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ROYAL SIGNALS & RADAR ESTABLISHMENT

PERFORMANCE OF ROLLING BALL AND ISOMETRIC JOYSTICK ON A 2-D TARGET ALIGNMENT TASK

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ROYAL SIGNALS AND RADAR ESTABLISHMENT

Memorandum

TITLE: PERFORMANCE OF ROLLING BALL AND ISOMETRIC JOYSTICK ON A 2-D TARGET ALIGNMENT TASK

AUTHOR: Mr A Jackson

DATE: April 1984

SUMMARY

A Rolling Ball and a Rate Controlled Isometric Joystick were employed in a target alignment task with dimensions comparable with those of many ATC tasks. In addition to amplitude and target width, variables included three levels of control-display relationship (gain), and direction of movement. The two devices were compared on a number of dimensions including overall performance time, the rate of incorrect responses, adherence to Fitts' Law and directional biases. This last factor proved significant only in the case of the joystick. The study concluded that; a) the rolling ball was still the preferred device for the ATC environment and should be retained; b) control-display relationship had no effect on the performance measures employed.

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1 INTRODUCTION

1.1 BACKGROUND TO THE STUDY

During the summer of 1982 an experiment was conducted at RAF. IAM Farnborough, to investigate the factors involved in establishing suitable control display relationships for rolling ball devices. The experimental task was chosen to span the range of movements and resolutions typically encountered in ATC applications. The experimental design was extremely complex and raised some fundamental questions concerning the concept of control/display gain as a determinant of performance. An IAM Report covering the more complex aspects of these studies is in preparation. A brief report, including a description of the design is to be found in Marshall (Marshall, 1982).

While the experiment was in progress, IAM obtained access to a rate controlled isometric joystick under examination by ATCEU (Hurn) for its potential as an ATC input tool. This device, commonly referred to as a 'force' joystick, superficially resembles a conventional joystick control but is rigidly fixed and, instead of generating an output with magnitude proportional to position, produces pulses of a fixed magnitude at a rate proportional to the shearing force applied by the hand. Only a few studies have been reported using this device (Card et al, 1978; Mehr, 1973; Albert, 1982) and it was appropriate that a trial should be conducted to gain first hand experience of the device's performance. It was recognised that the task used in the rolling ball experiment, involving sequences of target acquisitions in two dimensions on the surface of a radar-type CRT, would be suitable for evaluation purposes. Further, the rolling ball study could be used as a baseline to allow some comparison of the two devices. A description of the conduct of the joystick trials can be found in Culbert (Culbert, 1982).

The present document describes the relevant details of the two experiments, treating them as a single comparative study. It then reports the results and goes on to discuss the consequences for the use of the two devices in ATC. Individual sections describe the limitations on the comparisons possible between the two devices, the design, the method, the statistical analysis of the data, and the results and conclusions.

Note that devices such as the mouse and the graphics tablet with bug, which can offer high performance, are not considered suitable for the ATC environment because of demands for space and the undesirability of trailing wires.

2 COMPARABILITY OF THE TWO DEVICES

The fact that the rolling ball is a position device while the force joystick is a rate device makes direct comparison between the two devices difficult. If suitability for a particular task was being considered, one in which the devices could only be installed with a single control/display relationship, then a simple comparison on some performance measure might suffice to select the more appropriate device, This would be because the entire linkage between the operator and the display would be examined in the context of the application. The present requirement is for a general comparison of the two devices to cover a class of applications with a further, special interest in the manipulation of the control/display relationship, irrespective of the technical details of the implementation. As a result a more detailed consideration of the operator display linkage is necessary.

The linkage can be divided into two main parts; the operator-control component and the control-display component as shown in Figure 1. These can be varied independently, although some characteristics of the second component may exert a significant effect on the first as a result of the operator's ability to adapt to the characteristics of the linkage. The second component can be further divided into device characteristics, display characteristics, and the control/display relationship which links the two. In this particular study interest is centered on the device characteristics and on the effect which they have on the performance of the overall linkage. The specific consequences of their effects on the initial, operator-control component of the linkage is discussed briefly after considering the second component in more detail.

The characteristics of the display can be controlled by using the same stimulus materials, on the same display device under the same ambient lighting conditions for both devices, but manipulation of the control/display relationship is much more difficult to achieve. In this particular case there is even a difficulty in finding a means of describing the relationship which is equally applicable to the two devices.

Control/display Gain is defined as the ratio of system output to system input and this is typically taken to mean the ratio of control movement to display movement. This is a useful definition when considering positional devices like the rolling ball or the conventional joystick. The definition yields the same results irrespective of whether displacements or velocities of movement are considered, just so long as there are no system lags. In the case of the force joystick, which cannot be displaced, input to the system does not vary in magnitude but only in the frequency with which it occurs. Input is measured in terms of applied force and output in terms of the rate of pulses.

Conventionally, a rolling ball outputs pulses proportionately to its displacement. A count of these pulses is stored in an accumulator which is examined at intervals by the system which then updates the position of the cursor in the display file. There is, however, an alternative which could be employed to allow the ball and the joystick to be implemented in a relatively similar manner. If the system polls the ball with a high enough frequency each pulse can be detected individually, checked for direction of motion and the display file updated appropriately. This can be done equally readily for both devices provided that the system polls faster than the maximum output rate of either. In the present case the highest pulse rate produced by the joystick is 1KHz, corresponding to an applied force of 8.9N (2lb.f) and, on the rolling ball, to a peak ball velocity of 470 mm/s (18.4 in/s). A study by Rogers (Rogers, 1963), which showed that maximum ball velocity was a function of movement amplitude and direction, found average peak velocities of 610 mm/s (24 in/s) for 102 mm (4 in) excursions on the display (Figs 2 (a) and 2 (b)). However, the control/display gain in his study was held constant at 0.4 which meant that the ball was moving through 254 mm (10 in) to achieve the 102 mm of display movement. In keeping with the distinction made in the following section between ball parameters and display parameters, it is reasonable to assume that the peak ball velocity is a direct function of ball, rather than display displacement, and accordingly the present study limited ball movements to a maximum of 102 mm. An examination of Figure 2 (b) shows that this corresponds to velocities of below 380 mm/s (15 in/s) in Rogers' data. (It was not possible to obtain a direct measure of peak ball velocity in this study but the average velocity for the initial, and fastest component, of the fastest movement over the 102 mm distance, was 105 mm/s. This figure is considerably less than the 470 mm/s ceiling corresponding to 1KHz polling so that although some ball pulses may have been missed the effect must have been very small.)

Given this method of implementation, the control/display relationship can be modified by employing a multiplication factor to vary the number of display displacements arising from a single pulse of either device.

At an earlier point in this section it was suggested that characteristics of the control device, and possibly of the control-display relationship would have consequences for the operator-control component; that is, the way in which the individual acts upon the device. In this study there is no obvious way in which these consequences can be separated out from the effects on overall performance. However, in order to acknowledge that these effects exist, the study distinguishes between the effects that control/display relationship has separately on the two devices by referring to the relationship as GAIN only in the case of the rolling ball and by using the term SENSITIVITY when discussing the rate device, the force joystick.

3 DESIGN

The study had two main objectives.

i To examine positioning performance with the isometric joystick over a range of parameters comparable to those found in the ATC environment.

ii To compare performance characteristics with those of the rolling ball.

In order that the stimulus materials should be comparable across devices the joystick evaluation employed the same programmes and a subset of the experimental materials and conditions, employed in the ball study. The original rolling ball design allowed for the examination of three levels of control-display gain (G); two levels of target width (W); two levels of movement amplitude (A) and the direction in which movements were made (D), with six levels. In addition, the primary variable of the experiment was the means by which level of gain was manipulated. Buck (Buck, 1980) has pointed out that there are two ways in which control-display gain can be varied. For example, if gain is to be increased, this can be achieved either by holding the display parameters constant and decreasing the magnitude of the control movements needed for the translation or, alternatively, control parameters can be held constant and the display dimensions can be increased. The first of these two methods was labelled Control Variation (CV) and was presented to one group of six subjects, in the rolling ball study. This is the means by which gain has been manipulated in most previous researches. The second, Display Varied

(DV), condition was presented to a second group of subjects. A detailed description of the reasoning behind the design will be provided in the IAM report on the rolling ball but it is also to be found in a series of working papers (Jackson 1981, 1982). Since the resulting experiment was very large (in excess of 83,000 response latencies were collected), a complete replication was not considered for the force joystick. Instead it was decided that either the CV or the DV conditions should be repeated as closely as possible using the joystick in place of the ball.

There was some difficulty in determining which of the two conditions was most appropriate, but the CV condition was finally adopted. This had the advantage of testing the joystick over a wider range of linkages with the system and of using the form of Gain/Sensitivity variation most frequently employed in the literature; hopefully extending the range of comparability of the findings. It had the disadvantage that it limited the range of both display target widths and amplitudes to only two levels. Table 1 outlines the CV conditions as they were employed across the ball and joystick devices. For the purposes of the present study, these two conditions, labelled BALL and JOYSTICK constitute the two levels of the between groups factor CONTROL.

		DISPLAY		CONTROL		RELATIONSHIP
COND	GAIN/SENS	AMPL	TGT	AMPL	TGT	(1 device pulse produces)
A	1.0	A,2A	W,2W	A,2A	W,2W	2 display incr *
B	2.0	A,2A	W,2W	A/2,A	W/2,W	4 display incr
D	0.5	A,2A	W,2W	2A,4A	2W,4W	1 display incr

* One ball pulse = 0.462 mm of movement, and is twice as large as one display increment (0.233 mm).

TABLE 1 Details of the targets and amplitudes assigned to the Control Varied condition of the rolling ball study. A = 26.8 mm and W = 5.5 mm.

Each of the two Control conditions consisted of three blocks of experimental trials A, B and D, the block names being those employed in the original study. These blocks corresponded to different levels of GAIN in the ball conditions and different levels of SENSITIVITY in the joystick conditions. The relationship between Gain and Sensitivity has been discussed in the section entitled "Comparability of the Two Devices". The overall design of the study is summarized in Figure 3 and the following paragraphs deal with the detailed construction of each of the blocks.

As far as display parameters are concerned, all six blocks are identical; differences occurring only in the device employed and the control-display relationship. In Table 1 there are three main blocks with Gain/Sensitivity levels of 1.0, 2.0 and 0.5 respectively. The displayed amplitudes and target sizes are common to all three blocks and the extreme right hand column shows how the control-display relationship was varied. In the case of the rolling ball, which outputs pulses proportionally to displacement, each output pulse was examined to determine its direction and the display file was updated by the number of screen increments indicated for that Gain condition. Exactly the same procedure was followed for the joystick pulses to achieve the corresponding Sensitivity levels. One effect of this procedure was to ensure that the minimum display movement which could be produced on the display was identical across device conditions with the same Gain/Sensitivity level.

Within a single block there were 72 trials. The precise structure of these trials is shown in Figure 4. Each trial required the acquisition of four targets in a short sequence. Each sequence involved a single target width (W) and two instances of each of the two amplitudes (A) assigned to that block. Six permutations result from the possible orderings of these two amplitudes and these were cycled under two other factors, the target width (W) and the direction of the first movement in the sequence (D), to produce 72 trials each of 4 acquisitions. Six movement directions were employed at 60 degree intervals to the horizontal as shown in Figure 5. Targets were hexagonal in shape with target width being defined as the distance between parallel faces. If acquisition movements proceeded by the shortest possible routes (as shown by the direction vectors linking targets), then the cursor would always enter a target through the mid-point of a side. After the first movement in a sequence, direction was chosen randomly with the constraint that the target always remained on the screen.

In this study, since direction was of interest, analysis was carried out only on the first movement of each sequence. This fact is reflected in Figure 4 and the trial tree has been divided into two subsets of 36 on the basis of the amplitude of the initial acquisition movement. Thus within a block trials can be described by Target (2) x Amplitude (2) x Direction (6) x Sequence of remaining amplitudes (3). A summary of the factors and levels is provided in Table 2.

FACTOR NAME	LEVELS	DESCRIPTION	LOCUS
1. Control (C)	2	a) Joystick b) Rolling Ball	Between Subject Groups
2. Direction (D)	6		Within Blocks, Between Trials
3. Amplitude (A)	2	a) 26.8 mm (small) b) 53.6 mm (large)	Within Blocks, Between trials
4. Target Width (W)	2	a) 5.5 mm (small) b) 11.0 mm (large)	Within Blocks, Between Trials
5. Gain/Sensitivity (G)	3	a) 1.0 b) 2.0 c) 0.5	Between Blocks and Days
6. Replications (R)	4	only 2, 3 and 4 analysed	Repetitions of block assigned to Day

TABLE 2: Summary of experimental factors and levels.

This design allows the examination of several dimensions on which we might expect the two devices to differ. Briefly, these are:-

1 Simple overall performance in terms of latencies and/or errors. This should show as a main effect of the Control variable.

2 Differences in the ability to make small, high resolution movements might express themselves in the Control x Target Width interactions.

3 Differences in the ability to trade-off these small, high resolution movements with large scale rapid movements. The gain of a device is chosen to facilitate this trade-off for a particular task. The Gain/ Sensitivity variable should serve as an indicator of such differences.

4 There is an apparent contradiction between the concept of gain, and Fitts' Law (Fitts, 1954) which can be used to relate acquisition time, amplitude of movement, and target width independently of gain (see Appendix 1). The rolling ball is usually assumed to be a Fitts' Law device and there is a limited amount of data to suggest that the force joystick can be considered as one (Card et al, 1978). This issue is testable using the current design.

5 Directionality: The Rogers study (Fig 2 (b)) showed that the peak velocity of a rolling ball is a function of direction. It is quite probable that two devices which require different patterns of muscle movements for their operation, might display different directional characteristics.

4 METHOD

4.1 SUBJECTS

Six male and six female subjects, aged between 19 and 25, from the Royal Air Force Institute of Aviation Medicine voluntarily participated in the experiment. Six subjects took part in the Rolling Ball condition and six used the Joystick with the constraint that equal numbers of males and females were in each group. All subjects were right handed, employing their favoured hand to control the appropriate input device and their other hand to press the response button. Subjects had normal or corrected vision.

4.2 APPARATUS

This consisted of a Digital PDP8 computer, a DEC 3381 CRT display, a Measurement Systems Inc. Model 869 force joystick, and a Marconi F3052-22 rolling ball. The rolling ball had a diameter of 76.2 mm and protruded 12.7 mm above a surface plate to present a surface arc of 64.0 mm. The radar CRT had a circular display surface and an effective screen diameter of 370 mm which was addressable in cartesian coordinates. The devices were polled at a rate of 1KHz and the screen was refreshed at 50Hz. Technical details of the two input devices are provided in Appendix 2.

4.3 EXPERIMENTAL TASK

Initially, the subject's task was to press the response button, at which point a hexagonal target (parallel sides W apart; see Fig 5), a cursor and a straight line connecting the two, appeared on the radar CRT. For each experimental trial the subject was required to use the appropriate input device to move the cursor until *it was inside the* target hexagon and then press the response button, causing the appearance of the next target in the sequence. If the subject pressed the button while the cursor was not positioned within the target, the system recorded the latency and noted the error but made no overt change in the display. The next target only appeared after a correct acquisition response. Targets were presented in sequences of four, after which the cursor was repositioned in the center of the screen. At this point it was necessary for the subject to press the response button again to initiate the next trial sequence.

4.4 *PROCEDURE*

Subjects were tested individually and participated at the same time on three successive days. Within each session, subjects received four replications of one of the three Gain/Sensitivity blocks. Order of conditions was counter-balanced across days. Within each replication, the trial order was randomised at runtime. Each subject was seated facing the radar display with the input device and response button on a horizontal surface in front of them, as shown in Figure 6. Subjects were given a set of instructions to read (Appendix 3), detailing the task to be performed. Room lighting was reduced and the subject performed the first sequence of four targets with the experimenter present to ensure that the instructions had been understood. The experimenter then left the room and the subject continued. A minimum of two response times (latencies) were recorded for every acquisition in a trial; time from target appearance until the initial entry of the cursor into the target figure and time from target appearance until a correct final acquisition response had been made with the push-button. The system also recorded overshooting of the target by noting the time on each occasion that the cursor crossed the target boundary moving inwards, prior to final acquisition.

Table 3 (a). T <r> Overall latency until acquisition response. ANOVA summary table of main effects and significant interactions.

FACTOR	LEVELS	df	SS	MS	F	SIGN
Control (C)	2	1,8	26.2034	26.2034	5.110	NS
Direction (D)	6	5,40	2.4207	0.4841	15.588	***
Amplitude (A)	2	1,8	28.3424	28.3424	325.840	***
Target Width (W)	2	1,8	23.7031	23.7031	251.101	***
Gain/Sensitiv (G)	3	2,16	0.3127	0.1564	0.110	NS
Replication (R)	3	2,16	1.9512	0.9756	37.093	***
SIGNIFICANT INTERACTIONS						
C x D	-	5,40	1.5050	0.3010	9.961	***
D x G	-	10,80	0.4532	0.0453	3.244	**
A x W	-	1,8	0.0314	0.0314	6.379	*
W x G	-	2,16	0.1831	0.0916	9.768	**
G x R	-	4,32	0.5041	0.1260	2.699	*

Table 3 (b). T <e> Latency until target entry. ANOVA summary table of main effects and significant interactions.

FACTOR	LEVELS	df	SS	MS	F	SIGN
Control (C)	2	1,8	120.7830	120.7830	13.398	**
Direction (D)	6	5,40	4.0962	0.8192	15.052	***
Amplitude (A)	2	1,8	53.4351	53.4351	721.379	***
Target Width (W)	2	1,8	29.6949	29.6949	673.645	***
Gain/Sensitiv (G)	3	2,16	0.9005	0.4502	0.629	NS
Replication (R)	3	2,16	0.7136	0.3568	6.626	**
SIGNIFICANT INTERACTIONS						
C x D	-	5,40	2.3038	0.4608	8.446	***
D x A x G	-	10,80	0.4624	0.0462	2.007	*
A x G x R	-	4,32	0.2009	0.0502	2.771	*
D x A x Q x G	-	10,80	0,3741	0.0374	2.577	**
D x A x W x R	-	10,80	0.3807	0.0381	2.058	*

Table 3 (c). T <t> Latency between target entry and acquisition response. ANOVA summary table of main effects and significant interactions.

FACTOR	LEVELS	df	SS	MS	F	SIGN
Control (C)	2	1,8	109.392	109.392	7.106	*
Direction (D)	6	5,40	5.6762	1.1353	3.666	**
Amplitude (A)	2	1,8	0.0005	0.0005	0.002	NS
Target Width (W)	2	1,8	6.3491	6.3491	14.313	**
Gain/Sensitiv (G)	3	2,16	3.1564	1.5782	0.262	NS
Replication (R)	3	2,16	11,5644	5.7822	44.131	***
SIGNIFICANT INTERACTIONS						
D x G x R	-	20,80	2.7856	0.1393	1.865	*
C x D x A x W x R	-	10,80	1.5730	0.1575	1.998	*

Significance Level: *probability < 0.05; ** probability < 0.01; *** probability < 0.001. Data subject to natural log transformation.

TABLE 3. ANALYSIS OF LATENCY DATA FROM ROLLING-BALL JOYSTICK COMPARISON EXPT.

5 ANALYSIS AND RESULTS

5.1 RESPONSE LATENCIES

All response latencies were recorded by the PDP-8 to the nearest centisecond. A sample printout is provided in Appendix 4. Since direction was systematically controlled only for the first movement in a sequence of four, the initial analysis derived from 72 acquisitions per replication block rather than 288. A preliminary analysis of within-session learning effects revealed that the first block of each session showed a higher degree of variability than the others and as a consequence analysis was confined to replications 2, 3 and 4 of each session. The following analyses were therefore based on data from 7776 acquisitions.

Several response latencies were recorded for each of these acquisitions. The two primary measures were T <r>, the latency from target appearance until a correct acquisition response was made and T <e>, the time between target appearance and the cursor first making contact with the target boundary. The system also recorded overshoots by noting the latency of all target boundary crossings on an inward direction and the latency of incorrect acquisition responses. All trials with false acquisition responses were excluded from the latency analysis.

T <r> may be regarded as an overall performance measure incorporating target location (the leading direction vector was intended to minimise the visual search components), movement to the target region, fine adjustments to enter the target, recognition that the cursor is correctly located in the target, and the latency of the push-button acquisition response. As such it represents a realistic measure of general task performance but since it is subject to a large number of variables, detailed effects specific to a particular component of the acquisition, may be masked. In order to allow a more detailed interpretation, the overall measure can be decomposed into two components. The first is available as T <e> and embraces all factors up until the initial target contact and the second can be derived, for every acquisition, by subtracting T <e> from T <r>, ie

$$T_{<t>} = T_{<r>} - T_{<e>}.$$

The T <t> component reflects latency from target entry until the final acquisition response is complete. If overshooting is not evenly distributed across factors, the fact should be reflected in the T <t> measure. The data for all three measures was subjected to natural logarithm transformation prior to inclusion in identical 6 factor Analysis of Variance (ANOVA) with Control (C) as a between groups factor, and Direction (D), Amplitude (A), Target Size (T), Gain/Sensitivity (G) and Replications (R) as within subjects factors. The main effects and significant interactions for T <r>, T <e> and T <t> are shown in Table 3, parts (a), (b) and (c) respectively.

5.1.1 ERROR DATA

All acquisitions in which a false acquisition response was noted were excluded from the latency analyses. This error data was analysed separately in an ANOVA of exactly the same structure as that employed for the latency data. (Each cell of the latency analysis contained the mean latency for three trials - averaged across the sequences of following amplitudes, see Fig 4). An error was scored as "1", the absence of an error as "0", so that the corresponding cells of the error analysis held a value between 0 and 3. No transformation was employed. The summary table resulting from the error ANOVA is shown as Table 4.

5.2 RESULTS

Since this short paper is specifically concerned with the comparisons of the two input devices, the following section will deal with Control and Control related effects separately from the other effects in the analysis. The mean acquisition and response time over the whole study was 1181 ms and the average error rate was 4.09%.

5.2.1 CONTROL RELATED EFFECTS

5.2.1.1 MAIN EFFECTS

Although the overall performance data (T <r>) showed the joystick to be 238 ms slower than the rolling-ball on average this result fell just short of significance ($F = 5.11$; df 1,8; $p = 0.05$ level requires a value of $F = 6.61$); however, the decomposition of overall latency into T <e> and T <t> was shown to be justified by the observation of significant main effects of input device in both of these analyses. The apparent contradiction is explained by the fact that these two effects lie in opposite directions. In the analysis of latency up until first target entry the rolling-ball (mean 647 ms) was significantly faster than the joystick (mean 995 ms) with probability at the 0.01 level. In contrast, the within target times revealed that the joystick (247 ms) was faster than the rolling-ball (372 ms, $P < 0.05$).

5.2.1.2 INTERACTIONS

The only interpretable interaction involving the choice of input device is the Control x Direction interaction. Although this effect is highly significant in the T <r> data ($F = 9.691$; $p < 0.001$), it seems to derive almost entirely from the initial component of motion, prior to target entry where it shows comparable significance ($F = 8.446$; df 5,40; $p < 0.001$) in the T <e> data. The interaction falls short of significance in the T <t> analysis ($F = 1.894$; $p = 0.117$). The interaction is shown in Figure 7. An analysis of simple main effects, Direction within Control, was carried out on both the T <r> and T <t> data, using Studentized Neumann-Keuls comparison criteria. In both cases the rolling ball data showed no effect of direction whatsoever while the effect of direction with the joystick was significant at the $p < 0.001$ level. More specifically, for T <e> directions 2 and 5 (the horizontal directions) were faster than the other four directions ($p < 0.001$) and in the remaining four directions 1, 4, and 6 were faster than direction 3 ($p < 0.05$). In T <r> directions 2 and 5 were again faster than the other four directions which did not differ significantly from one another ($p < 0.001$). The T <t> condition showed a higher variability which tended to wipe out any effects and its inclusion in the T <r> data accounts for the inability to separate out the direction 3 effect.

The error analysis showed no effects of the Control factor with the exception of a partially supported, five way interaction C x D x A x G x R, which reached the 0.05 level of significance.

5.2.2 OTHER EFFECTS

5.2.2.1 MAIN EFFECTS

DIRECTION (D): This effect was present in all three latency measures but not in the error data. Its nature is covered by the discussion of the C x D interaction above.

AMPLITUDE (A): This showed a massively significant effect in T <r> and in the T <e> component but unsurprisingly disappeared completely in the T <t> component. The result showed that the smaller amplitude movement was accomplished more rapidly than the larger movement (mean differences: T <r> = 247 ms, T <e> = 231 ms, T <t> = 0). There was no obvious speed-accuracy trade-off, the larger amplitude showing a significantly higher error rate at 4.86% as compared with the lower amplitude at 3.34%, $p < 0.05$.

TARGET WIDTH (W): This effect was significant in T <r> and in both components T <e> and T <t>, with larger targets being acquired more rapidly than smaller targets (mean differences: T <r> = 227 ms, T <e> = 172 ms, T <t> = 30 ms). The effect was mirrored in the error data with performance on larger targets significantly more accurate than smaller at 3.08% and 5.09% respectively, $p < 0.01$.

REPLICATION (R): All three latency measures showed the effect of block replication and, in every case, this can be interpreted as an improvement in performance with practise.

5.2.2.2 INTERACTIONS

The C x D interaction has already been discussed. The remaining interactions present a somewhat confused picture, with no particular interaction emerging across measures although the Gain/Sensitivity factor is notable for the range of its interactions with other variables.

6 DISCUSSION

At the conclusion of the Design section a number of dimensions for comparison of the two devices were listed. These dimensions are used to structure the following discussion of the results. The extremely clear and strong effects attributable to well established factors like amplitude and target width imply that confidence may be placed in the power of the experiment.

6.1 OVERALL PERFORMANCE

The rolling ball was on average some 238 ms faster than the joystick on overall performance although this did not achieve significance owing to the high variance of the data. This variance arose from differences between the devices on the decomposed components of the acquisition task. The ball was significantly faster than the joystick in reaching the boundary of the target for the first time. This effect was large, being of the order of 350 ms, a large fraction of the acquisition time. Conversely, once the target had been reached, the force joystick was some 80 ms faster than the rolling ball. Given that this final component (mean 303 ms) included the latency to decide that acquisition had occurred and make the response, a component that might be expected to be around 200 ms, this is a substantial improvement. It may be explained by considering that the cursor stops as soon as pressure on the joystick is removed while the rolling ball possesses inertia and the correct forces must be applied to bring it to a standstill. There was no difference between the devices in terms of error rate. Although the overall result is non-significant it may be felt that an average saving of 25% suggests that the ball is the favoured device on this dimension.

6.2 DIFFERENCES IN THE ABILITY TO MAKE SMALL, HIGH RESOLUTION, MOVEMENTS

There was no evidence for a Control x Target Width effect within the ranges used in the present study, even though the Target Width effect was clearly present in all measures. It might be imagined that the improved performance of the joystick in the T <t> component would suggest an advantage but even in that case the C x W interaction falls well short of significance.

6.3 DIFFERENTIAL EFFECTS OF GAIN/SENSITIVITY.

The absence of an overall effect of the Gain/Sensitivity factor is striking and lends strong support to a related finding by Buck (Buck, 1980). There is also no evidence of any C x G interaction, again a dramatic finding when we consider that this is the area in which the anticipated differences in the devices' conceptual implementations were most likely to reveal themselves. There is now very strong evidence that, so long as a device is well implemented and working within sensible ranges of control-display relationship, Gain is NOT a critical determinant of performance. In most examples in the literature relationships of about 1:1 seem to produce satisfactory results. However, before dismissing the concept of Gain entirely, note should be taken of the following considerations:

a. The number of interactions in which the factor was involved.

b. The fact that within any one session, only a single gain was employed. When a range of gains, with switching between them is possible, the situation may be considerably more complex.

The issues associated with gain form a more central theme of the proposed IAM Report on the rolling ball experiment.

6.4 FITTS' LAW DEVICES

In order to establish to what extent the two devices could be described by Fitts' Law a new analysis was performed on the T <r> data with Amplitude and Target Width concatenated into a single factor based on a formula described by Welford (Welford, 1968, p 147), log <base 2> (A/W + 0.5). This factor was substituted for the A and T factors in the ANOVA, and a single linear contrast was extracted, employing the appropriate 'by subjects' variance components as error terms. This effectively performed a linear regression across all other factors, but it also allowed for the examination of the interaction of Fitts' Law with the other factors. The ANOVA revealed that the linear component of the Composite factor was highly significant ($F = 134.86$; df 1,8; $p << 0.001$). The non-linear component of the Composite was also significant at the $p < 0.05$ level ($F = 5.89$; df 2,16). The Composite x Control interaction failed to reach significance, which indicated that there was no significant difference in how well Fitts' Law described the two devices ($F = 3.18$; df 1,8). The approximate Fitts' Law functions are shown in Figure 8. The Linear Composite x Direction and Linear Composite x Direction x Control interactions were both significant at $p < 0.001$ and $p < 0.05$ respectively. These interactions are shown in Figures 9 (a) and 9 (b) and, without further statistical analysis, it is clear that they broadly follow the pattern revealed in the primary analyses in which the rolling ball displayed no directional effects while the joystick showed strong directionality. It is interesting to note that D2 and D5 have the least slopes and lowest intercepts, while D1 has a higher intercept and D3, D4 and D6 appear to share a common, steeper slope.

Overall the Welford form of Fitts' Law proved to be a very powerful predictor of performance. In spite of the fact that the non-linear component of the composite factor was significant, the linear component accounted for an extremely substantial 99.8% of the variance attributable to Amplitude and Target Width. In Figure 8 the approximate slope and intercept values are:

Joystick T <r> = 0.64 + 0.29 log <base 2> (A/W + 0.5) seconds

Ball T <r> = 0.58 + 0.21 log <base 2> (A/W + 0.5) seconds

This compares with the joystick values obtained by Card et al (1978) of:

T <r> = 0.99 + 0.22 log <base 2> (A/W + 0.5) seconds

Clearly there is substantial agreement.

6.5 DIRECTIONALITY

These effects were very clear. Errors did not vary as a function of direction but response latencies did show a marked effect of the order of 120 ms maximum. This effect was entirely ascribable to the Joystick and may be interpreted in terms of the muscle groupings involved. The fastest movement was in the horizontal plane, the line of action which results from gross movements of the forearm. Next fastest were D1 and D4 which result from the natural folding and unfolding of the wrist in right handed subjects. Movements in the third plane may rely largely on pressures produced by co-ordination of finger and hand muscles. These findings are reflected in the different slopes of the Fitts' Law functions.

In addition to these comparisons between the devices, an analysis was conducted which extracted the effect of days from the data. This produced a significant Days x Control interaction which showed that the joystick showed more protracted learning effects than the rolling ball. Over the three days, the ball showed no learning effects while the joystick was significantly slower for Day 1 than for Days 2 and 3.

7 SUMMARY AND CONCLUSIONS

7.1 Although there was no main effect of devices, the rolling ball was substantially faster than the force joystick. This difference was highly significant for the initial component of acquisition movements. The rolling ball also reached a plateau on the learning curve significantly faster than the joystick and performed equally well in all the movement directions sampled. The joystick showed strong directional biases.

7.2 In conditions where only a single gain was available at any one time, Gain/Sensitivity was not a significant determinant of performance. Generally a Control-Display relationship of roughly 1:1 would seem appropriate.

7.3 Fitts' Law proved to be a very powerful predictor of performance on the devices. Card, Moran and Newell's (1983) emphasis on its usefulness in the design process would appear to be completely justified.

7.4 Conclusion - while the force joystick provided good performance on this task, the rolling ball was a more satisfactory device on all comparison criteria which revealed differences. Unless specific implementation conditions argue to the contrary, the rolling ball should remain the favoured device in the Air Traffic Control Environment.

ERROR DATA

TABLE 4 Error Data: ANOVA summary table of main effects and significant interactions

FACTOR	LEVELS	df	SS	MS	F	SIGN
Control (C)	2	1,8	2.4691	2.4691	2.153	NS
Direction (D)	6	5,40	0.2176	0.0435	0.377	NS
Amplitude (A)	2	1,8	1.2978	1.2978	8.670	*
Target Width (W)	2	1,8	2.3472	2.3472	13.703	**
Gain/Sensitiv. (G)	3	2,16	0.4375	0.2188	0.623	NS
Replication (R)	3	2,16	0.0301	0.0151	0.059	NS
SIGNIFICANT INTERACTIONS						
D x G	-	10,80	1.8866	0.1887	1.989	*
A x R	-	2,16	0.9452	0.4726	9.108	**
D x A x R	-	10,80	2.2492	0.2249	2.075	*
A x W x G	-	2,16	0.5625	0.2813	5.420	*
C x D x A x G x R	-	20,160	3.5355	0.1768	1.171	*

Significance Level: * probability < 0.01; ** probability < 0.05;
*** probability < 0.001.

TABLE 4. ANOVA of distribution of errors (incorrect acquisition responses).

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APPENDIX 1

FITTS' LAW

Fitts' Law emerged from work carried out by Fitts (Fitts, 1954), in an attempt to use Communication Theory to link the amplitude, duration and variability of human movements. These studies resulted in the establishment of Fitts' Index of Difficulty (Eqn 1) which implies that an increase in target width (W) or a decrease in amplitude of movement (A) increases the difficulty of a task.

$$I.D. = \log_{2}(2A/W) \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

This formula can also be expressed in terms of the total movement time (T) as in Equation 2.

$$T = a + b.\log_{2}(2A/W) \qquad \ldots\ldots\ldots\ldots\ldots (2)$$

where a and b are regression constants. Fitts saw the constant b as a measure of the information processing rate of the sub-system under examination and values of between 30 and 120 ms/bit have been quoted in the literature for hand movements with higher time values where manipulative devices are involved.

Fitts' Law was originally formulated on a range of direct hand-eye coordination tasks (repeated touching between two plates, insertion of pins into sockets), but the insertion of remoting components into both the visual (microscope, TV camera) and motor (Control devices) aspects of the task has not significantly impaired its ability to account for large parts of the task variance. It is important to note that this formula makes no allowance for the effects of Gain as the ratio of amplitude and target width remains constant with gain variation. Gain effects do not seem compatible with the ability of Fitts' Law to describe a wide variety of control-display systems.

The form of Fitts' Law employed in the current study is quoted in Welford (Welford, 1968) and suggests that the relevant amplitude is actually measured from the starting position, not to the middle of the target region, but to the far boundary; hence the addition of half the target width in Equation 3.

$$T = a + b.\log_{2}((A + 0.5W)/W = a + b.\log_{2}(A/W + 0.5) \quad \ldots\ldots (3)$$

Crossman (Crossman, 1957), describes a further correction which allows for the fact that subjects do not necessarily employ the complete width of the target in making their responses. The EFFECTIVE Target Width W (e) can be computed from the spatial distribution of movement end-points and this value, together with the analogous amplitude value A (e) can then be substituted in Eqn 3. Statistically, it can be argued that if more than 4% of acquisitions lie outside the target area then W (e) > W, and if less than 4%, W > W (e). Since computation of W (e) and A (e) requires the absolute spatial positions of all acquisitions in order to establish the relevant distributions, this procedure was not followed. However, the average error rate in the study was 4.09% which strongly suggests that W and W (e) were equivalent in this situation.

The theoretical basis of Fitts' Law is the subject of some controversy (see Sheridan, 1979; Langolf et al, 1976; Howarth et al, 1971) and since

Fitts' original statement in terms of information theory a number of other formulations have been offered, including derivations based on Control Theory. The interested reader is referred especially to the Langolf et al, the Welford, and the Card, Moran and Newell references. The latter provides a simple and satisfying derivation of the law in terms of the cycle times of components of the Human Informations Processing system. For present purposes, irrespective of its theoretical status, Fitts' Law in the form of Equation 2, remains a very powerful descriptor of manually mediated tasks.

APPENDIX 2. TECHNICAL DETAILS OF INPUT DEVICES

ROLLING BALL

Type:	Marconi F3052-22 Tracker Ball Controller. Marconi Electronic Devices Ltd, Carholme Road, Lincoln, LN1 1SG, England.
Dimensions:	Diameter 76.2 mm, protruding 12.7 mm above surface plate.
Operation:	Rotation of the ball is transmitted to two orthogonal shafts corresponding to two axes of movement. Ball to shaft diameter ratio is 10.8 to 1. A slotted disk is mounted at the end of each shaft interrupting the light falling on an associated pair of photosensitive devices. The phase difference within a pair indicates the direction of motion for that axis. On the F3052-22, the disks each carry 48 slots producing 518 pulses per ball rotation (nominal 512).

The device was polled at 1 KHz to establish the presence or absence, and direction of movement on each shaft.

FORCE JOYSTICK

Type:	Measurement Systems Inc. 869-10-01, Force Operated Two Axis Joystick with Pulsed Outputs. (Model 469 Joystick and Model 31C10 Two Axis Pulse Generator). Measurement Systems Inc., 121 Water Street, Norwalk, CT 06854, USA.
Dimensions:	Stick height 33.02 mm, diameter 9.14 mm.
Operation:	The joystick is rigid and produces two pulsed outputs proportional to the applied force on two axes. Pulse rate varies from 0-1 KHz corresponding to applied forces of 0-1 kg.f (approximately). The output/force function is not completely linear being slightly flattened at the high end and intentionally incorporating a small dead zone at the low end.

This device was also polled at 1 KHz.

APPENDIX 3 INSTRUCTIONS TO SUBJECTS

ROLLING-BALL CONDITION

Please read these instructions carefully .....
This is an experiment to investigate the use of the rolling ball as an input device. When the experiment begins, a small cross will appear in the centre of the screen. This cross is the cursor and is controlled by the movements which you make on the ball. However, the ball will not move the cursor until you press the illuminated button. When you press the button a hexagon will appear on the screen. This is your target. Your task is to use the ball to move the cursor until it is inside the target hexagon. As soon as it is, press the button again to tell the computer that you have acquired the target. If you are inside the target area the computer will immediately present another target hexagon for you to find. Your task is to acquire all the targets as quickly and with as few mistakes as possible. Targets come in sequences of four. At the end of the sequence the cursor will reposition itself in the centre and you will have to press the button again to start the next sequence. Each block consists of a number of sequences and takes about ten minutes. When you finish a block, call the experimenter. If you wish to take a rest during a block, you may do so by finishing a sequence and not pressing the button to start the next sequence. When you wish to continue press the button and the block will recommence.

If you have any questions, please ask the experimenter. Thank-you very much for your participation.

JOYSTICK CONDITION

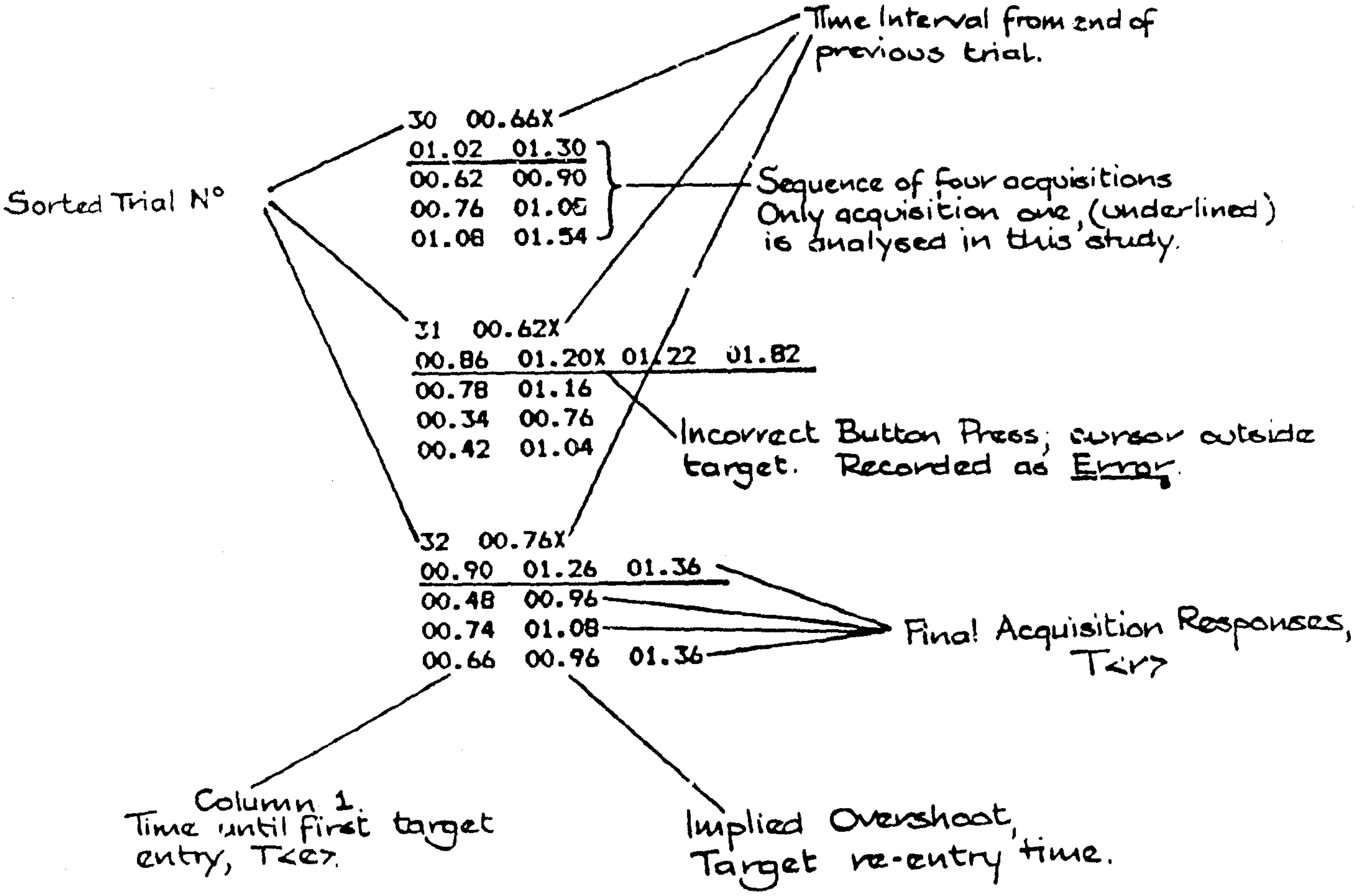
Please read these instructions carefully ....
This is an experiment to investigate the use of the pressure joystick as an input device. When the experiment begins, a small cross will appear in the centre of the screen. This cross is the cursor and is controlled by movements which you make with joystick. However the joystick will not move the cursor until you press the button. When you press the button, a hexagon will appear on the screen. This is your target. Your task is to move the cursor, by means of the joystick into the hexagon. Once you believe the cursor to be inside, again press the button. If you are inside, then another hexagon will appear, and you repeat the procedure. If, when you press the button, the cursor is not inside the hexagon, then a new target will not appear and you must adjust the position of the cursor and press again. The targets come in sequences of four, and you must try to complete each sequence as quickly and with as few errors as possible. After the fourth target has been successfully achieved the cursor will return to the centre of the screen. You initiate the next sequence of four by again pressing the button. If you wish to take a short rest between sequencies you are free to do so. Sessions last for about 10 minutes and you will know the session is over when pressing the button fails to initiate the next sequence. When this happens tell the experimenter.

If you have any questions please ask the experimenter. Thank you very much for your participation.

NOTE: Both sets of instructions were presented to subjects, typed on single sheets of paper. The slight differences in the instructions are unfortunate and derive from changes made by the student experimenter who ran the joystick condition as his project at IAM. The differences are not considered to be of a significant nature and should have had no effect on the outcome of the comparative analysis.

APPENDIX 4.

SAMPLE OF SUBJECT RESPONSE DATA



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30  00.66X
01.02  01.30
00.62  00.90
00.76  01.06
01.08  01.54

31  00.62X
00.86  01.20X 01.22  01.82
00.78  01.16
00.34  00.76
00.42  01.04

32  00.76X
00.90  01.26  01.36
00.48  00.96
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00.66  00.96  01.36
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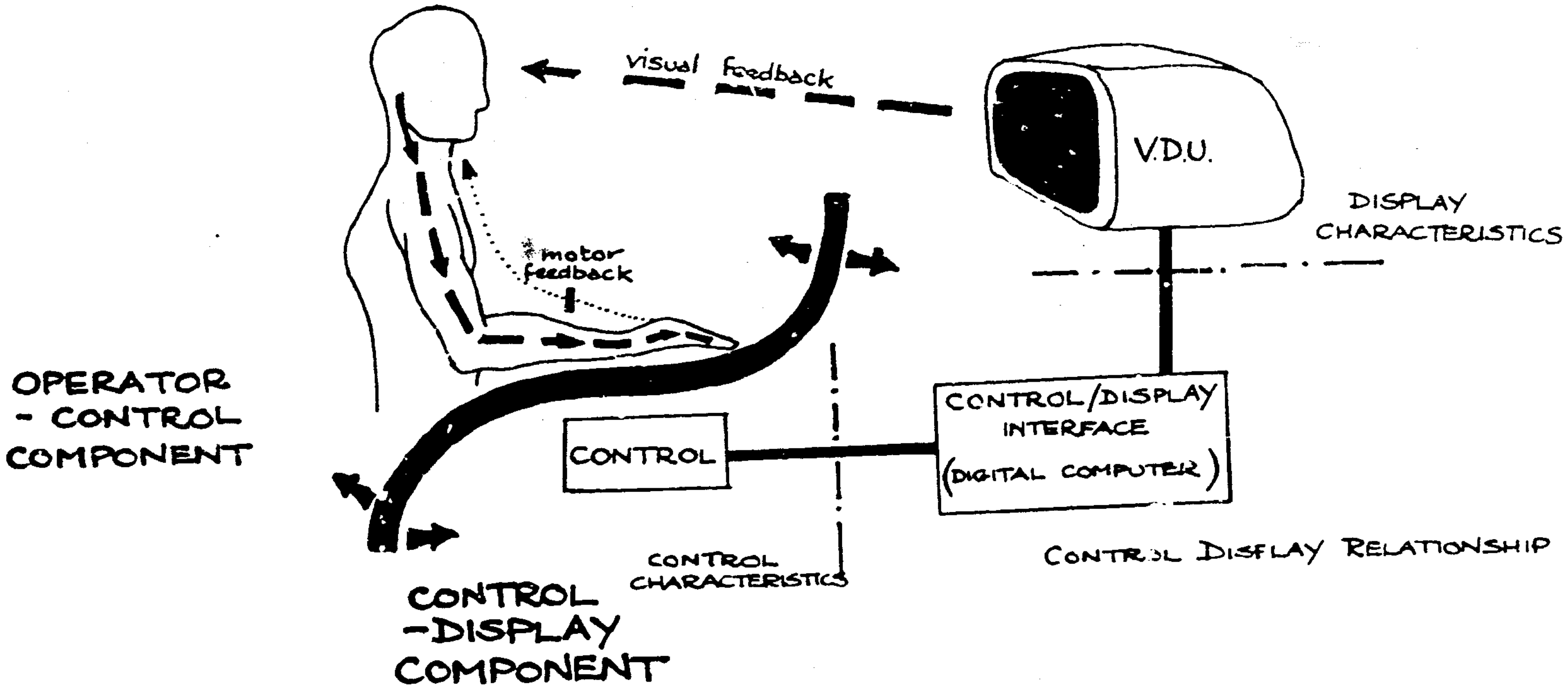


Fig 1. The Man-Computer Graphics Input Control Loop.

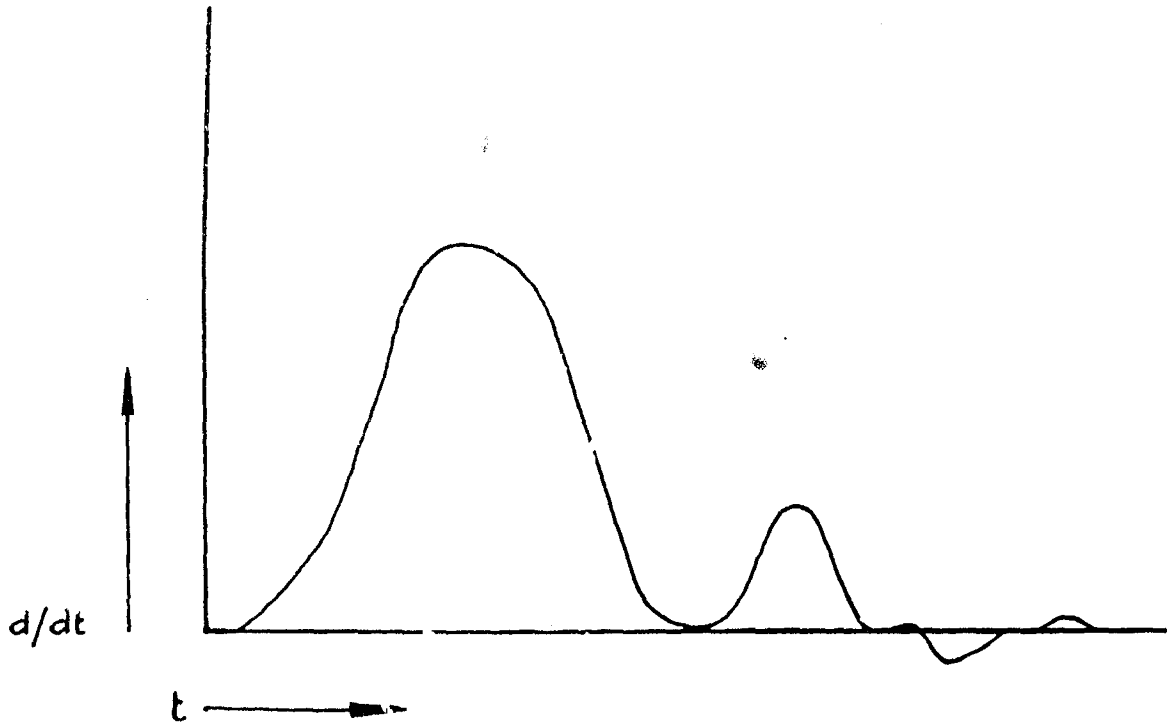


Fig 2a. Typical velocity function according to Rogers (1963).

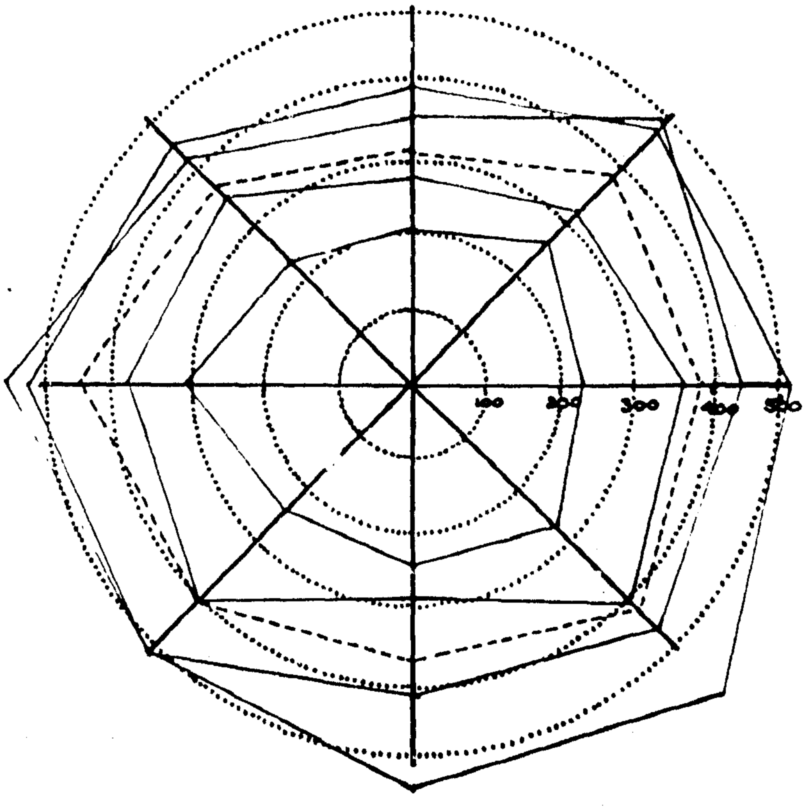


Fig 2b Maximum velocity versus target direction, averaged across movement amplitude(---) Data Rogers (1963).

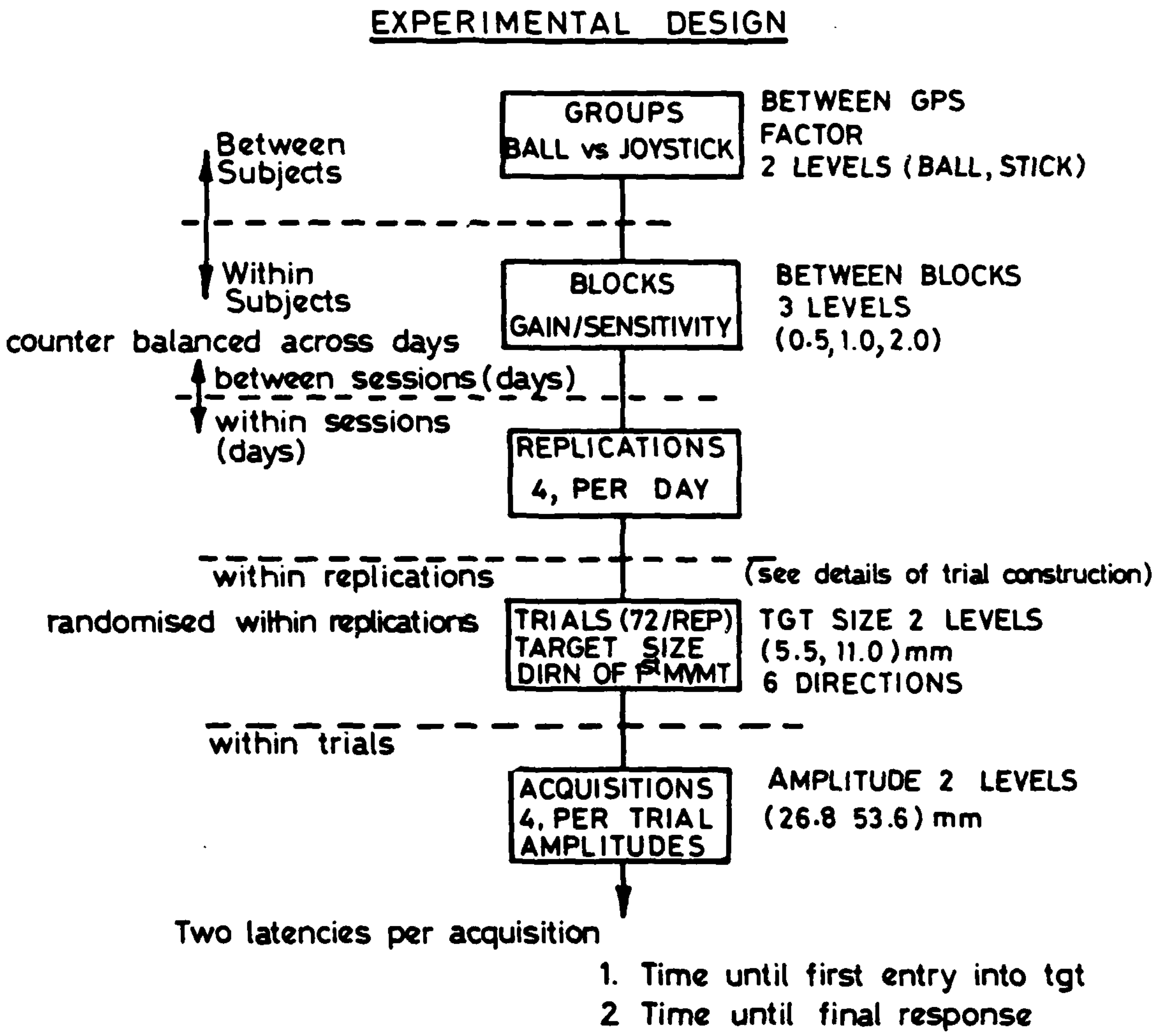


FIG. 3. THE STRUCTURE OF DESIGN

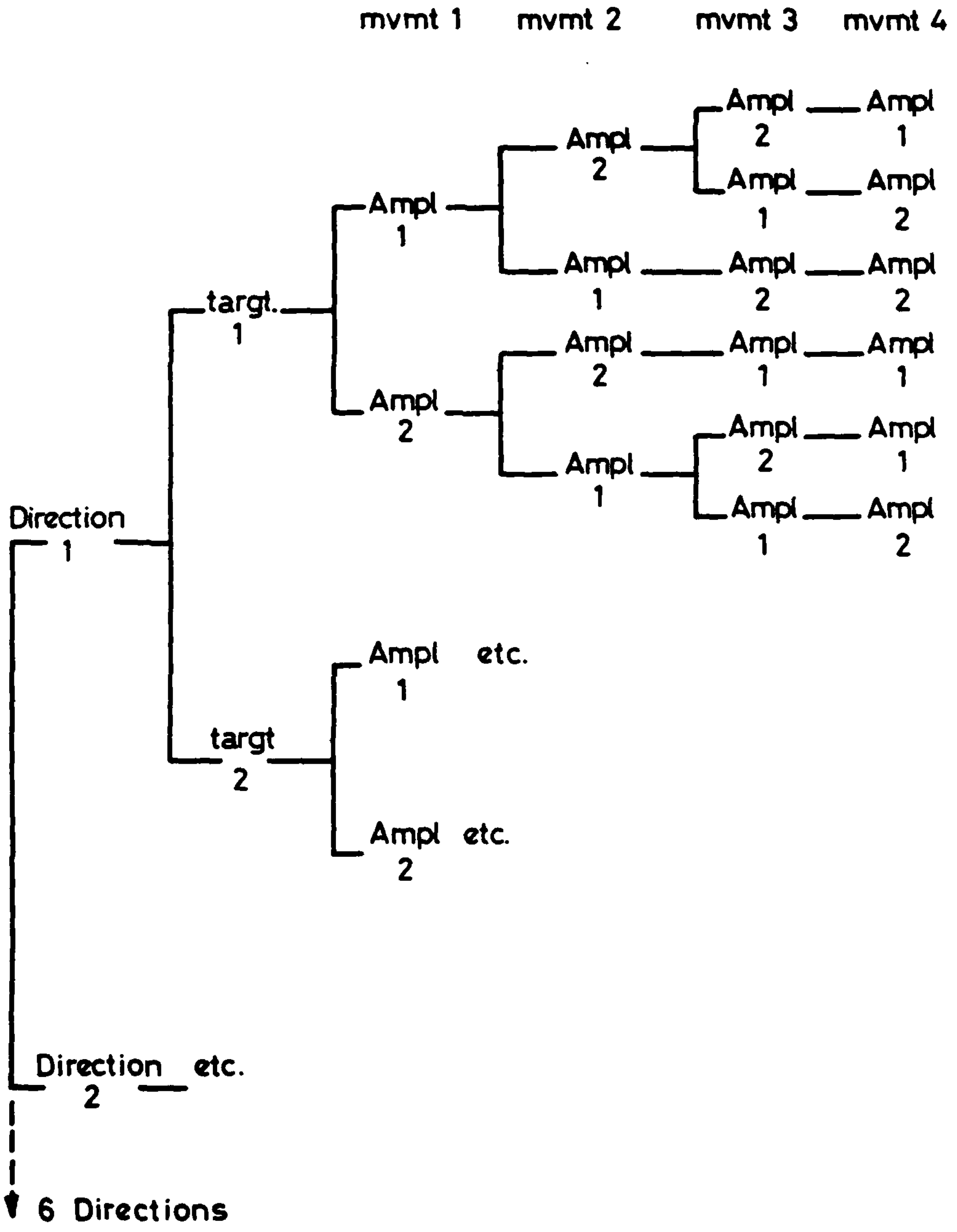


FIG. 4. THE CONSTRUCTION OF THE 72 TRIALS IN A BLOCK

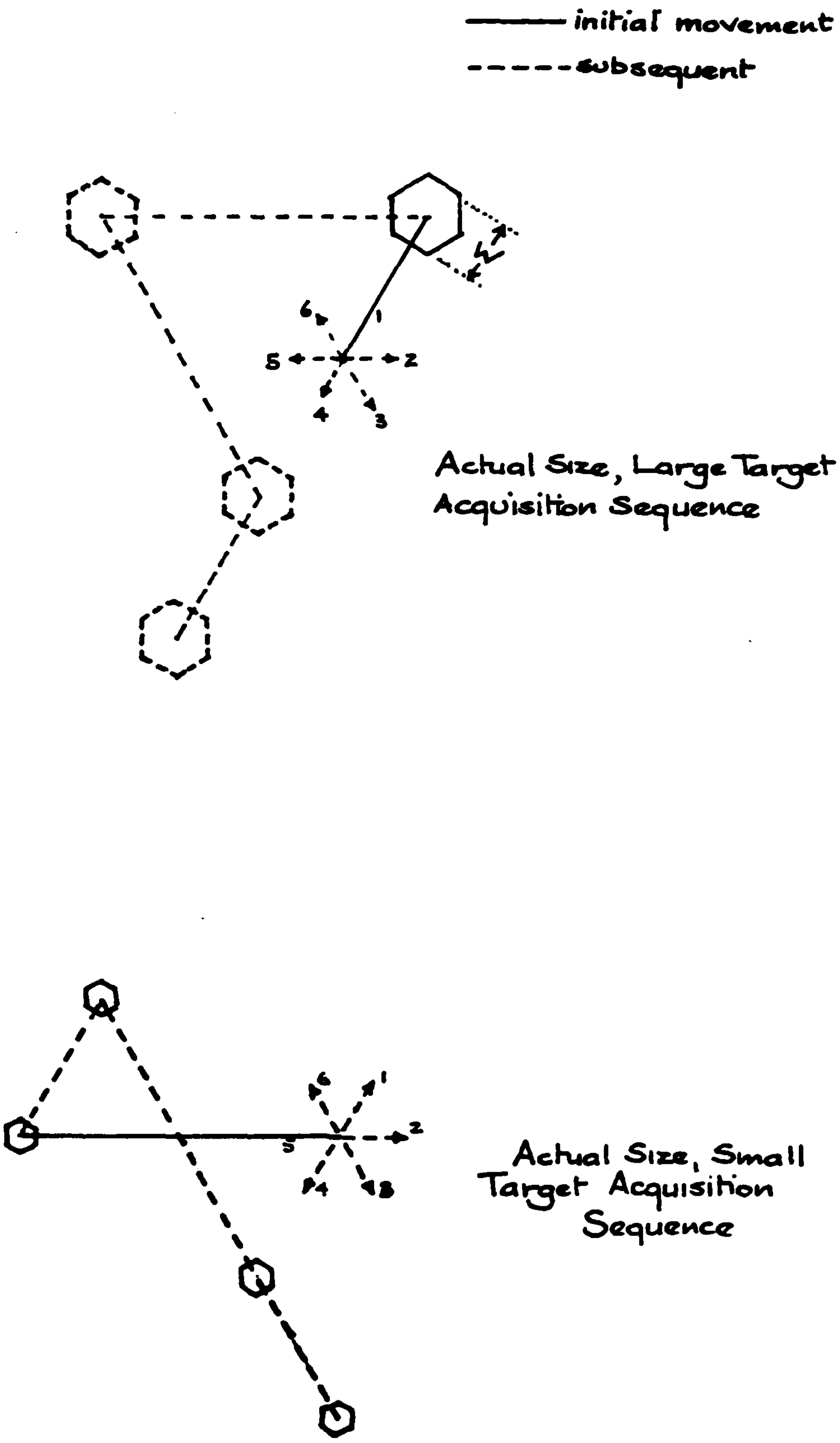


Figure 5. Sample acquisition sequences, target sizes and directions.

FIG.6 THE EXPERIMENTAL ENVIRONMENT

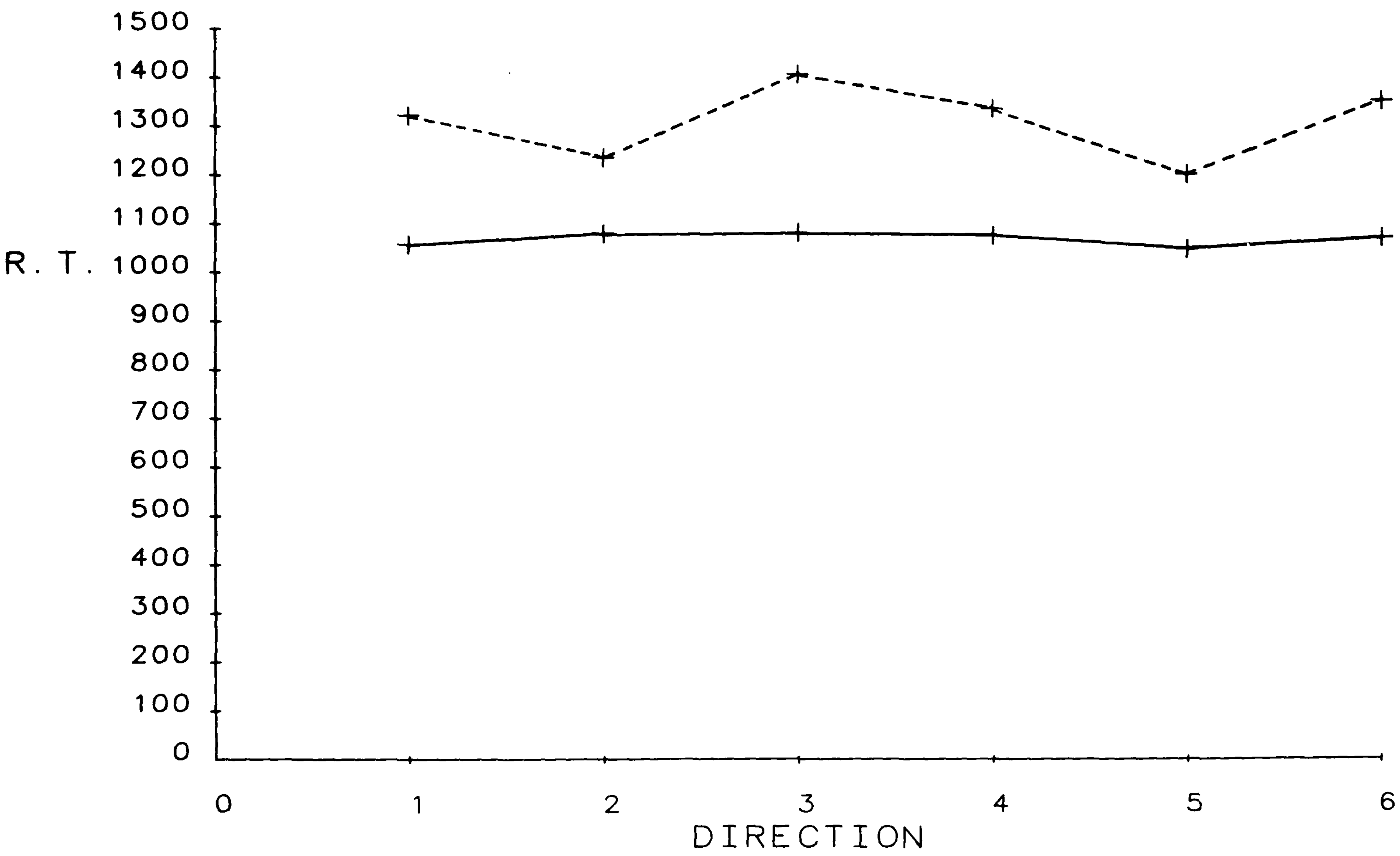


Fig 7(a). CONTROL X DIRECTION
T<r> DATA

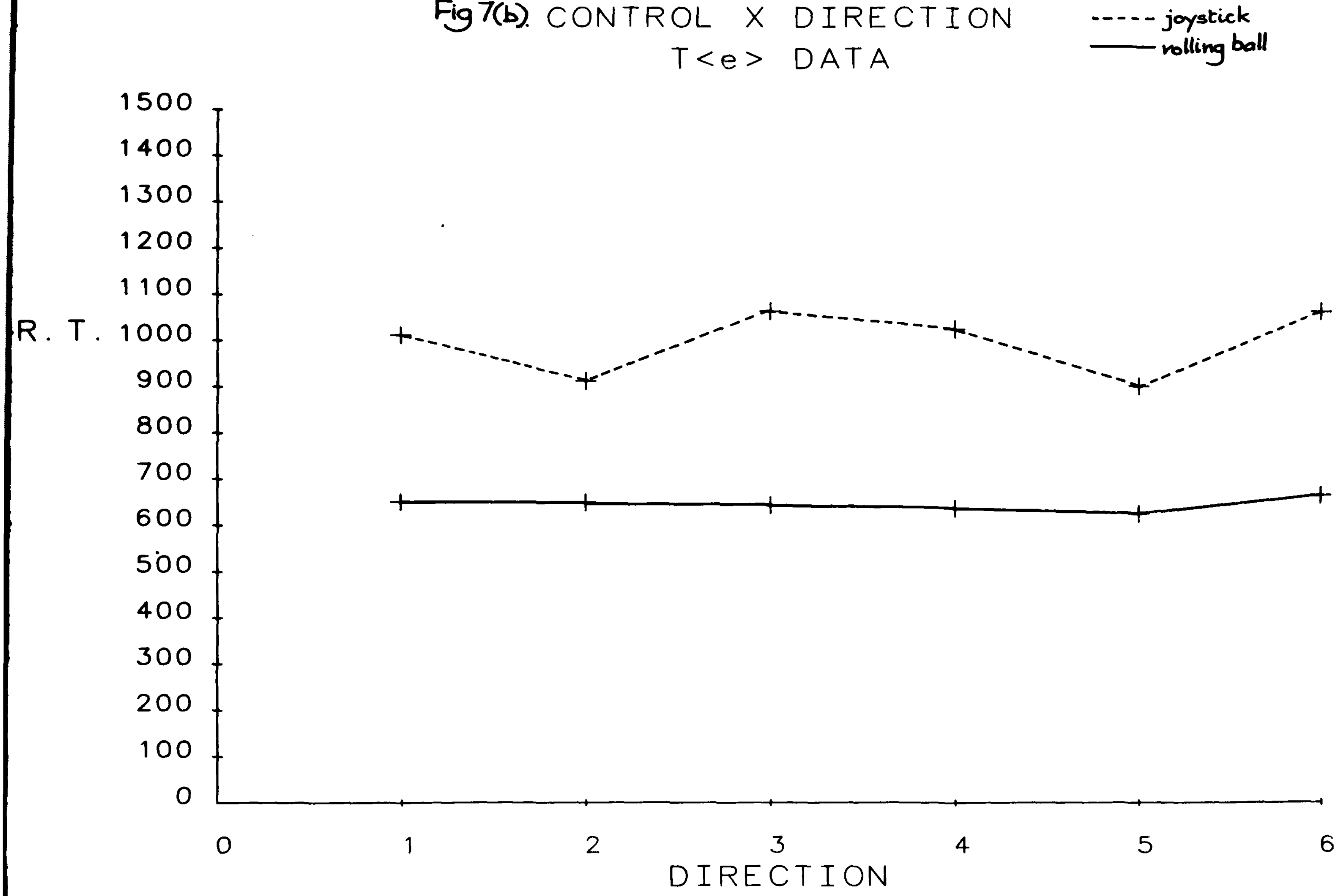
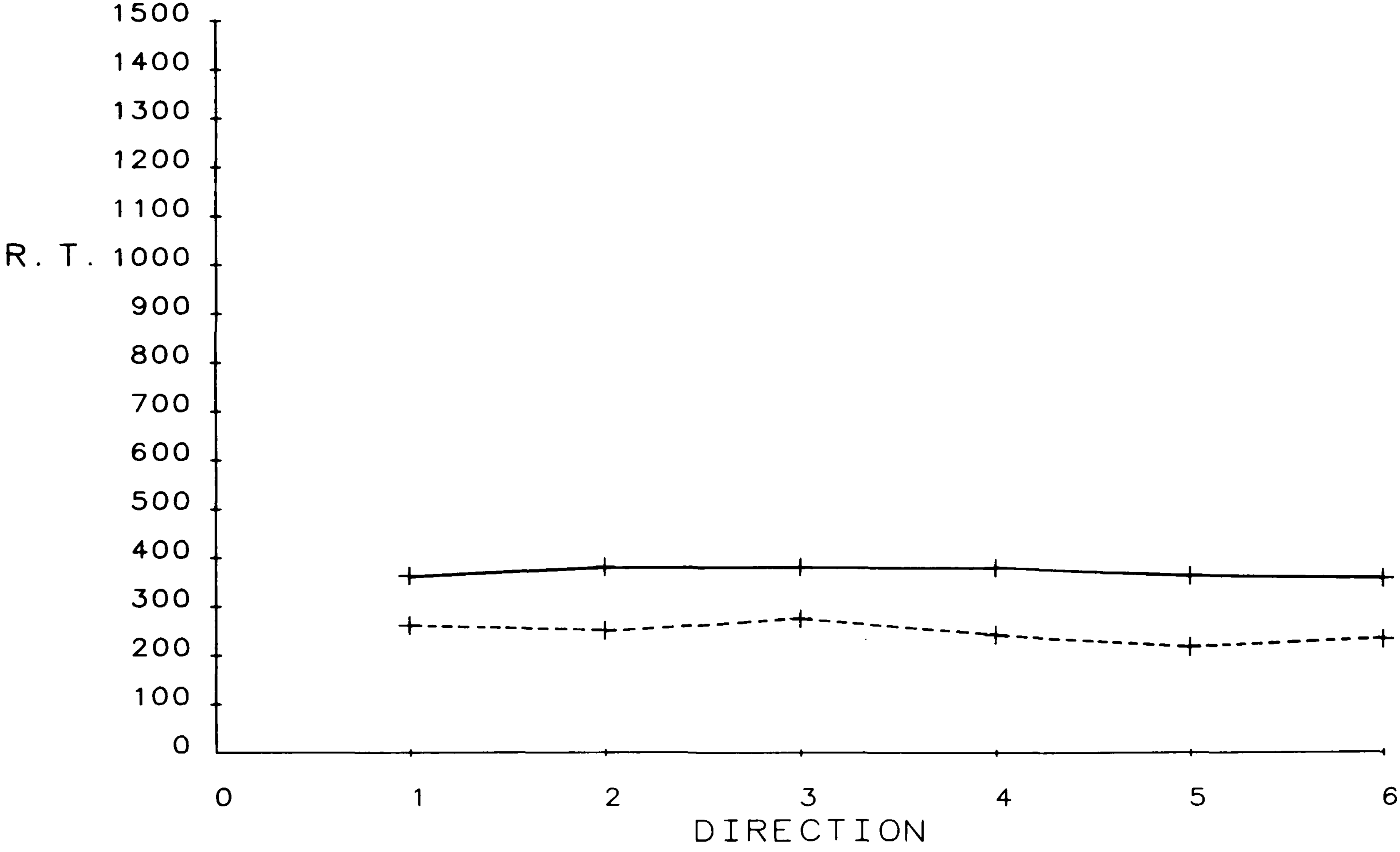


Fig 7(b). CONTROL X DIRECTION
T<e> DATA

Fig. 7(c) CONTROL X DIRECTION
T<t> DATA



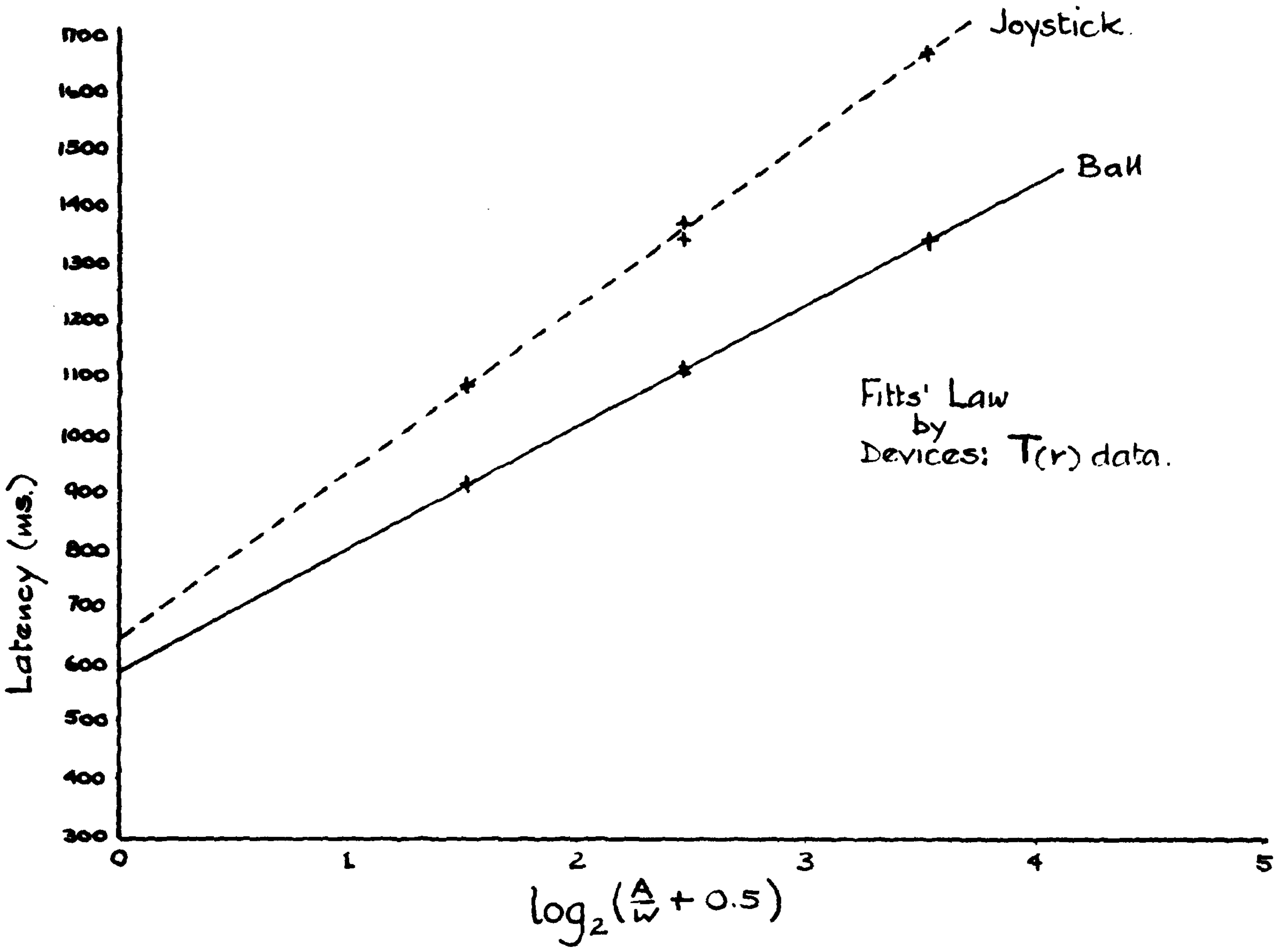


Figure X. Fitts Law functions for the two devices.

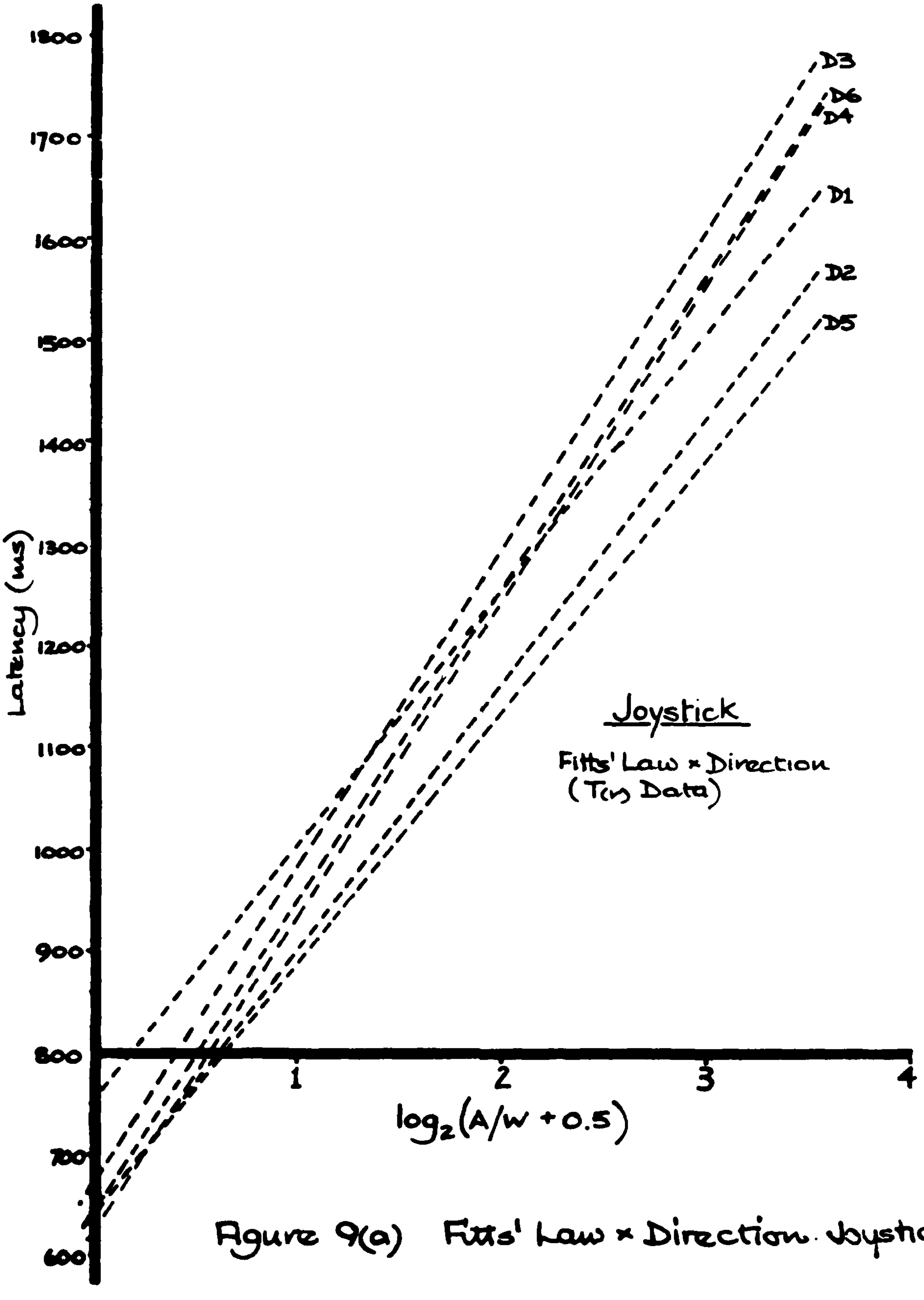


Figure 9(a) Fitts' Law × Direction Joystick

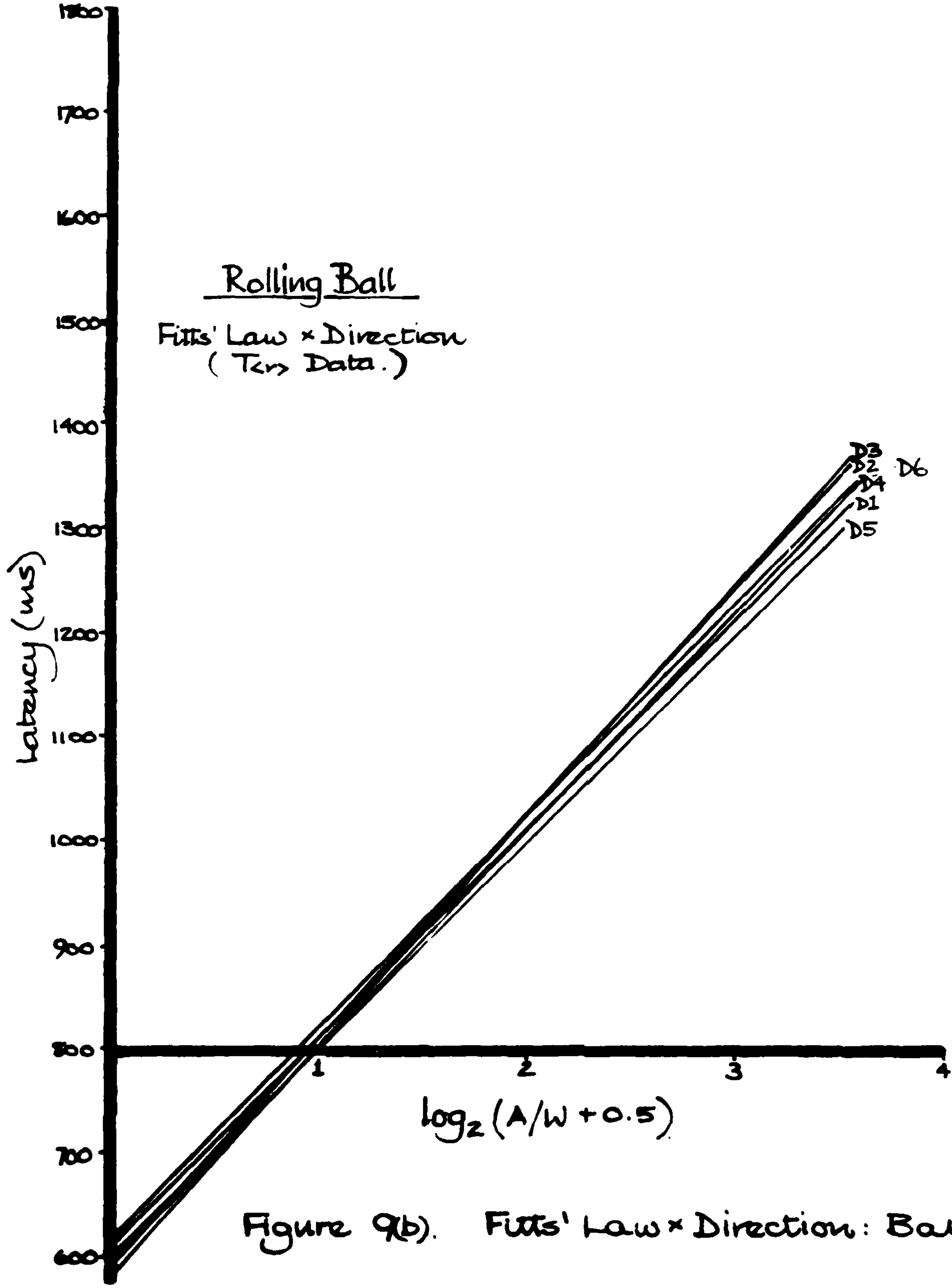


Figure 9(b). Fitts' Law × Direction: Ball.

DOCUMENT CONTROL SHEET

Overall security classification of sheet ......UNCLASSIFIED..

(As far as possible this sheet should contain only unclassified information. If it is necessary to enter classified information, the box concerned must be marked to indicate the classification eg (R) (C) or (S))

1. DRIC Reference (if known)	2. Originator's Reference Memorandum 3695	3. Agency Reference	4. Report Security Classification U/C

5. Originator's Code (if known)	6. Originator (Corporate Author) Name and Location Royal Signals and Radar Establishment
5a. Sponsoring Agency's Code (if known)	6a. Sponsoring Agency (Contract Authority) Name and Location CAA, Ch.Sc

7\. Title
Performance of Rolling Ball and Isometric Joystick on a 2-D Target Alignment Task

7a. Title in Foreign Language (in the case of translations)

7b. Presented at (for conference papers) Title, place and date of conference

8. Author 1 Surname, initials Jackson, A	9(a) Author 2	9(b) Authors 3,4...	10. Date 4.7.84	pp. ref.

11. Contract Number	12. Period	13. Project	14. Other Reference

15\. Distribution statement

Descriptors (or keywords)

Rolling Balls, Isometric Joysticks, Input devices, Fitts' Law, Gain

continue on separate piece of paper

Abstract A Rolling Ball and a Rate Controlled Isometric Joystick were employed in a target alignment task with dimensions comparable with those of many ATC tasks. In addition to amplitude and target width, variables included three levels of control-display relationship (gain), and direction of movement. The two devices were compared on a number of dimensions including overall performance time, the rate of incorrect responses, adherence to Fitts' Law and directional biases. This last factor proved significant only in the case of the joystick. The study concluded that; a) the rolling ball was still the preferred device for the ATC environment and should be retained; b) control-display relationship had no effect on the performance measures employed.

Keywords include