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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.

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 (Rutledge and Selker, 1990). Whilst isometric joysticks have been analysed in previous work (Card et al., 1978; Epps, 1986; Mithal and Douglas, 1996), 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

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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			•			
	GulfstreamG150	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	•				•	•

sources, more efficient and high performance input devices will be of enormous benefit and help to improve the quality of decision-making processes (Alfredson et al., 2011). 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 performance 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. (1978) 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 (1986) 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 (Fitts, 1954). 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 (1992):

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

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 (Drewes, 2010; Hoffmann, 2013). 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:

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

where I'_d is a modified index of difficulty which takes into account a normalised spread of end points for a given target (Crossman, 1957; Welford, 1960, 1968). This adjustment relies on the assumption that the end points are normally distributed which has often been seen to be the case (Crossman, 1960; Fitts, 1954; Flowers, 1975). This leads to the effective width

$$W' = 4.133\sigma, \quad (3)$$

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 (iso, 2000).

More recent studies have also looked to characterise the efficiency and accuracy of cursor movement (MacKenzie et al., 2001; Oirschot and Houtsma, 2001). 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 MacKenzie et al. (2001). Phillips and Triggs (2000) (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 (1996) 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 Phillips and Triggs (2000) 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