Performance, Characteristics, and Error Rates of Cursor Control Devices for Aircraft Cockpit Interaction

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Abstract. This paper provides a comparative performance analysis of a hands-on-throttle-and-stick (HOTAS) cursor control device (CCD) with other suitable CCDs for an aircraft cockpit: an isotonic thumbstick, a trackpad, a trackball, and touchscreen input. The performance and characteristics of these five CCDs were investigated in terms of throughput, movement accuracy, and error rate using the ISO 9241-9 standard task. Results show statistically significant differences ($p < 0.001$) between three groupings of the devices, with the HOTAS having the lowest throughput (0.7 bits/s) and the touchscreen the highest (3.7 bits/s). Errors for all devices were shown to increase with decreasing target size ($p < 0.001$) and, to a lesser effect, increasing target distance ($p < 0.01$). The trackpad was found to be the most accurate of the five devices, being significantly better than the HOTAS fingerstick and touchscreen ($p < 0.05$) with the touchscreen performing poorly on selecting smaller targets ($p < 0.05$). These results would be useful to cockpit human-machine interface designers and provides evidence of the need to move away from, or significantly augment the capabilities of, this type of HOTAS CCD in order to improve pilot task throughput in increasingly data-rich cockpits.

Keywords: HOTAS; Human-machine interface; Cursor control devices; Throughput; Error rates.

1 Introduction

The hands-on-throttle-and-stick (HOTAS) paradigm emerged in the 1950s with the idea of placing buttons and switches on the flight control sticks in an aircraft's cockpit. This enabled pilots to access vital cockpit functions and fly the aircraft simultaneously. Without having to move their hands to reach control switches pilot's could access the cockpit functions quicker and maintain a higher degree of flight control. It also negated the need to redirect focus to confirm the location of switches, with pilots instead utilising haptic memory. The first operational HOTAS system appeared in the early 1960s in the English Electric Lightning. Buttons, triggers, and rotary sliders were placed on a separate sidestick behind the throttle lever to enable a single pilot to control the radar and gunsights along with flight control via the main flight stick and throttle. Most fast jets have since employed integrated target designator controls (TDC) into sidesticks and later into the throttle lever to enable pilots to interact with increasingly complex display management systems. For example, the F-35 cockpit design is notable for the large touchscreen display and lack of panel switches, instead locating all physical switches on the throttle and stick. There are 14 individual multi-function switches, rockers, sticks, and buttons on the throttle quadrant, and another 12 on the sidestick. Many of the these switches have different haptic forms to allow pilots to identify them by touch, thus providing the increased situational awareness and also identification during low-light conditions. Like the F-16 and also the Rafale, the TDC on the F-35 throttle is positioned for the pilot to use their thumb. Other systems such as that used for the Eurofighter Typhoon are configured for the pilot to use their fingers (specifically the middle finger) where the TDC is an isometric-type joystick similar to that originally developed by IBM [42]. Whilst isometric joysticks have been analysed in previous work [11, 22, 38], the spatial and ergonomics of the interaction are notably different with a HOTAS fingerstick TDC.

The introduction of multi-function displays (the key component in the 'glass cockpit') into all types of aircraft require interaction devices capable of navigating and manipulating data presented on these displays. Table 1 shows typical cursor control devices (CCDs) found in a variety of example aircraft. Modern civil jet airliners have incorporated keypads, keyboards, and trackpads that have benefited from years of development as office workplace devices. These are typically supplemental to the main flight controls and provide far greater capability when interacting with the aircraft's flight management systems. In the smaller cockpits of fighters space for such supplemental CCDs is severely limited. Whilst touchscreens are integrated with the main MFDs in some modern 5th generation aircraft the main cursor control, particularly for weapons targeting, is still achieved with an isometric TDC. With increased cognitive requirements of pilots to manage large data from a multitude of sources, more efficient and high performance input devices will be of enormous benefit and help to improve the quality of decision-making processes [3]. The aim of this work is to evaluate a variety of different CCDs in comparison with, and in the context of taking the place of, a standard HOTAS TDC. Therefore, the standard performance metrics, namely, selection time and throughput are investigated. Since pilot commands often have high risk associated with erroneous input, an analysis of performance should also look at the rate of error in cursor control selection.

This paper provides an analysis of five suitable CCDs for aircraft cockpit operation with the ISO 9241-9 standardised test setup. The analysis of such devices reported in this paper is tailored to be representative of the ergonomic restraints present with a fighter aircraft cockpit display. The performance and characteristics of operation of the devices was measured across two repeated measures, within-participants experiments and examined with accuracy metrics designed to provide quantitative comparison between devices. Related work on CCD per-

Table 1: Types of cursor control devices (CCD) in various aircraft

	Aircraft	Type	Year	Thumbstick	Fingerstick	Trackpad	Trackball	Touchscreen	Voice
Civil	Boeing 777	Jet airliner	1995			•			
	Gulfstream G150	Business jet	2001	•					
	AugstaWestland AW139	Utility helicopter	2003	•					
	Airbus A380	Jet airliner	2007			•	•		
Military	A-10 Thunderbolt II	4th gen. jet fighter	1977		•				
	AH-64 Apache	Attack helicopter	1986	•					
	Dassault Rafale	4.5th gen. jet fighter	2001	•				•	•
	Eurofighter Typhoon	4.5th gen. jet fighter	2003		•				•
	Boeing KC-767	Refuelling tanker	2005			•			
	F-35 Lightning II	5th gen. jet fighter	2015	•				•	•

formance is discussed in section 2. Following this, details of the experiment are given in section 3. Section 4 presents the analysis of the performance comparison between the CCDs. A discussion of these results and their implications is given in section 5, followed by the conclusions from this work.

2 Related work

2.1 General cursor control performance

There have been many studies on the performance of various CCDs, including isometric pointing sticks, in a general context. Card *et al.* [11] investigated the selection time performance of a mouse, a bespoke isometric joystick, and keyboard keys on a text selection task. Whilst the joystick performed increasingly better than the keys as distance and size (i.e. character length) increased, the joystick was comparably similar in terms of error rates reported for medium sized character strings and actually worse for strings larger than 10 characters. Epps [22] investigated a variety of touchpads, trackball, mouse, isometric and isotonic joysticks and showed the suitability of the Fitts' law in modelling the selection time. In doing so it was noted the mouse performed superior to the other device types, with the two joysticks performing the worst in terms of selection time over increasing task difficulty.

The vast majority of studies focus on selection time, t, as a key performance metric, which is then fitted to a variation of Fitts' original movement model [23]. Four decades of HCI research has seen multiple different forms used, but common preference now is to use the Shannon Form of Fitts' law, proposed by

MacKenzie [34]:

$$t = a + bI_d = a + b\log_2\left(\frac{D}{W} + 1\right), \tag{1}$$

where the parameter I_d is the selection task's index of difficulty. This has become the most widely used version of Fitts' law in the HCI field, though not without some detractors [21, 29]. However, in lieu of any conclusive results, the Shannon formulation of Fitts' law remains the standard model. Equation (1) also drives the definition of a device's throughput, T:

$$T = \frac{I'_d}{t} = \frac{1}{t}\log_2\left(\frac{D'}{W'} + 1\right), \tag{2}$$

where I'_d is a modified index of difficulty which takes into account a normalised spread of end points for a given target [14, 46, 47]. This adjustment relies on the assumption that the end points are normally distributed which has often been seen to be the case [15, 23, 24]. This leads to the effective width

$$W' = 4.133\sigma, \tag{3}$$

and also

$$D' = \frac{1}{l}\sum_{i=1}^{l}\bar{D}_i, \quad \text{and} \quad \sigma = \sqrt{\frac{1}{l-1}\sum_{i=1}^{l}(x_i - \bar{x})^2},$$

with x being the selection end point location relative to the target centre. In this way the throughput provides an indication of both speed and accuracy with the CCD. It is also the definition for throughput as specified in the ISO 9241-9 standard for evaluating point tasks [1].

More recent studies have also looked to characterise the efficiency and accuracy of cursor movement [37, 40]. This analysis essentially amounts to looking at the spatial variation in the distance from a straight-line path between the cursor origin and target taken by the cursor, though a larger variety of movement metrics is illustrated in [37]. Phillips and Triggs [41] (who studied a mouse, digitising pen, laptop pointing stick; specifically a Toshiba 'AccuPoint', and trackball) also considered the velocity and acceleration variation along the cursor path, noting numerous jerks for the AccuPoint (and also the Trackball) which correlated with poor trajectory control, especially for targets with large seperation. This was explained by the difficulty in participants' ability to relate CCD movement to cursor movement, making it harder for participants to plan longer cursor pathways. Mithal and Douglas [38] considered the velocity profiles for both a pointing stick and the mouse and noted considerable jitter and jerkiness picked up by the pointing stick due to the required force sensitivity of such devices, which is exacerbated by greater force needed for longer distance travel. It was also the explanation given for considerable overshoots in target acquisition. On the other hand, it was postulated in [41] that these devices have some advantage in terms of their fixed orientation to the display, unlike the mouse and pen which require a brief element of cognition for the user to align the orientation of the CCD's movement with that of the on-screen cursor. That said, the throughput benefit would easily make up for this brief limitation.

2.2 Cockpit cursor control performance

Many of the previously mentioned studies include a within-participant comparison with a mouse which is arguably the benchmark. Results from most related work highlight the enduring superiority of the mouse as an input device. However, the high vibration and high acceleration environment of cockpits eliminates it as a viable option for the pilot. Doyon-Poulin and Routhier [20] evaluated the performance of an 'aviation' trackball (which, unlike a standard desk trackball that lays flat on a desktop, is recessed in the front of an inclined hand grip). Interestingly, they noticed the participants' performance was about one-third that of previously reported performance for a desktop trackball, but offered no explanation for this difference. In [43] a series of one and two dimensional pointing tasks to evaluate different trackball configurations aimed at operation in microgravity was performed. The outcome was similar though not as pronounced. The larger size and resistance of the aviation trackball also made it more accurate than two other desktop-based trackballs. As the cockpits of highly manoeuvrable fighter aircraft are more compact and susceptible to considerably higher vibrational and G-forces than civil aircraft, the use of such devices present many challenges.

The desire to maintain a HOTAS philosophy has seen modern jet fighters continue to employ finger- or thumb-operated isometric TDC joysticks to control cursors on MFDs. In modern 4.5 and 5th generation fighters, touchscreen and direct voice interaction are being explored. Touchscreens are increasingly of interest due to a substantially reported throughput, in some cases as high as 7–8 bit/s [5, 35]. An early study into touch-sensitive overlays by Curry [16] reports an almost halving of selection time compared to conventional TDCs and instructional voice commands. A series of studies by Liggett *et al.* [32, 33] drew similar conclusions, observing touch screen interaction to be faster than a TDC joystick, which itself was faster than voice control. However, the conventional TDC was found to be more prone to input error than both voice and touchscreen methods. This is an important factor to consider since in highly dynamic, high-stress, and high risk environments accuracy is of considerable importance.

Despite the apparent superior throughput of touchscreens there remains work in fully characterising the ergonomic factors and robustness under turbulence [6, 7]. Earlier experimental work by Bauersfield in this area [8] indicated effects on input precision (i.e. finger slippage). More recent work by Cockburn *et al.* [13], which compared touch and trackball CCDs, showed the same outcome in terms of touch displays, but also that subjective workload increased with vibration. A trackball was found to be faster and more accurate than touch at higher turbulence setting. It should be noted that an accurate representation of turbulence is not a trivial matter - the simulations in [8] were noted by participant pilots as being limited in their realism due to the absence of accompanying G-forces experienced in turbulence and the experiment in [13] shared the same limitation. More complex, six-axes simulators are required to simulate accurate turbulent conditions [18, 30]. Studies into the specific effects of G-force, which would be present not only in turbulence but to a greater extent in high-speed manoeuvring, show almost exponential effects on selection time and throughput [4, 31].

3 Experiment

3.1 Method

The ISO 9241-9 is a standardised set of tests for evaluating non-keyboard input devices for office work environments [1]. Increasingly it is promoted as the preferred test for evaluating CCDs [19, 39, 45]. One such test (Fig. 1) incorporates multi-directional pointing. The participant starts the task by selecting the topmost target (target 0), and then proceeds sequentially along the targets via the path illustrated with the arrows in Fig. 1. The next target in the path should be highlighted for the subject, with the task concluding at target 25. The targets may be either squares or rectangles. However using square targets adds the complication of what to use for the target width parameter, W, since the length

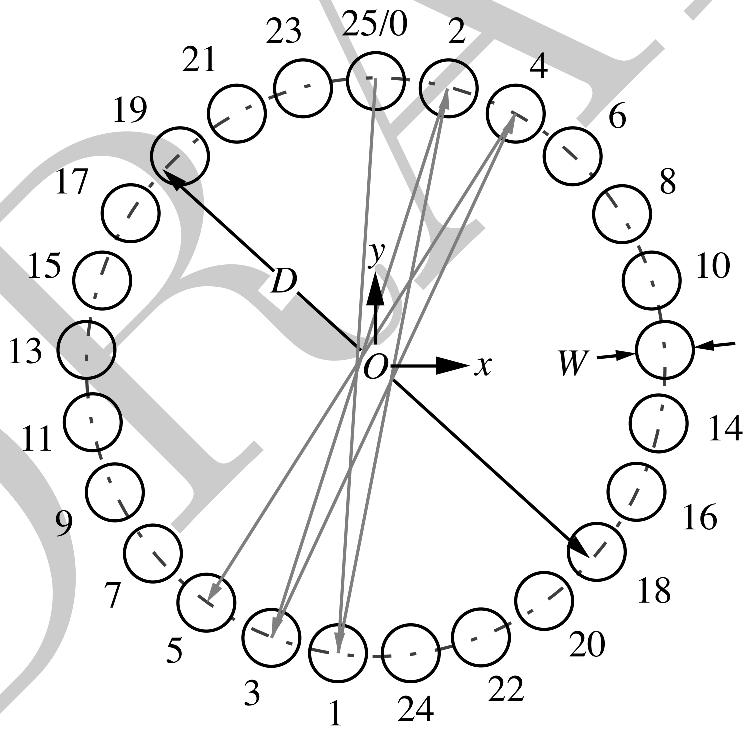


Fig. 1: The ISO 9241-9 multidirectional selection task.

of the target along a straight line between it and the previous target would vary around the circular path [36]. This length is uniform when using circular targets. A standardised progression pattern for the targets is also beneficial, compared to a randomised order, to reduce any initial time required by participants to locate the next target in the overall time recorded.

Each target in the multidirectional task is located at a some angle α, taken from the vertical line which intersects target 0/25 and the centre of the arrangement, O. Given l targets (where l exists in the set of odd natural numbers only) the circumference of the arrangement in Fig. 1 may be divided into l segments which each subtend an angle $2\pi/l$. If the sequence of targets is as illustrated in Fig. 1 where the current target, i, orientated at the angle α_i about O is on the far side of the circle from the preceding target, then the current target is always orientated $\beta_i = \alpha_i - \pi/2l$ degrees about the preceding target[1].

The direction of the origin of the cursor movement must be taken into account for multi-directional movement tasks otherwise the value of W' will likely be much larger than is actual. This will be especially true for large targets, where users will likely select the targets as soon as they are in the periphery of the target box. In [39] and other related works a *task axis* is proposed which eliminates the second dimension since the deviation in the selection is now with regards to the location of the selection point projected on a line between the centre of the current target and the 'source' of the cursor movement (Fig. 2). The parameter x^* is used to represent the one-dimensional deviation from the target centre along the task axis.

[1] See the Appendix for more detail.

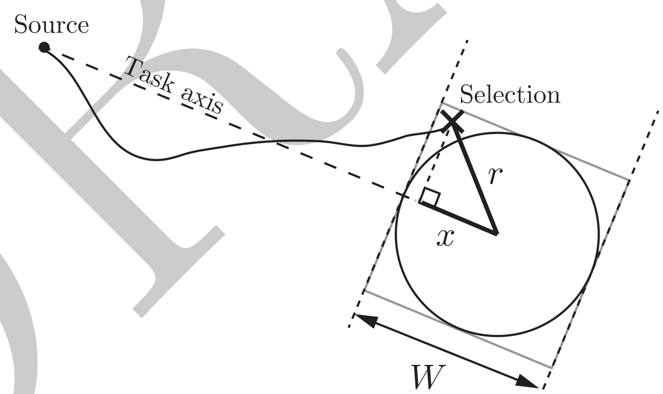


Fig. 2: Projection of the target selection onto the task axis. Note that whilst x^* is satisfied as being inside the 1D target (i.e $x^* \leq W/2$), the selection is outside the 2D circular target (i.e. $r > W/2$). Were the target square, however, the selection would in fact be located inside the target boundary. Hence, the geometry of the target should guide the acceptance criteria, especially for error prediction.

The angle ψ, being the equivalent of β but with the source as the previous target selection point, is used to resolve the selection coordinates to the task axis and, hence, obtain x^*. The parameter r is taken to be the radial distance from the centre of the target. For calculating the throughput the one-dimensional distance is used whereas for error analysis the deviation in terms of the radial distance is needed, as illustrated in Fig. 2. The 'source' of movement is taken as the location of the cursor immediately after selecting the previous target.

3.2 Equipment

The multidirectional selection ISO task was programmed in MATLAB, consisting of 25 circular targets in the fashion illustrated in Fig. 1. The diameter of the configuration[2], D, and the target width, W, were chosen to provide a sufficient range of I_d (see Table 3 later). Participants were seated as illustrated in Fig. 3 and viewed the multidirectional task on a 9.7 inch LED backlit capacitive touchscreen display (an Apple iPad Air) with 264 pixels-per-inch and a screen resolution of 1024×768 pixels. The display was connected to an Intel Core 2 Duo (2.5 GHz) laptop from which the selection task was administered. The fingerstick CCD was part of a Thrustmaster HOTAS Warthog replica A-10C throttle quadrant. As its name eludes to, this peripheral is a replica of the throttle controls used on the American A-10 Thunderbolt II jet aircraft introduced in the late 1970s and similar to the systems in some existing aircraft, such as the Eurofighter Typhoon. This throttle quadrant features a finger-operated pointing device (isometric joystick) as shown in Fig. 4, with selection by pressing in the stick along its z-axis. The (left) thumbstick of an Xbox360 Controller for Windows was used for the thumbstick-type device (an isotonic joystick) with a similar mechanism for selection as the HOTAS fingerstick. The trackball device used was a Kensington Orbit Optical trackball which features ambidextrous button-placement and a 4 cm (1.57 inch) diameter ball. The trackpad was a Bluetooth-connected Apple Magic Trackpad which provides a 13×13 cm^2 (26.2 sq. in.) tracking surface. Selection was either through tapping or pressing in the tracking surface. Each device being tested was located in the same position (next to the participant's left thigh, but height-adjusted for comfort). The only exception was the touchscreen which, as previously mentioned, was the capacitive screen on the Apple iPad Air tablet.

The input device control software ControllerMate (v. 4.9.3) was used to remove pointer acceleration and adjust the CD gain for the CCDs (except the touchscreen). The software enables custom acceleration profiles to be created by varying a cursor/device speed function plot (as illustrated in Fig. 5). These were set to a linear mapping for each and then the gradient of the line adjusted for each participant prior to the beginning of the experiment. Each CD gain value

[2] If D is taken to be the diameter of the arrangement then, strictly, the distance between targets is $D\cos(\pi/2l)$. However the error will be small for large l and, by using D' to compute the throughput, the distance is no longer directly dependent on the diameter of the configuration.

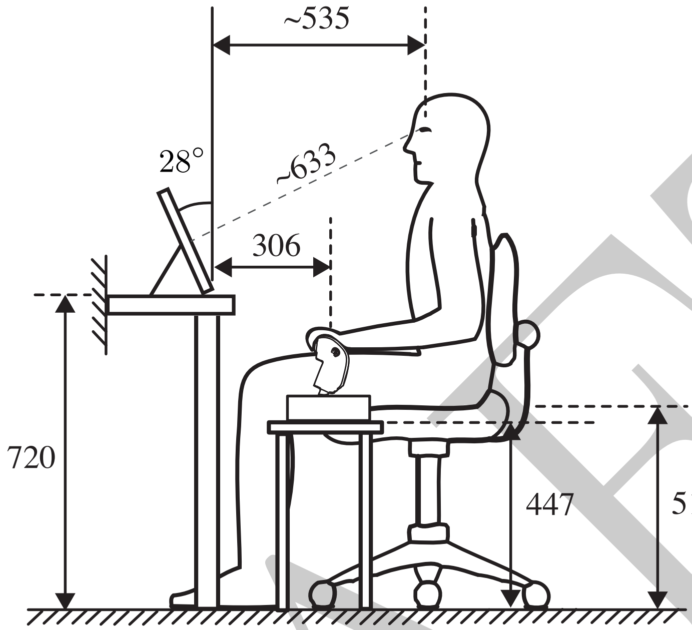


Fig. 3: Experimental layout (with HOTAS fingerstick CCD shown). Measurements in mm.

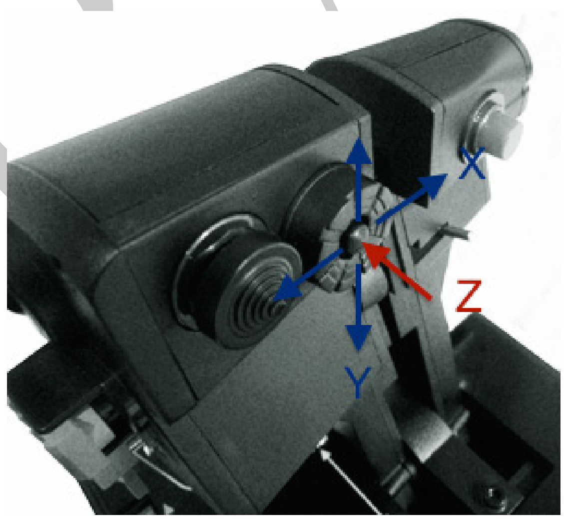


Fig. 4: Thrustmaster A-10C throttle quadrant, showing X, Y, and Z axes on the isometric TDC fingerstick.

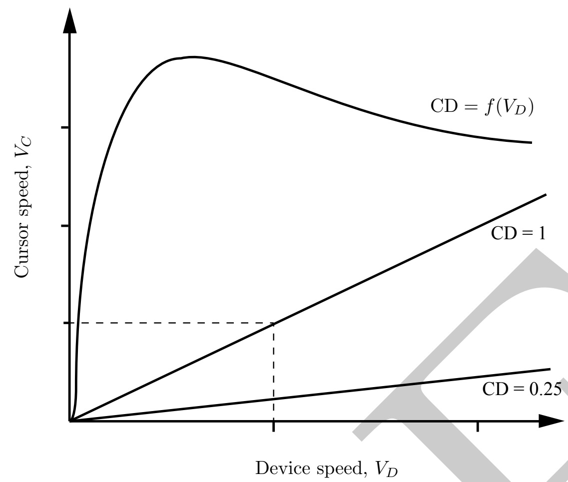


Fig. 5: Illustrative CCD acceleration curves (cursor speed vs. device speed). The CD gain is the ratio of cursor to device speeds, CD = V_C/V_D. Pointer acceleration is used in most operating systems where the CD gain is some function of the device input speed. Removing pointer acceleration results in a linear slope i.e. constant CD gain.

shown in Table 2 is effectively the gradient of the line illustrated in Fig. 5 for each participant which maps the input from each device to the output displayed by the cursor. The thumbstick and fingerstick CCDs operate mechanically different to the trackball and trackpad. In order to implement the two stick CCDs in the same fashion a virtual mouse was setup in order to map the input (in terms of the signal bit value) into a device speed. Thus, for the thumbstick, cursor speed was directly proportional to displacement with a maximum speed achievable at the physical stop. For the HOTAS fingerstick, cursor speed was directly proportional to applied force.

3.3 Participants

Data comes from two separate within-participants experiments (see Table 2) with members of the general public and university staff. Although active pilots would have been the preferred participants, the information obtained from the participants here will at least be indicative of pilots undergoing initial training of TDCs. The first experiment involved six participants between 23 and 56 years of age ($\mu = 37.3$ years) who performed the trials with the HOTAS fingerstick, trackpad, trackball, and touchscreen. A second experiment group, carried out at a later date, involved another six participants (22 to 35 years of age, $\mu = 30.5$ years) performing the same task with the HOTAS fingerstick and thumbstick devices. The same setup, common equipment, and task was used in both participant groups. All participants were right-hand dominant. Most par-

Table 2: CCD profiles

Participant	Age	Gender	CD Gains			
			Fingerstick	Thumbstick	Trackpad	Trackball
1	23	F	0.0625	-	2.1*	4
2	55	F	0.0416	-	1.8	8
3	56	M	0.0625	-	2.1*	4*
4	27	F	0.0625	-	1.8*	3
5	32	M	0.0625	-	1.8	3
6	31	M	0.0833*	-	2.1*	6*
7	34	F	0.0625	0.143	-	-
8	22	F	0.0416	0.091	-	-
9	31	M	0.125	0.167*	-	-
10	31	M	0.0625	0.167*	-	-
11	30	M	0.05	0.167*	-	-
12	35	F	0.05	0.125	-	-

*Indicates prior experience with a similar device.

ticipants had prior use with standard laptop trackpads and tablet touchscreens, whilst only two of the participants had previously used a trackball. Only one participant had prior use of the HOTAS fingerstick. Although three participants had used laptop-based pointing sticks previously, these are considerably different in feel and positioning so were not considered prior experience. Any prior experience with similar devices is of no significance as participants used their left hand in the configuration shown in Fig. 3 to operate the devices in emulation of a typical aircraft cockpit layout. The only exception to this is with the thumbstick device. All previous use of the devices by participants had been with their right hand except for the thumbstick. Three of the participants who used the thumbstick had used such devices previously.

The independent variables were the CCD, the target width, W, and target amplitude, D. The constant CD gain was also allowed to be selected by the participants according to their preference, but this was mainly for comfort and usability than for examining the effects on the interaction. Differences in CD gain between devices are not informative in itself since they only reflect the nature of the input mechanism for the device. It may however provide some expectation in the selection time performance from each device.

3.4 Procedure

Before the task was performed for each device the CD gain for that device (where applicable) was calibrated for each participant. This approach was favoured over using the same CD gain for each subject, as this may have impaired their optimal performance. Participants were introduced to each CCD and asked to practice using it with the multidirectional task. This served to familiarise the participants

Table 3: Task configurations

Trial	Target Width			Target Amplitude			D/W	I_d
	(pixels)	(mm)	ν^* (deg)	(pixels)	(mm)	ν^* (deg)		(bits)
1	114	10.5	1.00	130	11.7	1.12	1.14	1.10
2	73	7	0.66	130	11.7	1.12	1.78	1.48
3	36	3.5	0.33	130	11.7	1.12	3.61	2.21
4	114	10.5	1.00	780	70	6.65	6.84	2.97
5	73	7	0.66	780	70	6.65	10.68	3.55
6	36	3.5	0.33	780	70	6.65	21.67	4.50

*Visual angle, $\nu = \text{atan}(c/d)$, is the angle on the eye subtended by an object of size c, viewed at a distance d. The value shown is based on an average distance for a pair of eyes 23.5 inches ($\sim$ 600 mm) from the display. The actual value will vary based on the upper-body dimensions of the participant, which was not recorded.

with using both the CCD and the task itself, thereby reducing potential contamination from learning effect. The highest difficulty configuration of targets ($W = 3.5$ mm, $D = 75$ mm) was presented, and participants were asked to perform the task to determine whether they were happy with the current CD gain of the device in terms of both sensitivity and control speed. High CD gains were started with, and reduced in the ControllerMate software in a stepwise fashion by asking if participants preferred the current or previous CD setting in terms of both sensitivity and control speed. This was repeated until participants chose the previous setting from the newest one, thereby identifying the lowest CD gain they were satisfied with using.

Once each device was calibrated, participants were asked to complete the six trials as outlined in Table 3 using the device. Each trial consisted of selecting the 25 targets in the manner outlined in §3.1. The order of the trials was randomised to eliminate order effects. The order the participants used the devices was also randomised for the same purpose.

4 Results

MATLAB and its Statistics Toolbox was used to perform the post-processing and the statistical analysis. Outliers in the data sets were removed by retaining only data inside the interquartile range of the data for each block. For repeated measures ANOVA tests sphericity was evaluated using Mauchly's test and the degrees of freedom were corrected when necessary using the Greenhouse-Geisser correction when $\varepsilon < 0.75$, and the Huynh-Feldt correction when $\varepsilon > 0.75$, where ε is the estimate of sphericity. When ANOVA results were significant, post-hoc pairwise comparison tests were made with the Tukey-Kramer test. A significance level of 95% was adopted throughout.

4.1 Selection time and throughput

The requirement for (3), which determines I'_d and thus both the selection time, t and the throughput, T, is that the scatter of x^*_i, for all i, is normally distributed. This was checked and observed to be the case to a reasonable degree for all devices. The distributions of the HOTAS fingerstick and thumbstick had the least peakedness of the five devices indicating there were less large, infrequent deviations with these devices. This is likely the consequence of the particularly low CD gains used for these devices.

In Fig. 6a the average selection times at the values of I_d investigated are shown. The effective index of difficulty is also calculated and the target selection times against I'_d are shown in Fig. 6b. In Fig. 6a the data points from the HOTAS fingerstick of both participant groups are shown separately and there is no significant different between the two groups[3]. Whilst there is larger spread in the HOTAS fingerstick selection times overall it can be seen to follow Fitts' law to a reasonable degree.

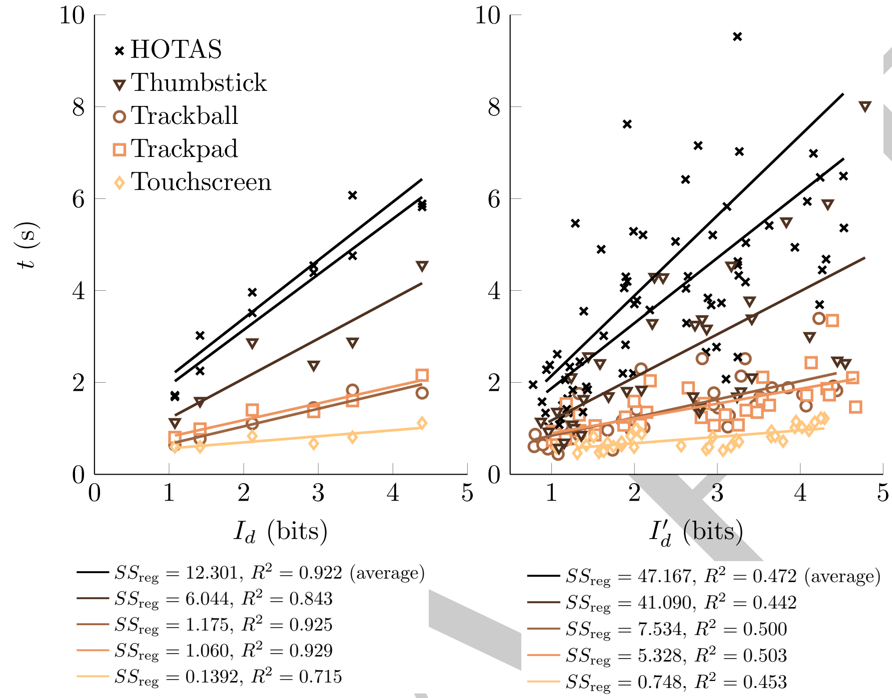
The throughput, T, is computed as an average over all m trials and n participants:

$$
\begin{aligned}
T &= \frac{1}{n}\sum_{k=1}^{n}\left(\frac{1}{m}\sum_{j=1}^{m}\left(\frac{1}{l}\sum_{i=1}^{l}\frac{I'_{d,ijk}}{t_{ijk}}\right)\right)\\
&= \frac{1}{n}\sum_{k=1}^{n}\left(\frac{1}{m}\sum_{j=1}^{m}\left(\frac{1}{l}\sum_{i=1}^{l}\frac{1}{t_{ijk}}\log_2\left(\frac{\bar{D}_{ijk}}{4.133\sigma_{x,ijk}}+1\right)\right)\right),
\end{aligned}
\tag{4}
$$

for $k = 1, \ldots, 6$ participants in each group, who each perform $j = 1, \ldots, 6$ trial blocks, consisting of $i = 1, \ldots, 25$ targets. For each device these are shown in Table 4. Note there are two experimentally determined values of T for the HOTAS fingerstick, and the average of these is used. The difference in throughput is also visually evident from Fig. 6 by inspection of the slopes of the linear fits. Regardless of the bandwidth metric preferred ($1/b$, $1/b'$, or T) the overall pattern is the same. The touchscreen produced the highest throughput average ($T = 3.7$ bits/s) whilst the HOTAS fingerstick offered a throughput of below one: $T = 0.7$ bits/s. The only noticeable difference between metrics is the significant difference in b' between the trackball and trackpad. There was a statistically significant effect ($F_{4,20} = 47.80$, $p < 0.001$, $\eta_p^2 = 0.91$) between three groups of devices: the 'sticks', the 'trackers', and the touchscreen, as shown in Fig. 7.

The effect of the index difficulty (and more specifically its constituent parts, D and W) on both selection time and throughput are shown in Fig. 8. A three-way ANOVA ($W \times D \times \mathrm{CCD}$) for selection time, t, shows strong effects from W ($F_{1.04,5.18} = 46.97$, $p < 0.001$, $\eta_p^2 = 0.90$), D ($F_{1,5} = 99.64$, $p < 0.001$, $\eta_p^2 = 0.95$) and CCD ($F_{1.92,9.59} = 28.97$, $p < 0.001$, $\eta_p^2 = 0.85$), and interactions

[3] To obtain a balanced data set for ANOVA tests only the HOTAS fingerstick data from the first participant group was used. When compared to results using data from the second participant group the significance results are the same.



(a) (b)

Fig. 6: Plot of (a) index of difficulty against average selection time across participants and targets, and (b) effective index of difficulty against average selection time across targets.

between $W \times$ CCD ($F_{2.15,10.74} = 13.42$, $p < 0.001$, $\eta_p^2 = 0.73$) and $D \times$ CCD ($F_{1.58,7.92} = 16.38$, $p < 0.01$, $\eta_p^2 = 0.77$). In terms of throughput, significant effects due to D ($F_{1,5} = 185.75$, $p < 0.001$, $\eta_p^2 = 0.97$) and CCD ($F_{4,20} = 57$, $p < 0.001$, $\eta_p^2 = 0.92$) were found, as well as a smaller but still significant effect due to W ($F_{1.10,5.51} = 9.43$, $p < 0.05$, $\eta_p^2 = 0.65$). Also, an interaction effect was noticed between $D \times$ CCD ($F_{4,8} = 8.03$, $p < 0.01$, $\eta_p^2 = 0.80$). An interesting break in the linearity of the increasing selection times with I_d can be seen in Fig. 6a, and more clearly in Fig. 8. The average selection time for $I_d = 2.21$ are almost always larger than those for $I_d = 2.97$. Recall from Table 3 that the target widths for these conditions were 3.5 mm and 10.5 mm respectively. This peculiarity is a result of the quantisation of I_d with the chosen values of D and W. The break occurs between the two values of D used. There is a substantial increase in throughput for the touchscreen between this break. This behaviour can be seen with the other devices but is not as marked as with the touchscreen due to the fact that t increases very minimally across the I_d range for the touchscreen device. The throughput then drops sharply with larger I_d

Table 4: Fitts' law performance calculations

	Fingerstick	Thumbstick	Trackball	Trackpad	Touchscreen
a (s)	0.79	0.35	0.28	0.45	0.43
$1/b$ (bits/s)	0.81	1.15	2.61	2.79	7.59
a' (s)	0.43	0.24	0.45	0.57	0.40
$1/b'$ (bits/s)	0.63	1.07	2.53	3.10	7.12
T (bits/s)	0.69	1.23	2.14	1.99	3.74

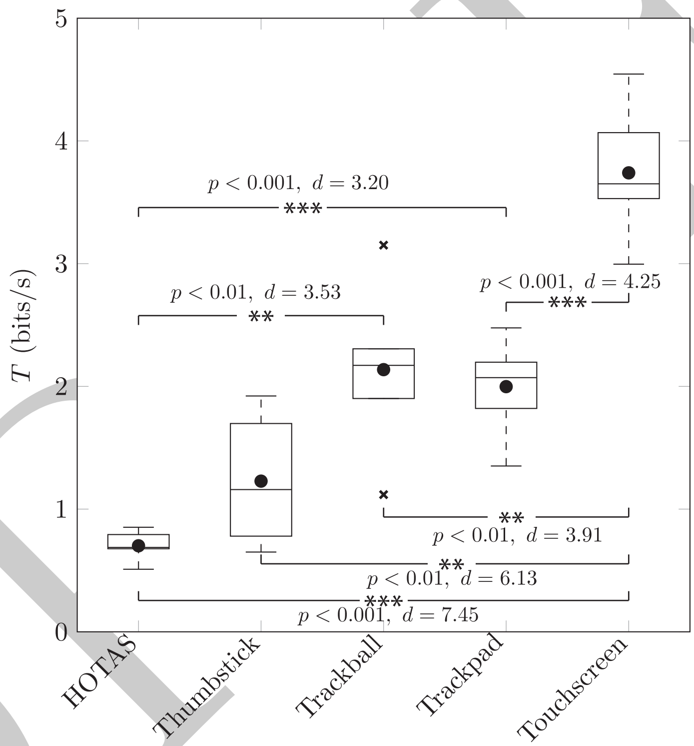


Fig. 7: Average throughput, T, for each CCD. The black circles ● show the standard mean whilst the crosses × show outliers. The parameter d is Cohen's effect size.

(Fig. 8b) in an almost linear fashion with decreasing target size W. The presence of this break indicates that the effect of W on I_d is larger than that of D, being more noticeable at particular configurations of D and W. This effect has been

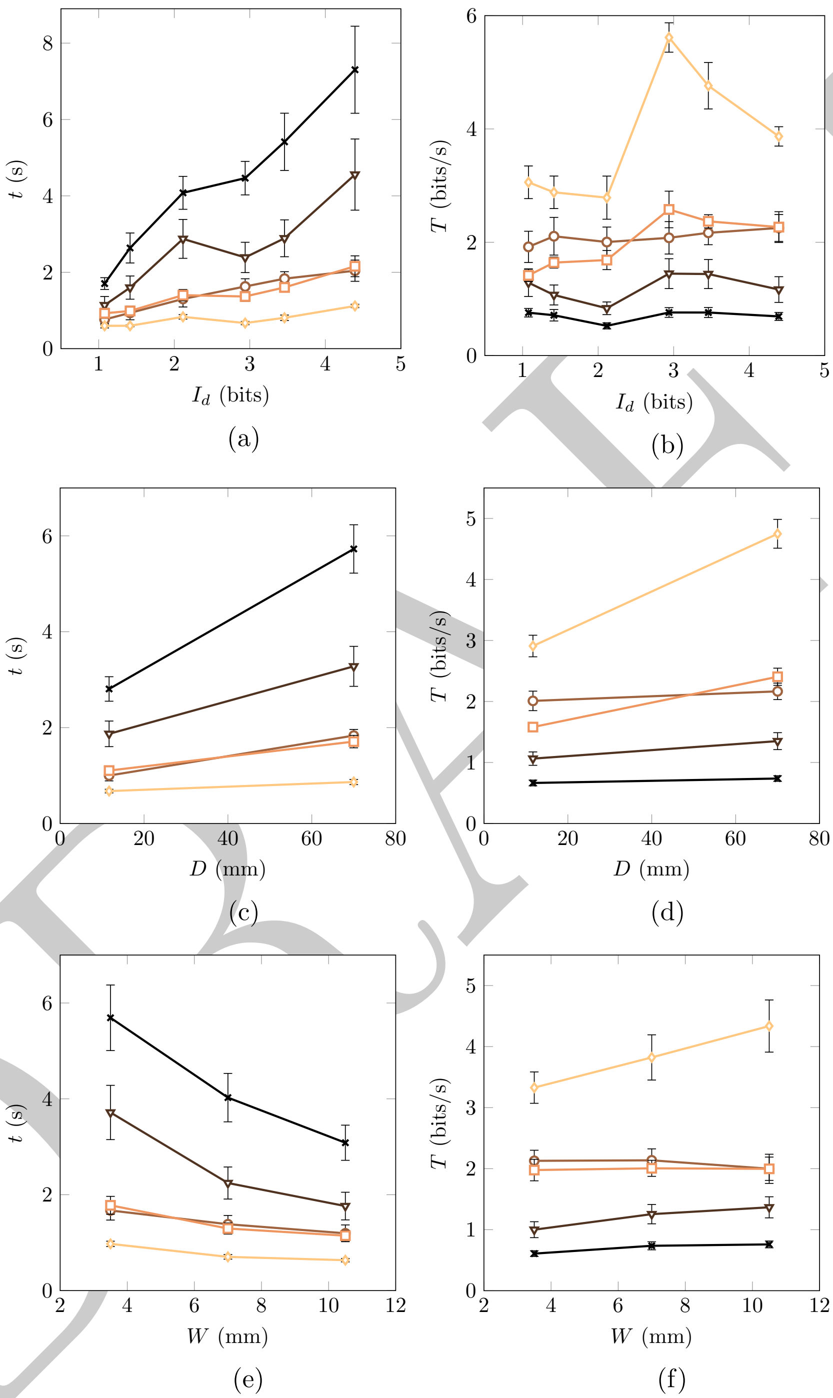


Fig. 8: Interactions of t and T with I_d, D, and W.

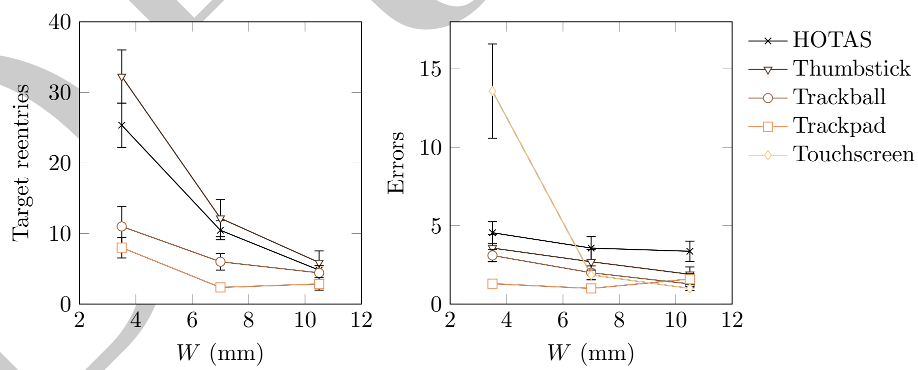
observed elsewhere [48, 52], and is the result of the equivocalness of D/W as a third independent variable in what amounts to a two degrees-of-freedom problem [26]. The choice of D and W was made to ensure a suitable range for I_d, but has resulted in the quantisation in the results between the two values of D. Note that this does not conflict with the idea that D and W are not equal in their effects on the resulting performance, as will be seen later. Furthermore, this behaviour is not evident when compared to I'_d shown in Fig. 6b.

4.2 Error rate

For a target of width, W, a selection (correct or not) occurs at range r from the centre of the target. If $2r \leq W$ the selection is correct, otherwise the selection is an error. The error rate is simply the number of first selections that were erroneous as a ratio of the total number of targets, i.e. $f(E) = E/25$. This is different from the total sum of errors made in a given trial as shown in Fig. 9b, though the interactions are very similar.

Inspecting Fig. 10 shows that the trackpad was the most accurate in terms of first-time selections, followed by the trackball, thumbstick, HOTAS fingerstick. It would also suggest that the touchscreen performs the worst overall but this is misleading since the larger mean is due to the significant reduction in accuracy for small targets, which manifests itself in the large variation. Indeed, considering only the larger two target widths, the touchscreen performs similar to both trackball and trackpad (Fig. 9b).

No significant difference between the CCD means is found from a one-way ANOVA ($p = 0.197$) however a $D \times W \times$ CCD ANOVA finds significant effects from all three main variables (W: $F_{2,10} = 32.12,\ p < 0.001,\ \eta_p^2 = 0.87$, D: $F_{1,5} = 29.23,\ p < 0.01,\ \eta_p^2 = 0.85$, CCD: $F_{4,20} = 4.84,\ p < 0.01,\ \eta_p^2 = 0.49$), and an interaction from $W \times$ CCD ($F_{1.39,6.95} = 9.28,\ p < 0.05, \eta_p^2 = 0.65$). Evidently, but perhaps not suprising, the target width W has a significant impact on the



(a) (b)

Fig. 9: Interactions of (a) target re-entry and (b) errors with W.

error rate. Similar levels and interactions are obtained when performing three-way ANOVAs on the total errors shown in Fig. 9, whilst for the number of target re-entries significant effects due to the three main variables (W: $F_{2,10} = 93.63$, $p < 0.001$, $\eta_p^2 = 0.94$; D: $F_{1,5} = 25.70$, $p < 0.01$, $\eta_p^2 = 0.84$; CCD: $F_{3,15} = 7.76$, $p < 0.01$, $\eta_p^2 = 0.61$) and interaction effects from $W \times D$ ($F_{2,10} = 5.88$, $p < 0.05$, $\eta_p^2 = 0.54$) and $W \times$CCD ($F_{1.68,8.38} = 7.11$, $p < 0.05$, $\eta_p^2 = 0.59$) were found.

An ANOVA on the data set found the trackpad was significantly more accurate than the HOTAS fingerstick ($p < 0.05$, $d = 0.76$) and the touchscreen ($p < 0.05$, $d = 0.91$) in terms of both first-time selection errors, and similarly with overall errors during a task. The trackball, thumbstick, and HOTAS had very similar error rates (in ascending order), whilst the touchscreen error rate was affected by the poor performance across different values of W ($p < 0.05$, average $d = 1.5$). Both trackpad and trackball produced the least target re-entries when compared to the HOTAS fingerstick and thumbstick, which produced the most. Across the two smallest target widths the HOTAS was considerably less accurate than the trackpad ($p < 0.01$, $d = 1.33$ for $W = 3$ mm; $p < 0.05$, $d = 0.74$ for $W = 7$ mm). There was also stronger sensitivity from decreasing target widths

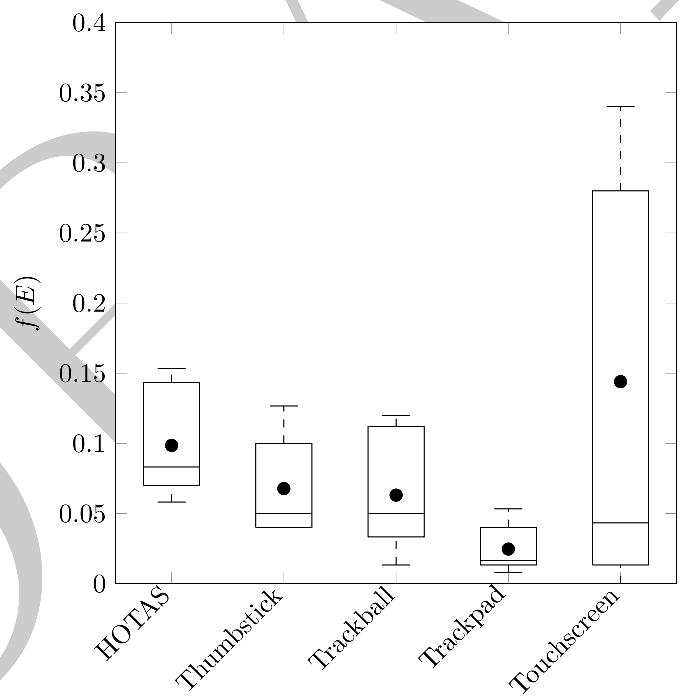


Fig. 10: Average error rate, $f(E)$, for each CCD. The black circles ● show the standard mean.

in the order of: thumbstick ($p < 0.05$, $d = 2.08$), HOTAS fingerstick ($p < 0.001$, $d = 1.57$), trackball ($p < 0.05$, $d = 0.63$) and trackpad ($p < 0.05$, $d = 0.47$).

4.3 Cursor control efficiency

Fig. 11 shows the cursor control behaviour parameters defined in [37], described in Table 5, for the range of I_d used in this study. These are adopted as a measure of participants' efficiency at using the CCDs. Note that equivalent values of these parameters for the touchscreen would need the participant's finger tip movements to have been recorded. This was not done in this study. Table 6 summarises the results from the $W \times D \times$ CCD ANOVA on each parameter. Main effects from D and CCD were evident across all parameters. Target width, W, also had an effect on the parameters, except for movement variability (MV).

From Fig. 11 the task axis crossing (TAC) and movement direction change (MDC) increase in an almost linear fashion with I_d for the most part. The participants appear least efficient with the HOTAS and most efficient with the trackpad, with significant differences between the HOTAS and the thumbstick

Table 5: Cursor movement parameters

TAC	Total Axis Crossing	The number of times the cursor crosses the task axis.
ODC	Orthogonal direction change	The number of times the cursor direction changes, orthogonal to the task axis.
MDC	Movement direction change	The number of times the cursor direction changes, parallel to the task axis.
MV	Movement variability	The variation in the cursor movement orthogonal to the task axis.
ME	Movement error	The mean magnitude of the distance orthogonal to the task axis.
RMSO	Movement offset (RMS)	The RMS of the orthogonal distance of cursor movement orthogonal to the task axis.

Table 6: $W \times D \times$ CCD ANOVA significances for cursor movement parameters

Parameter	W	D	CCD	$W \times D$	$W \times$ CCD	$D \times$ CCD	$W \times D \times$ CCD
TAC	***	***	***	***	n.s.	*	n.s.
ODC	***	**	*	n.s.	n.s.	n.s.	n.s.
MDC	***	***	***	n.s.	n.s.	*	n.s.
MV	n.s.	***	***	n.s.	n.s.	***	n.s.
ME	**	***	***	*	n.s.	***	n.s.
RMSO	*	***	***	n.s.	n.s.	***	n.s.

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, n.s. $p > 0.05$

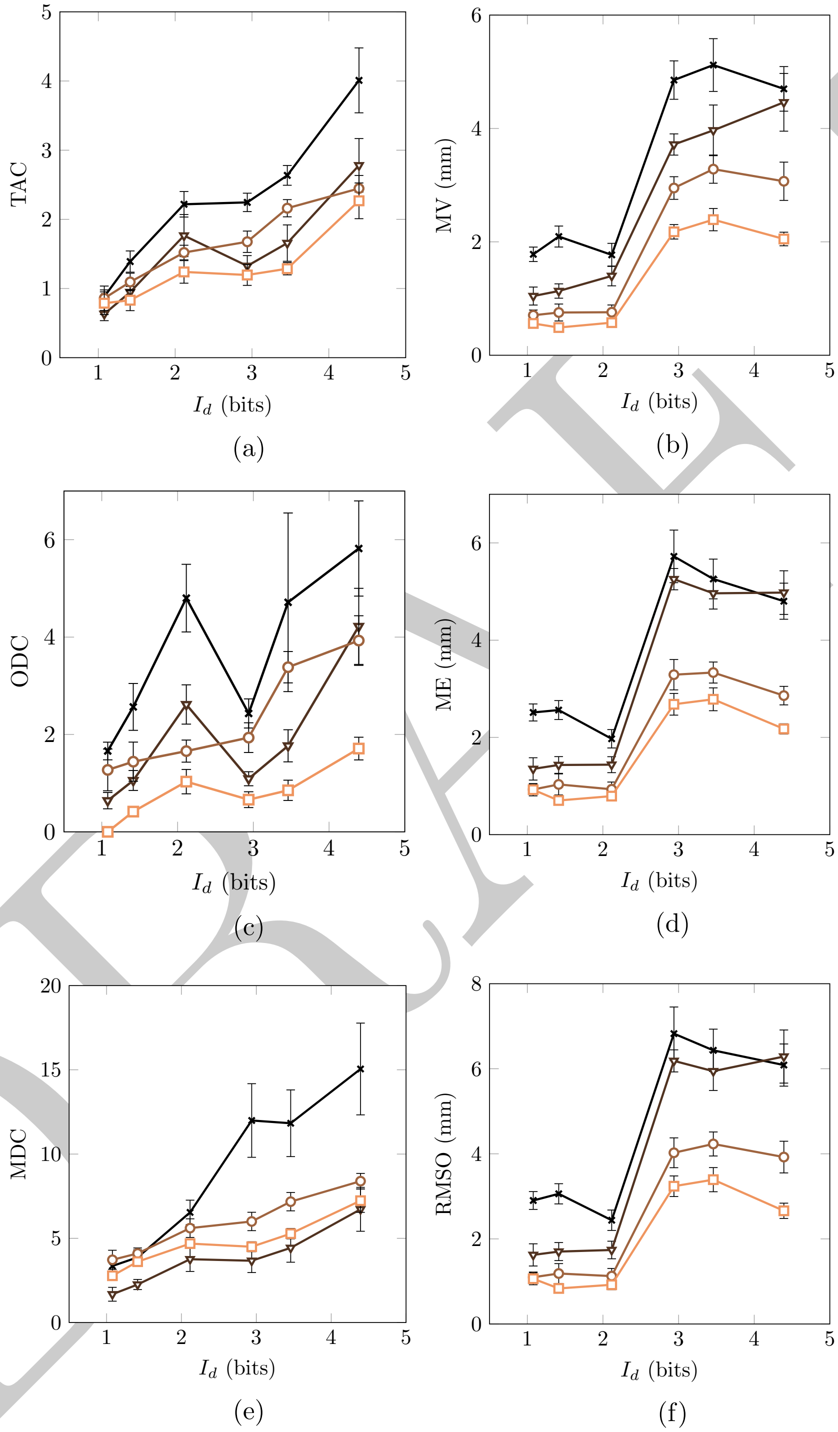


Fig. 11: Cursor control accuracy interactions.

($p < 0.05$, $d = 0.92$) and between the HOTAS and trackpad ($p < 0.01$, $d = 1.45$). The trackpad total axis crossing was also significantly different from that of the trackball when considering the main effect ($p < 0.05$, $d = 0.64$), but not from the interaction with D. For all devices there was a very noticeable difference in total axis crossing between target distances ($p < 0.001$), the strongest effect on the HOTAS fingerstick ($d = 3.42$, compared to 2.17 for the thumbstick, 2.01 for the trackpad, and 1.95 for the trackball). Changes in direction orthogonal to the axis, ODC, were only influenced by the main effects for all levels of W and D. From Fig. 11c the ODC appears to be influenced quite strongly by W, with lower values across all devices encountered for larger targets widths. Statistical significance was found between the smallest two target widths ($p < 0.05$, $d = 0.83$) and between the smallest and largest target width ($p < 0.01$, $d = 1.37$), suggesting the effect becomes smaller at increasingly smaller targets, though this is not evident in Fig. 11c.

Unlike the TAC and ODC, where participants were clearly most efficient with the trackpad, for the movement direction change (MDC) the thumbstick was marginally better than the trackpad, and this was statistically different at the smallest target distance ($p < 0.05$, $d = 0.31$). In most cases the thumbstick was also superior to the trackball with regard to these parameters, arguably because the trackball is inherently harder to operate in a consistent direction. At the largest target distance there was significant difference between the HOTAS and the other three devices ($p < 0.05$, average $d = 1.8$)). All devices had statistically significant MDC between both target distances, with the MDC of the HOTAS being noticeably worse for the I_d with the larger value of D ($p < 0.01$, $d = 1.96$).

For the other efficiency measures the behaviour between devices is quite consistent. As can be expected the HOTAS performs the worst, followed by the thumbstick, then the trackball, and participants were most efficient (movement-wise) with the trackpad. For the I_d values given by the lower D however, the performance with the thumbstick was more comparable to the trackball and trackpad. The target distance, D, had a noticeably larger impact on the movement efficiency than the target width.

For the movement variability (MV, see Fig. 11b) both HOTAS and thumbstick were significantly different from the trackball (both $p < 0.05$) and trackpad (both $p < 0.01$) but the effect (Cohen's d) is greater between the trackpad than the trackball, and further greater for the HOTAS. At the larger target distance the thumbstick was only significantly different to the trackpad, whilst the trackpad become significantly more efficient than the trackball ($p < 0.01$, $d = 1.52$). There was significant difference between both levels of D for all CCDs ($p < 0.001$). Target width, W, was found to have no significant effect ($p = 0.062$, $\eta_p^2 = 0.43$).

The movement error (ME, Fig. 11d) show disparate differences between the 'sticks' (the HOTAS and thumbstick) and the 'tracker' devices (trackball and trackpad), especially for the larger value of D (corresponding to the three largest I_d). At $D = 7$ mm the HOTAS varied significantly from the other devices, most strongly from the trackpad ($p < 0.01$, $d = 2.36$) which was also significantly different from the thumbstick ($p < 0.05$, $d = 0.91$). At the larger target separation the thumbstick was more comparable to the HOTAS performance, with both being significantly different from the trackball ($p < 0.05$, average $d = 3.1$) and trackpad ($p < 0.01$, average $d = 4.4$). There was strong significant difference between both levels of D for all CCDs ($p < 0.001$). Similar behaviour (except for the $W \times D$ interaction) can be seen with the RMSO movement offset, shown in Fig. 11f. However, there was a much greater difference between the trackball and trackpad at the largest target distance ($p < 0.05$, $d = 1.51$).

From these results it can be concluded that larger target distances negatively affect both the frequency and magnitude of variability, error, and offset of cursor movement to a target. Target width affects the frequency of these, but not so much the magnitude. The HOTAS fingerstick performs the worst for all parameters, whilst participants are most efficient with the trackpad. The only exception is with the thumbstick at smaller target separation, which seems better at avoiding backward movements along the task axis.

5 Discussion

5.1 CCD performance

The results from this study highlight the poor performance of the HOTAS fingerstick in comparison to other potential cockpit CCDs in most situations. Although the sample size was relatively small, the differences were sufficient to uncover statically significant differences in places, and they generally conform to other results from existing studies. The configuration of the HOTAS fingerstick no doubt impacts on the performance as the index and middle finger have noticeably less dexterity than the thumb [49]. However, they require significantly less space than other types of pointing devices. Isotonic joysticks (such as the thumbstick evaluated in this work) are more favourable with regard to feedback since they work on displacement, as opposed to force input. This provides greater kinesthetic feedback and, as shown in this study, marginally (but not significantly) better throughput. Both of these devices were used with the selection achieved through depressing the joystick. Participants noted this led to difficulty in selection, especially for the force-driven HOTAS fingerstick (see also [44]). Had the thumbstick been isometric it is expected that the throughput would have suffered due to the lack of feedback and sensitivity when using it to select targets, but control efficiency may have been greater due to the greater dexterity of the thumb.

Comparison of throughput across different studies is fundamentally limited when the range of I'_d is dissimilar [51]. Within studies this is not an issue, but these throughput values would only strictly be comparable to other studies if the same difficulty index range and experimental conditions were used. Hence the normal Fitts' law parameters were also reported for reference. This is, however, the benefit of using a formalised test such as the ISO standard. Generally, the values for each throughput definition shown in Table 4 are in agreement with regards to the respective performance of each device. The only exception to this is that the slope-inverse metric ($1/b'$) suggests the trackpad is (quite) superior to the trackball, whereas the mean-of-means approach (i.e. the throughput, T) suggests the opposite. The Fitts' law slopes for the trackball and trackpad were however very similar so this may simply be regression noise. Interestingly, the orthogonal axis accuracy (i.e. TAC) of cursor movement was greater with the trackpad than trackball ($p < 0.05$) – the same observation made in [37]. Given the reciprocal relationship between speed and accuracy in the definition of throughput, the speed must be higher with the trackball, specifically the ballistic phase of movement where participant's generally chose to 'flick' the trackball in the desired direction of movement. This was observed in the experimental data. A throughput value in the region of 2 bits/s for the trackball and trackpad (sometimes referred to as a touchpad) is quite common in many other studies and agrees well with the results obtained here. (see [45] for a thorough listing). Throughput values for the HOTAS fingerstick were noticeably different in this study (0.7 bits/s) compared to typical values of 2 bits/s found in [19]. The value of mean-of-means throughput, T, obtained in this study for the touchscreen (3.7 bits/s) was noticeably smaller than in [35] – the significant difference in that study was the much smaller screen (a 4.7 inch mobile phone) and less restrictive positioning of the touch device that may have allowed participants to operate at faster speeds. By comparison, the display in [5] was a 15.6 inch laptop screen and the value of $1/b$ obtained was 8.3 bits/s – reasonably similar to that obtained in this study.

It also remains unclear whether rate-limited devices such as the HOTAS fingerstick and isotonic thumbstick truly follow Fitts' model since the motion is practically devoid of any ballistic component. The same argument may be made for the touchscreen, but for the opposite reason – participants motion was almost apparently ballistic, though it is possible the corrective motion is simply implemented in a seamless fashion with the ballistic phase due to the natural aptitude of participants with their hands and arms. Given the variation in accuracy of touchscreen devices between small and large targets (due to purely physical limitations of the participants finger size), further modifications to Fitts' law that incorporate precision limits (such as in [9]) could yield better regression models when dealing with small targets.

In this work pointer acceleration was disabled across the CCDs evaluated. Pointer acceleration (i.e. a speed-based adaptive CD gain) has been shown to offer a small performance advantage over constant CD gains when selecting small targets separated by large distances [12]. In [20] using pointer acceleration reportedly yielded a 44% increase in throughput for an aviation trackball from 1.33 bit/s to 1.93 bit/s. However, achieving a suitable speed-accuracy balance through varying the CD gain introduces a substantial variable as it is often user-specific. For the HOTAS fingerstick very low values of CD gain were required by all participants in order to achieve a useable level of accuracy, which negatively effects the movement time possible with the device. At such small levels it is unlikely pointer acceleration would make a marked difference to selection time performance. A hotspot-sensitive adaptive CD gain, where the CD gain is significantly higher when there are no active targets to select in the proximity of the cursor, or a complimentary pointing mechanism such as in [53], would be effective to improve performance with this limitation in place.

5.2 Operational considerations

The effects of turbulence, engine vibrations, and G-forces were not considered in the experimental setup and would undoubtedly degrade the performances demonstrated, especially the selection accuracy, as evidenced in the related work cited in §2.2. Such degradation would result not only from the induced movement on the pilot's limbs, but also their visual acuity of the symbology on the displays due to cockpit vibration and relative head movements. The devices that incorporate fixtures for the pilot to grasp whilst operating the CCDs (such as the throttle quadrant or existing aviation trackballs) would be advantageous in limiting the impact on cursor control, whereas helmet-mounted displays would help to limit motion blur. Those two approaches are already well established solutions in modern aircraft, but the problems indicate the operational constraints on using the higher throughput devices such as a mouse or touchscreens. Modern civilian transports have incorporated trackpads and trackballs in cockpits for CCD operation, though these environments are less dynamic than typical fighter jet scenarios. The results obtained in this study would confirm the suitability of these devices and, taken on face value, would suggest these two devices to also be the better option for improving CCD control in fighter aircraft cockpits, as they are evidently superior to the HOTAS isometric fingerstick employed in this study.

With that said, however, a considerable benefit of the HOTAS CCD is that a pilot's hand is supported due to their grasp of the throttle lever and flight stick. This helps to reduce the negative effects from vibration- or turbulence-induced tremor [28] and the impact of G-forces. Tremor has been shown to be a significant problem in office computing isometric sticks, especially when selecting small targets [38]. The detrimental affect will be even more so in a highly dynamic environment such as an aircraft's cockpit, though gloves may to some extent provide some damping to finger tremor. That said, users of isometric joysticks are frequently malaise due to the lack of tactile feedback and this is very likely to be exacerbated by a pilot's gloves. Isotonic joysticks would therefore seem to be the better CCD in terms of reduced impact of vibration and providing kinesthetic feedback, but the physical size of the stick would need to be optimised to limit undesired input from turbulence or G-forces. Whilst touchscreens potentially offer the best throughput, difficult selection in high-G and high-vibration environments, together with difficulties in selecting small and highly-crowded symbols, would limit overall performance unless such situations could be avoided. These difficulties would be exacerbated with the use of pilot gloves which would effectively increase the size of the users finger and restrict haptic feedback [16].

Another operational aspect to consider is that target selection tasks on most aircraft MFDs may not typically involve significant or prolonged movement of the cursor between targets, unlike the ISO task carried out in this work. Therefore the poor selection time performance indicated in this study may not necessarily impact the overall performance as much as implied by treating it as a device for prolonged, repetitive movement. However, the underlying issues of movement accuracy for pointing sticks are demonstrated here and elsewhere, and there is an increasingly growing consensus that traditional HOTAS TDCs will not be adequate for future cockpit designs where more data will need to be presented and interacted with [17, 27, 32], thus increasing the frequency the CCD is used.

It was noted that both the trackball and trackpad allowed free movement of forearm limbs, whereas the finger and thumbstick did not. It has been suggested that users naturally employ different muscle groups at different CD gains and task scales [2, 10, 25]. As pointed out in [12], intuition would suggest performance barriers in the form of increased clutching and muscle coordination at low levels of CD gain and limits of fine muscle control at high gains. Distal muscles in the arm are far smaller and require less energy to move at a given speed than the proximal ones, so it makes sense that users would exercise these when the required range of movement can be achieved with the current CD gain without clutching. Most able-bodied participants are likely more precise with the use of their distal muscles compared to the proximal ones. Clutching is motor-intensive so the introduction of the larger muscles (that provide greater force) is possibly a means to achieve the desired cursor movement with the least effort of the two approaches. This does assume participants try to achieve the same level of performance regardless of the cursor speed and movement distance. Thus, were a user's forearms restricted during movement (as is the case of the aviation trackball in [20, 43]) then it seems likely that the throughput would be reduced due to the lack of additional motor control provided by the wrist and proximal limbs. This would explain the apparent reduction in throughput between the desktop trackball (2 bit/s) and the aviation trackball (∼1.63 bit/s) seen in [20], and between a desk-based isometric joystick (∼2 bit/s) and the HOTAS fingerstick results (0.7 bit/s) obtained in this study. When all muscle groups are able to operate in tandem both movement range and dexterity can be maximised, which would naturally lead to improved performance [50].

6 Conclusions

A repeated measures experiment, utilising two groups of six participants, was carried out to evaluate the the performance of five viable devices for cursor control in an aircraft cockpit scenario using the standard circular ISO 9241-9 task. The experiment recorded cursor control and selection data to facilitate the analysis of performance in terms of selection time, throughput, error, and various cursor control efficiency parameters.

The throughput of a modern hands-on-throttle-and-stick (HOTAS) finger-operated isometric pointing stick was found to be significantly weaker than either a trackpad or a touchscreen ($p < 0.001$) and a trackball ($p < 0.01$), and slightly poorer (but not significantly different) than an isotonic thumbstick. Similarly, no significance was found in throughput between the trackball and trackpad, but the touchscreen was significantly better ($p < 0.001$). Thus the joystick, tracking devices, and touchscreen formed three separate performance groups in terms of both selection time and throughput. The data also suggests that trackballs perform better than trackpads at smaller target separation, and vice-versa at larger target separation due to the impact of clutching for the trackball. When compared with throughput of existing works there is reasonable agreement with these values. However, it was postulated that the restriction of the wrist motion when operating these devices works to reduce the throughput of a device, due to the unavailability of the forearm muscles in complimenting the muscles in the palm controlling the device. In this work the throughput for the HOTAS fingerstick (0.7 bits/s) was observed to be lower than results for desk-based finger-operated isometric joysticks from existing works (typically 2 bits/s). Similarly, the throughput with the desktop-based trackball (2 bits/s) was larger than an 'aviation' trackball in existing work (about 1.6 bits/s), where the wrist motion is limited in operating the device.

In terms of error rates, the trackpad performed better overall against the other devices, being significantly better than the HOTAS ($p < 0.05$). Despite the touchscreen's greater throughput performance, there were significant deficiencies using the device for small targets ($p < 0.05$). For larger targets, though, it had comparable error rates to the trackball and trackpad. Target re-entry (effectively a measure of homing efficiency) was poorest for the HOTAS and thumbsticks, but all devices suffered decreased homing efficiency at smaller target widths, the thumbstick suffering the worst. Similar results were obtained when examining the movement efficiency parameters, with strong significances due to target separation and CCD, and smaller effects due to target width. Interestingly, it was noted that both frequency and magnitude of the efficiency parameters were influenced by target separation, but target width effected the frequency much more strongly than the magnitude. It was also seen that at low target separation the thumbstick was close to the movement efficiency of the trackball and trackpads but degrades significantly at larger target separation. For the movement variability metric the thumbstick significantly outperformed the trackpad at the smallest target separation ($p < 0.05$).

On assessing these metrics solely the trackpad and/or touchscreen would be most suited as a CCD, and these results would be directly applicable to aircraft that undergo limited dynamic and low-G flight manoeuvres. However, in highly dynamic cockpits vibration- and turbulence-induced tremor are strongly present and this is likely to reduce the throughput of touchscreens considerably. Thumb-operated joysticks on HOTAS setups would seem to be the most appropriate arrangement for future, data-rich fighter cockpit environments that will require the interaction with multiple small symbology, maintain the compact use of space in the cockpit, and provide the necessary support for reducing the effects of tremor and G-forces. Assistive pointing software are likely the best approach to improving throughput performance in this environment.

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Appendix: Calculation of task axis-referenced parameters

With reference to Fig. 12, given, the location of the target, (x_i, y_i), and the location of the selection, (x'_i, y'_i), both relative to O, for the current target i of total targets l:

1. Compute ψ_i:

$$\psi_i = -\left(\text{atan2}\left(y_i - y'_{i-1},\ x_i - x'_{i-1}\right) - \frac{\pi}{2}\right).$$

2. Compute the distance $(\Delta x_i, \Delta y_i)$ relative to the centre of i:

$$\Delta x_i = x'_i - x_i, \quad \Delta y_i = y'_i - y_i.$$

3. Map the relative coordinates onto the task axis:

$$\begin{bmatrix} x_i^* \\ y_i^* \end{bmatrix} = \begin{bmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{bmatrix} \begin{bmatrix} \Delta x_i \\ \Delta y_i \end{bmatrix},$$

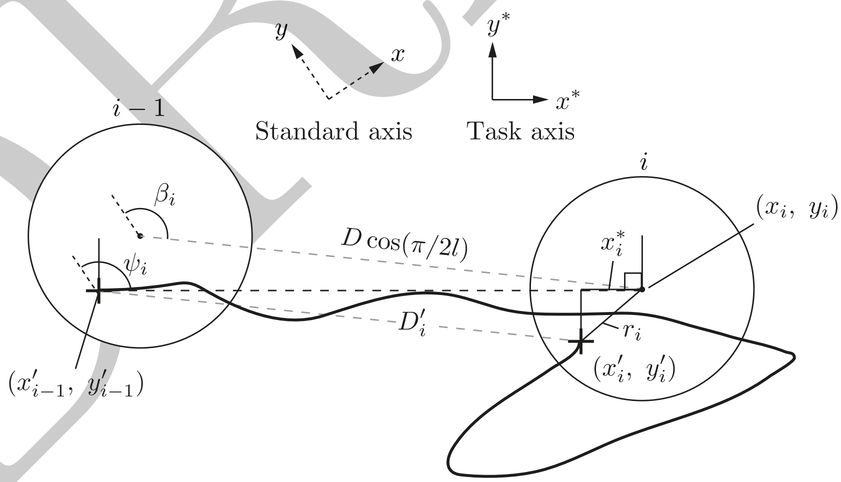

Fig. 12: Definition of target parameters.

where

$$\theta_i = \frac{\pi}{2} - \psi_i.$$

4. Then

$$\sigma_x = \sqrt{\frac{1}{j}\sum_{i=1}^{l}(x_i^* - \bar{x}^*)^2}, \qquad \sigma_r = \sqrt{\frac{1}{j}\sum_{i=1}^{l}(r_i - \bar{r})^2},$$

where

$$r_i = \sqrt{x_i^{*^2} + y_i^{*^2}}.$$

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