$, $f=0.28$; (1) vs. (2) $F_{(1,75)}=9.66$, $p < 0.01$, $f=0.90$).

Time to end of transport phase (*t*-min)

When participants were aiming at targets of small and medium size, the end of the transport phase occurred earlier during short movements to small targets than during long movements to medium targets (Fig. 7C; Long-Medium (LH) Short-Small (RH) (1) vs. equal

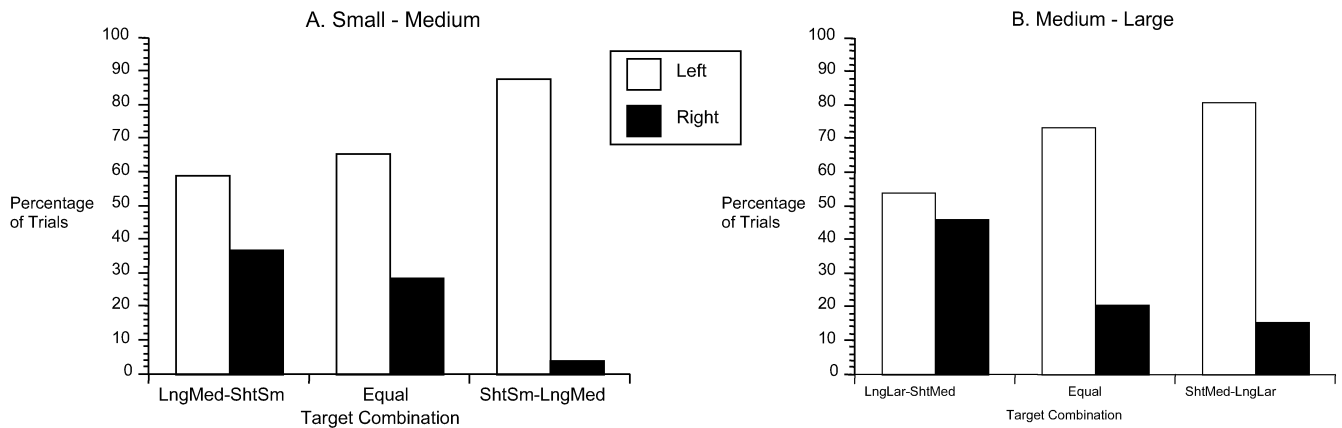


Fig. 9A, B Direction of the terminal eye movement. The proportion of eye movements made in each horizontal direction is shown for those conditions in which the ID values for the LH and RH targets were equal. The data presented in panel **A** corresponds to movements directed to small (10 mm) and medium (25 mm) sized

targets. The data presented in panel **B** corresponds to movements directed to medium (25 mm) and large (40 mm) sized targets (*solid bars* left directed eye movement, *open bars* right directed eye movement)

$F_{(1,75)}=4.40$, $p<0.05$, $f=0.48$; Short-Small (LH) Long-Medium (RH) (2) vs. equal $F_{(1,75)}=11.70$, $p<0.01$, $f=0.78$; (1) vs. (2) $F_{(1,75)}=19.04$, $p<0.01$, $f=1.26$). Exactly the same pattern of results was found for the end of the transport phase with the large and medium targets (Fig. 7D; Long-Large (LH) Short-Medium (RH) (1) vs. equal, $F_{(1,75)}=10.94$, $p<0.01$, $f=0.76$; Short-Medium (LH) Long-Large (RH) (2) $F_{(1,75)}=3.16$, $p>0.05$, $f=0.41$; (1) vs. (2) $F_{(1,75)}=16.17$, $p<0.01$, $f=1.16$).

Hover phase

As is apparent from inspection of Fig. 8C, D, the pattern of asynchronies present for the terminal 'hover' phase of the movements was the reverse of the pattern found during the initial phase of the movement. Even though the ID values were equal for each hand, the duration of the terminal low velocity phase was greater when participants made movements of short amplitude than when they made movements of long amplitude. This tendency was most prominent when the movements were directed to targets of small and medium size (Long-Medium (LH) Short-Small (RH) (1) vs. equal $F_{(1,75)}=6.83$, $p<0.05$, $f=0.60$; Short-Small (LH) Long-Medium (RH) (2) vs. equal $F_{(1,75)}=1.21$, $p>0.20$, $f=0.25$; (1) vs. (2) $F_{(1,75)}=8.62$, $p<0.01$, $f=0.85$) compared with medium and large size (Long-Large (LH) Short-Medium (RH) (1) vs. equal, $F_{(1,75)}=1.78$, $p>0.15$, $f=0.30$; Short-Medium (LH) Long-Large (RH) (2) $F_{(1,75)}<1$, $p>0.20$, $f=0.20$; (1) vs. (2) $F_{(1,75)}=3.10$, $p<0.05$, $f=0.51$). Although these asynchronies compensated for the complementary asynchrony in the duration of the primary submovement, they were not sufficient to ensure that the movements of the two hands were completed together.

Eye movements

Analysis of the median number of eye movements recorded during each condition revealed no reliable differences attributable to the index of difficulty of the left hand or of the right hand targets. The median number of eye movements in both cases was two. When examining the direction of the terminal eye movement, that is, the target that the eye was fixating at the time the task was completed, there was a strong overall tendency for the terminal eye movement to be directed to the left (binomial expansion $p<0.01$). This effect is shown clearly in the conditions in which the amplitude and target size combinations for the two hands were equal (Fig. 9A, B). In conditions in which the target amplitude and size were not equivalent for the two hands, the bias towards the left hand was moderated by an additional tendency for the terminal eye movement to be directed to the hand moving to the smaller of the two targets. In conditions in which movements were directed to targets of small and medium size (e.g. when the left hand moved a short distance to a small target and the right hand moved a long distance to a medium target) there was a high probability that the terminal eye movement would be directed to the left hand. In contrast, a larger number of terminal eye movements were directed to the right hand when the left hand moved a long distance to a medium target and the right hand moved a short distance to a small target. A similar pattern of results was present with the large and medium targets.

Discussion

The results of the third experiment shed light on the organisation of bimanual control in human adults. Kelso et al. (1979a, 1979b) have suggested previously that bimanual aiming movements are carried out synchronously-

ly—even when the limbs are moving to different targets at different distances. In line with other researchers (Marteniuk et al. 1984; Corcos 1984; Fowler et al. 1991), we found asynchronies in movement kinematics appearing at both the beginning and the end of some bimanual aiming movements. The temporal asynchronies appearing at the end of the movement (e.g. hover time) often acted to mitigate the asynchronies observed at the beginning of the movement (e.g. RT and tPkS). The picture that emerges from our analysis is one that supports a strategy to ensure that movements begin and end at approximately the same time under certain task conditions. Nevertheless, the success of this strategy should not be taken as evidence that asymmetric bimanual movements share common temporal control nor that they violate Fitts' law.

In our bimanual aiming task, participants adopted the use of a 'hover phase' at the end of the initial transport phase. The hover phase allowed the participant to rapidly transport one hand to a target and then wait for the other hand to be spatially positioned. The hover phase appeared to be particularly important when moving to small targets and allowed the participant to spatially align the two styli prior to issuing a final terminal movement command. This behaviour is likely to have emerged because of the limitations of the human visual system—it is simply not possible to use visual feedback to correct end-point errors of the two hands simultaneously when they are some distance apart. In terms of the coordination between hand and eye movements, eye-hand coupling is linked to the termination of the movement on the target in order to provide the manual system with sufficient information about the relative positions of the hand's target (Binsted et al. 2001; Helsen et al. 2000). The patterns recorded of eye movements made while the participants carried out the task made this very clear. For the equal ID conditions, participants favoured terminal eye movements directed to the left. This, however, was modulated by the target size. That is, when the left hand was moving to the smaller target of either pair there was a larger proportion of terminal eye movement to the left than when moving to the larger target of the pair, despite the ID values being equivalent. These observations are likely the result of an interaction between the visual demands and of manual asymmetries between right dominant and left non-dominant hands. It has been well established that the right hand performs with better accuracy and consistency in right handed participants when performing a manual aiming task (Roy and Elliott 1989; Elliott et al. 1995). As a result, it is likely that the left hand movements require greater input from the visual system, particularly when directed to small targets. In fact, participants tend to make larger initial saccades and more corrective saccades when aiming with the left hand than with the right (Helsen et al. 1998). Honda (1982) has shown that when subjects were asked to perform a bimanual aiming task, they tended to direct their eyes to the right (for right handed individuals). It has been speculated that movements of the preferred limb are more dependent upon visual monitoring and

therefore are executed in close connection with the oculomotor control system (Honda 1982).

The transport phase for the two hands when moving to targets with equal indices of difficulty (ID) showed a bias toward the right hand movement to be initiated slightly ahead of the left hand (our participants were all right handed) and reach peak velocity earlier, contrary to evidence from unimanual aiming studies which show a consistent left hand reaction time advantage (Carson 1989). The same pattern of results was found if the ID was greater for the left hand than the right. If the ID for the right hand were greater than the left, however, the left hand would tend to start moving before the right. It would appear that, in this bimanual task, the nervous system is biased towards ensuring that the hand with the 'easier job' moves first particularly when there are ID differences. As might be expected from the pattern of movement initiation, the right hand tended to show a longer hover phase if the ID were greater for the left hand or the targets were of equal ID. Conversely, the left hand tended to show a longer hover phase if the ID was greater for the right hand. The asynchronous nature of the hover phases meant that the movements of the two limbs finished in closer temporal proximity than would have been predicted from the asynchronies observed in reaction time or from the time to peak speed of the movement. The hover phases also meant that the temporal asynchrony at the termination of the movement was not influenced by the relative difficulty of the two targets.

In situations where the two targets had equal indices of difficulty, but unequal size and distance combinations, movement to the larger and further target (regardless of whether this was on the left or the right) was initiated first. Consistent with a faster RT for the larger and further target, there was also a shorter time to peak velocity. Furthermore, the transport component for the hand moving to this target was completed in advance of the other hand. Once more, the decreased duration of the transport phase was compensated for by an increased duration of the hover phase so that the initial movement asynchronies were ameliorated at the termination of the task.

The general pattern observed in the hand trajectories was reflected by the pattern of eye movements recorded during the experiments. It appeared that participants fixated one target and corrected the end-point spatial error of the hand moving to that target before changing fixation and correcting the spatial error of the other hand. Once the final hand was spatially aligned the system terminated the task by simultaneously moving the two hands down (without changing eye position from the final fixated target). In line with the bias shown by the right hand to initiate movement first, the eyes tended to move to the right followed by a change of fixation to the left when the targets were of equal ID. In situations where the IDs were unequal, the eyes tended to move left and then right when the right hand was moving a short distance to the smaller target. Conversely, the eyes tended to move right and then left when the left hand was moving a short distance to the

smaller target. These findings make sense in terms of the relative need for visual monitoring at the end of the movement.

General discussion

The results of the three experiments reported in this manuscript reveal a number of features about bimanual control in human adults. In line with a large body of research it was found that unimanual aiming movements were well described by Fitts' law, with the left hand moving more slowly than the right hand in a group of right handed participants. In situations where both hands were moved, the hands started and ended movement in close temporal proximity to one another as reported previously by Kelso et al. (1979a, 1979b). In bimanual trials, left hand movement time decreased when moving to large targets, while right hand movement time increased when the left hand was moving to small targets. This interaction between facilitation and inhibition of movement times depended not only upon what the one hand was doing, but upon what both hands were doing.

The fact that the two hands begin and end movement at approximately the same time has been used to suggest that Fitts' law is violated in bimanual aiming (e.g. Kelso et al. 1979a, 1979b; Marteniuk et al. 1984; Corcos 1984; Fowler et al. 1991). The results of the second experiment show clearly, however, that movement time for a particular limb within a bimanual aiming task can be described well by Fitts' law—as long as the demands of the task (including attention and what the other limb is doing) are constant. The bimanual data do not conflict with Fitts' law. We suggest that the task demands serve to modify the constants a and b in Fitts' law (Eq. 2), thereby preserving the essential nature of Fitts' relationship, that is, movement time varies linearly with ID.

In terms of attention, the bimanual movement times will be constrained by the extent to which attention shifts are required within an aiming task. Shifts in attention can either be covert (no change in eye position) or overt. Covert shifts of attention might be advantageous to the central nervous system in a number of situations as attention can be directed rapidly to objects of interest within the visual field without the inherent lags associated with the organisation of a motor response. Nonetheless, covert shifts of attention will often not suffice due to the rapidly decreasing resolution of the retinae as images fall away from the maculae. The anatomical organisation of the retinae means that eye movements must occur in tasks that require precise information on spatially separated targets of interest. In the third experiment we arranged the targets in the fronto-parallel plane so that the task would be extremely difficult (if not impossible) in the absence of eye movements.

The close temporal proximity between the start and end of the two hand movements has been taken previously as evidence for common temporal of the two hands (e.g. Kelso et al. 1979a, 1979b). A closer inspection of the

movement kinematics suggests, however, that the hands do not always move synchronously in bimanual aiming. We observed asynchronous timing when transported to different distances, with the hand moving to the further target beginning to move in advance of the other hand. Likewise, it was found that the timing at the end of the movement in the two hands was not completely synchronous, with a bias for the right target to be switched off before the left. Moreover, inspection of the movement trajectories revealed the presence of 'hover phases'. These phases represent dwell periods during which one hand is held steady whilst corrections are made to the spatial position of the other hand. These hover phases were most marked when the hands moved to different targets at different distances. Nonetheless, it was possible for the system to show synchronous movements when moving the two limbs by the same amplitude—particularly when moving the two limbs a short distance to large targets. These findings suggest that the nervous system can programme movements of equal duration for the two limbs but argue against the idea that the limbs share a common temporal signal when carrying out asymmetric aiming tasks.

One strategy that the participants could have selected when carrying out the task was to switch the targets off in a serial fashion (i.e. completing the right limb's movement before moving the left limb or vice versa). In agreement with a number of studies (Kelso et al. 1979a, 1979b; Marteniuk et al. 1984; Corcos 1984; Fowler et al. 1991) we found that no participant adopted this strategy—even though no instructions were given regarding the manner in which the task was to be performed. It is therefore worth asking why no one adopted a strategy of moving the limbs in a serial fashion? The best explanation for this finding is that the participants were instructed to move as quickly and accurately as possible. The fastest way to carry out the task appears to be for the two hands to move in a parallel fashion. The disadvantage of a 'parallel' strategy is the extra time required to plan bimanual as opposed to unimanual movement as illustrated by increased RTs for bimanual versus unimanual movement and the increased RT as the bimanual movement became more complex. Nonetheless, the cost of the increase in planning time seems to be outweighed by the saving in movement time. These results thus indicate that the participants selected a 'parallel' strategy because this was the most expeditious. It seems reasonable to suggest that this strategy might be altered if the task (or the participant's interpretation of the task) were to alter.

The general picture that emerges from these findings is revealing with regard to the organisation of bimanual aiming movements. The sequence of observed behaviour can be interpreted best as the nervous system carrying out the following steps:

- (i) Pre-programming the transport of the two hands to the targets
- (ii) Fixating one target

- (iii) Correcting any spatial end-point transport errors for the hand moving to the fixated target
- (iv) Changing fixation to the other target
- (v) Correcting any spatial errors in the hand moving to the newly fixated target
- (vi) Programming a final downwards movement (with the hand that first began the initial movement tending to be the hand that finishes first despite the 'catch-up' time provided to the other hand during the hover phase)

In summary, our findings suggest that bimanual aiming is a complex task that requires the nervous system to orchestrate a number of separate actions in an efficient manner. The fact that the nervous system conducts the various requisite actions in such a skilful manner can lead the observer to a mistaken impression regarding the nature of bimanual control. For example, the strategic use of dwell periods gives the appearance of almost perfect temporal synchrony between the two limbs. A detailed inspection of the movement kinematics reveals, however, that the close temporal proximity between the two limbs at the beginning and end of movement is not due to a simple coupling of the temporal command to the two limbs. Instead, the temporal co-ordination is based on a pattern of hand and eye movements that are organised with military precision. The seemingly effortless manner in which the two limb movements unfold in time in a co-ordinated fashion belies the pre-planning that occurs before movement begins and masks the elegant strategies employed by the adult nervous system.

Acknowledgement Preparation of this manuscript was partly supported by a grant from the National Health and Medical Research Council, Australia, to the authors.

References

- Binsted G, Chua R, Helsen W, Elliott D (2001) Eye-hand coordination in goal-directed aiming. *Hum Mov Sci* 20:563–585
- Bizzi E, Kalil RE, Tagliasco V (1971) Eye-hand coordination in monkeys: evidence for centrally patterned organisation. *Science* 173:452–454
- Carlton LG (1981) Visual information: the control of aiming movements. *Q J Exp Psychol* 33A:87–93
- Carson RG (1989) Manual asymmetries: In defense of a multifactorial account. *J Mot Behav* 21:157–162
- Cohen J (1969) *Statistical power analysis for the behavioral sciences*. Academic Press, New York
- Corbetta D, Thelen E (1996) The developmental origins of bimanual coordination: A dynamic perspective. *J Exp Psychol Hum Percept Perform* 22:502–522
- Corcos DM (1984) Two-handed movement control. *Res Q Ex Sport* 55:117–122
- Elliott D (1992) Intermittent versus continuous control of manual aiming movements. In: Proteau L, Elliott D (eds) *Vision and motor control*. North-Holland, Amsterdam, pp 3–31
- Elliott D, Lyons J, Chua R, Goodman D, Carson RG (1995) The influence of target perturbation on manual asymmetries in right-handers. *Cortex* 31:133–154
- Fitts PM, Peterson JR (1964) Information capacity of discrete motor responses. *J Exp Psychol* 67:103–112
- Fowler B, Duck T, Mosher M, Mathieson B (1991) The coordination of bimanual aiming movements: evidence for progressive desynchronization. *Q J Exp Psychol* A43:205–221
- Helsen WF, Starkes JL, Elliott D, Buekers MJ (1998) Manual asymmetries and saccadic eye movements in right-handers during single and reciprocal aiming movements. *Cortex* 34:513–529
- Helsen WF, Starkes JL, Elliott D, Ricker KL (2000) Coupling of eye, finger, elbow and shoulder movements during manual aiming. *J Mot Behav* 32:241–248
- Hering E (1868/1977) *The theory of binocular vision*. Plenum Press, New York
- Honda H (1982) Rightward superiority of eye movements in a bimanual aiming task. *Q J Exp Psychol* 34A:499–513
- Kelso JAS, Schönner G (1988) Self-organisation of coordinative movement patterns. *Hum Mov Sci* 7:27–46
- Kelso JAS, Southard DL, Goodman D (1979a) On the nature of human interlimb coordination. *Science* 203:1029–1031
- Kelso JAS, Southard DL, Goodman D (1979b) On the coordination of two-handed movements. *J Exp Psychol* 5:229–238
- Marteniuk RG, Mackenzie CL, Baba DM (1984) Bimanual movement control: information processing and interaction effects. *Q J Exp Psychol* A36:335–365
- Peters M (1981) Attentional asymmetries during concurrent bimanual performance. *Q J Exp Psychol* A33:95–103
- Robinson GH, Kavinsky RC (1976) On Fitts' law with two handed movements. *IEEE Trans Syst Man Cybern* 6:504–505
- Roy EA, Elliott D (1989) Manual asymmetries in aimed movements. *Q J Exp Psychol* 41A:501–516
- Schmidt RA (1988) *Motor control and learning: a behavioural emphasis*, 2nd edn. Human Kinetics, IL
- Steenbergen B, Hulstijn W, de Vries A, Berger M (1996) Bimanual movement coordination in spastic hemiparesis. *Exp Brain Res* 110:91–98
- Sugden D, Utley A (1995) Interlimb coupling in children with cerebral palsy. *Dev Med Child Neurol* 37:293–309
- Teasdale N, Bard C, Fleury M, Young DE, Proteau L (1993) Determining movement onsets from temporal series. *J Mot Behav* 25:97–106