Future Technology on the Flight deck:

Assessing the use of touchscreens in vibration environments

Louise V Coutts[a*], Katherine L. Plant[a], Mark Smith[b], Luke Bolton[b], Katie J. Parnell[a], Jamie Arnold[a], Neville A. Stanton[a]

aTransportation Research Group, Faculty of Engineering and Environment, University of Southampton, Southampton, UK;
bGE Aviation Systems Ltd, Bishops Cleeve, Cheltenham, Gloucestershire, UK

*Corresponding author email address: L.V.Coutts@soton.ac.uk

Acknowledgements: This project was co-funded by Innovate UK, the UK's Innovation Agency, with support from the UK Aerospace Technology Institute.

Abstract

Use of touchscreens in the flight deck has been steadily increasing, however their usability may be severely impacted when turbulent conditions arise. Most previous research focusses on using touchscreens in static conditions, therefore this study assessed touchscreen use whilst undergoing turbulent representative motion, generated using a 6-axis motion simulator. Touchscreens were tested in centre, side and overhead positions, to investigate how turbulence affected: (1) error rate, movement times and accuracy, (2) arm fatigue and discomfort. Two touchscreen technologies were compared: a 15" infra-red and a 17.3" projected capacitive touchscreen with force sensing capability. The potential of the force sensing capability to minimise unintentional interactions was also investigated. Twenty-six participants undertook multi-direction tapping (ISO 9241; ISO, 2010) and gesture tasks, under four vibration conditions (control, light chop, light turbulence and moderate turbulence). Error rate, movement time and workload increased and usability decreased significantly, with screen position and increasing turbulence level.

Practitioner Summary

This study evaluated the use of infra-red and projected capacitive touchscreen technologies using multi-directional tapping and gesture tasks, whilst being subjected to different levels of turbulence representative motion. Performance degraded significantly with increasing turbulence level and touchscreen location. This has implications for future flight deck design.

Keywords: aviation; touchscreens; cockpit; turbulence; multi-directional tapping test

Introduction

Over the past couple of decades the increasing complexity of the flight deck has resulted in a move away from the traditional overcrowded array of hundreds of mechanical switches, indicators, toggles and gauges into what is now termed the "glass cockpit" and features sensors, computational systems and a structured array of LCD electronic flight instrument displays. There are an ever growing number of functions available for implementation on the flight deck, such as the recent advances in aircraft sensing and data collection and processing. The currently crowded arrays of flight instruments leave no further potential for incorporating these newly available functions, leading to increasing need to move the "glass cockpit" onto the next stage. One solution to this problem is to replace the current set up with a suite of touchscreens that can be customised to provide an unlimited array of airframe specific user applications.

The use of touchscreens in safety critical systems such as the flight deck has been steadily increasing in recent years (Rockwell Collins, 2016 and Pope, 2009), since solutions to the historical barriers of lack of computing power (leading to slow response times and display update rates) have started to advance. Other barriers to use such as users less used to interacting with touchscreens, in the past displaying variable improvement to comparative performance with other technologies (Rogers et al., 2005) are now being overcome, due to the added value that touchscreens provide. In addition to providing more functionality, touchscreens may also provide ability to: give output or immediate feedback to the user in the same region as input (or selection) and reduce the need for recalling items; where a screen can inform the user of executable functions and hence now have great potential to reduce workload, head down scan time and increase safety. Glass cockpit implementations such as touchscreens also bring advantages to the manufacturer where user applications running on such systems can easily be updated and modified.

Whilst nowadays handheld touchscreens are successfully used in a multitude of applications, the use of a suite of fixed position touchscreens requires careful assessment where proximity becomes crucial due to the direct input requirement of touchscreens. The location of each device in relation to the user becomes an extremely important consideration; where increased levels of discomfort can arise where the user's arm needs to remain outstretched to interact with displays (Stanton et al., 2013, Shin and Zhu, 2011; Wang and Trasbot, 2011; Dul and Weerdmeester, 2001).

Orphanides and Nam (2017) recently performed the first review of studies that evaluated touchscreen interfaces with respect to their Human Factors and Ergonomic capabilities. They identified that selection for or against the use of touchscreens must take into account context of use to maximise safety, performance and user satisfaction. They assessed context of use along three dimensions; the implementation of the touchscreen interface technology, the task that the touchscreen enables and the human user of the touchscreen. These were drawn from Wickens et al., (2004) who identified these factors as key dimensions in display development and selection. One of the review criteria set by Orphanides and Nam (2017) in their assessment of the task dimension of touch screen use was the specific environments within which the touchscreen would enable the task to function. The review identified the use of touch screens in the road environment, extraneous moving environments, medical and other environments (i.e. aircraft, robotics or cycling); aircraft being categorized under other environments as only two papers were identified in this domain. These identified that the use of touchscreens in the cockpit can improve performance when compared with trackball inputs (Eichinger & Kellerer, 2014) as well as rotary controllers and touch pads (Stanton et al., 2013), however as only static conditions were investigated, these findings may not apply for non-static conditions. Touchscreens were also found to be more usable by those engaging with them in simulated cockpit environments when compared to alternative inputs (Stanton et al., 2013).

A major consideration when assessing touchscreen use in aircraft is the turbulent conditions under which pilots typically operate, where interaction will be further complicated by the inadvertent movement that turbulence gives rise to. This is an especially important consideration with predicted changes to climate in the coming years, where turbulence during flights is predicted to increase (Williams, 2017). Within the review conducted by Orphanides and Nam (2017), it was identified that extraneous environments are a key determinant of touchscreen ease of use and the corresponding performance of tasks that use touchscreen inputs. While they did not identify any studies that assessed conditions reflecting aircraft turbulence, numerous studies have explored the use of touchscreens in other environments with unwanted movements. These include agricultural tractors (Baldus & Patterson, 2008), and simulators that exposed participants to vibration conditions that replicated military maritime vessels (Bjorneseth, Dunlop and Hornecker, 2013; Yau, Chao and Hwang, 2008) as well as unfinished roads that military vehicles may encounter (Goode, Lenne and Salmon, 2012). The results from such studies identified that touchscreens provided quicker movement times in contrast to mouse and trackball inputs (Lin et al., 2010; Yau, Chao and Hwang, 2008). Suggesting them to be the preferred input method when rapid inputs are required. Yet, some issues with the use of touchscreens were identified with increased error rates found in vibrating conditions by Lin et al., (2010). Goode, Lenne and Salmon (2012) also found increased inaccuracies and high levels of workload when assessing the use of touchscreens in simulated conditions of military vehicles on unfinished roads, this was an effect that was not found to diminish with practise. Thus, suggesting some issues when interacting with touchscreens under conditions of inadvertent motions.

When interacting with touchscreens on the flight deck several issues can come into play, that previously didn't exist with traditional 'hard' (mechanical) controls. Some of these issues are worsened by turbulent conditions, particularly during configuration and emergency situations, such as accidental touches, absence of tactile and aural feedback, extended reach fatigue, loss of historically geographically fixed control locations, reduced display area of multimodal screens and glare (Federal Aviation Administration, 2011; Kaminani, 2012). Other problems may arise such as transmission problems due to build-up of dirt or grease from finger contact (Bhalla and Bhalla, 2010). In the past problems have arisen due to parallax effects where the distance between the LCD and the surface of the glass cover was too great (Noyes and Starr, 2007) and also with inadvertent activation via light beam interruption in infra-red screens (Schwartz and Adam, 1988). In helicopter trials, Avsar, Fischer and Rodden (2015) showed that a fixed screen is susceptible to higher error rates than a mobile handheld screen.

A very recent study by Cockburn et al. (2017) describes touchscreen use in a mocked up cockpit undergoing vibration simulating turbulence, in a similar manner to the study described below. Cockburn also assessed the use of stencil touchscreen overlays and compared performance against a trackball. Participants were asked to complete similar tasks whilst being subjected to varying levels of turbulence mimicking vertical displacement vibration, ranging from static to very uncomfortable (2.15 $m.s^{-2}$) with a mean motion frequency of 3.1 Hz (max. 5 Hz) and generally found that movement time and error rate increased with increasing vibration level. Whilst the range of accelerations imposed through the vibration platform was greater than the study currently being described, the accelerations were limited to the vertical direction only and did not include pitch and roll mimicking motion. The stencil was found to be generally unsuccessful at all vibration levels and tasks requiring pointing precision such as using a slider bar were more difficult to use than those with large targets. Drag based tasks, where maintained contact is required, were inaccurate compared to single press type tasks. In general movement times, error rates and subjective workload increased with vibration level.

The combination of using fixed touch screens within an unpredictable movement environment therefore has potential to lead to highly inefficient interactions, through both slow interaction (movement) times and also through increased errors, where target locations may be missed if simultaneous unpredictable movement occurs. So far, reported factors such as button size, proximity, screen gain and auditory feedback have been found to significantly affect movement time and error rates (Hoffman and Sheikh, 1994; Lin, Radwin, and Vanderheiden, 1992; Hancock and Caird, 1993, Bender, 1999; Dodd et al., 2014) whilst the use of novel technologies such as force sensing screens (Happich, 2015) and haptic feedback (Graham-Rowe, 2011) also have potential to further affect these parameters. However the majority of these reported findings do not investigate turbulence and only apply to static conditions. Fitts' law is now considered a useful model for human performance when evaluating a human computer interface (Soukoreff and MacKenzie 2004). Fitts (1954) described how difficulty of use depends (i) on the distance of the target button and (ii) inversely on the size of the button although this was established for static operation only. It is likely that the difficulty of use will greatly be increased when the device is also undergoing unpredictable movement, where static solutions such as increasing button sizes or positioning buttons more closely may not apply and could instead result in a trade-off with error rate.

Hoffman and Sheikh (1994) sought to expand Fitts' law for non-static applications, finding that movement times (time to reach target button) increased as target height (200 to 1mm) and width (40 to 10mm) decreased. We seek to further expand understanding of touch screen use by taking a human centred approach in evaluating how touch screen technology can be effectively implemented in the flight deck, despite the effects of turbulence. Resistive touchscreens have previously been found to outperform projected capacitive touchscreens (Dodd et al., 2014). Novel technology built into PCT screens can now sense force to gate out unintended touch by the user, similar to the effect inherent in resistive touchscreens, where users would have to press with force rather than tap, in order for the touch to register. Building on the work of Cockburn et al., (2017), using a Dell projected capacitive touchscreen (PCT), the current study investigated whether the force sensing capability of a PCT could improve interactions in a turbulent mimicking cockpit environment. The PCT force sensing technology enables this capability by the addition of a surface layer that measures tiny displacements and also has the capability, with the addition of suitable hardware, to provide the user with haptic feedback.

Use of both PCT and IRT touchscreen technologies were assessed whilst on a platform undergoing vibration representative of different states of aircraft turbulence in order to test the following hypotheses: with a suitably designed Human-Machine Interface (HMI), (1) touch interaction in an operational flight deck can be implemented with an acceptably low interaction error rate and (2) the touch interaction error rate in a turbulent flight deck environment can be reduced with the use of force sensing to confirm interactions; (3) the prototype implementation of force sensing on the touch is immune to the effects of vibration; (4) with a suitably positioned display and with suitable hand anchor points, users can operate the touchscreen in representative vibration conditions without suffering undue arm fatigue or discomfort; (5) single tap gestures will be performed with lower error rates than drag or multi-touch gestures in a turbulent flight deck environment. Specific attention was also given to developing Fitts' law to include extraneous motion, allowing movement time to be estimated for different magnitudes of aircraft vibration type motion, whilst also taking account of button size and proximity. In comparison to the PCT, fewer participants trialled the IRT touchscreen, therefore no statistical analyses were performed on data collected using the IRT and this data has been included for indication only.

Method

Participants

Twenty-six right-handed university-based participants (20 male and 6 female) took part in the study. It was considered unnecessary to use pilots for the basic tasks involved in this study, as the study tasks were not based on flight deck operations. Eight participants were aged 18-24, 12 were aged 25-34 and the remaining 6 participants were spaced evenly across age bands: 35-44, 45-54 and 55-64. For further standardisation, only right handed participants were included in the study. The study was approved by the University of Southampton local ethics research committee (reference number 27805).

Experimental Design

The study had two within-subjects factors: (1) touchscreen location (1: centre, 2: side and 3: overhead) and (2) vibration condition (intending to represent: control, light chop, light turbulence and moderate turbulence). This model produced a total of 12 conditions. The study used a randomised repeated measures design, so each participant took part in each of the 12 conditions. There were six dependent variables: task (movement) time, error rate/accuracy, workload, usability, hand discomfort and body discomfort. The statistical analysis was based on a full factorial model with two factors: touchscreen location and vibration condition.

Three subjective evaluation methods were also employed: system usability scale (SUS, Brooke, 1996), NASA Task Load Index (NASA-TLX, NASA, 1986; Hart and Staveland, 1988) and the Cornell University Questionnaire for Ergonomic Comfort (Hedge, Morimoto, and Mccrobie, 1999). SUS is a questionnaire which is used to assess the usability of a particular product (Stanton et al. 2005) and consists of ten questions. For this study SUS was used to assess each of the three touchscreens, where participants answered questions such as: 1. 'I think that I would like to use the touchscreen unit frequently' and 2. 'I found the touchscreen system unnecessarily complex'. The NASA-TLX questionnaire is a commonly used subjective technique to assess workload (Stanton et al. 2005) and asks participants to rate their experience according to six areas: mental, physical and temporal demand, overall performance, frustration level and effort.

Finally, the Cornell University Questionnaire for Ergonomic Comfort was employed to assess the effect of undertaking the tasks on regional discomfort and pain. The questionnaire asks participants to report the frequency with which they experienced pain in different parts of the body (neck, shoulder, upper back, upper arm, elbow, lower back, forearm and wrist) and seven areas of the hand (fingers relating to the (i) median nerve and (ii) ulnar nerve, thumb, upper palm, lower palm in the regions of the (i) lower thumb metacarpal and (ii) carpal bones and the dorsal surface in the region of the metacarpals), the level of discomfort experienced and whether or not the discomfort interfered with work tasks. For each individual part of the hand and body, there are three sub-scales: the first sub-scale measures the frequency with which the participant experiences discomfort on a five-point scale (0–4); the second sub-scale measures the level of discomfort (if any) on a three-point scale (1–3) and the third sub-scale measures the level of interference of the discomfort with work on a three-point scale (1–3). The scores for the three sub-scales are multiplied to produce a weighted estimate of discomfort for each hand and body part and then summed to produce overall discomfort scores for hand and body posture.

Equipment

Tests were conducted using the 6-Axis Motion Simulator at the University of Southampton, which was developed for vehicle research and is capable of providing faithful reproduction of vehicle motion environments. The simulator is able to provide motion in all three translation axes (fore-and-aft, lateral, and vertical) and all three rotational axes (roll, pitch and yaw) over a frequency range of 0 to 50 Hz. The mock up flight deck configuration was securely attached to the simulator's 3 metre by 2 metre moving platform, consisting of a Boeing 747 seat with five-point harness and framework upon which the touchscreens were securely attached (as shown in Figure 1). Two types of touchscreen technologies were employed: force sensing 17.3" projected capacitive touchscreen prototype flight deck display units and one 15" infra-red touchscreen, fixed in the positions indicated in Figure 1, in configurations as described below.

<u>Procedure</u>

For each vibration level, performance was assessed across the different tasks. Participants were asked to perform the tasks as quickly and accurately as possible using their right (dominant) hand only, ensuring test consistency and simplicity. Participants were told that they could anchor their right hand around the edge of the screen. The participants were continuously monitored to ensure that they did not use their left hand at all, including the tests, screen anchoring or supporting the right hand or arm. Participants were instructed to rest their left arm either in their lap or on the overhead cross bar (away from the overhead screen). Participants were asked to complete several tasks, including a 16 button force and non-force -sensing multi-directional tapping test (MDTT, as described in ISO 9241; ISO, 2010) across five different button sizes (1.0, 1.5, 2.0, 2.5, 3.0 cm diameter) and gesture tasks assessing: (i) ability to drag a ball to follow a ghost ball along a track, (ii) slider use and (iii) edge swipe, as shown in Figure 1 (d). For the MDTT, the task proceeded onto the next button location upon release of (i) a successfully located press for the non-force sensing test or (ii) a successfully located and sufficiently high force press for the force sensing test. Participants undertook these tasks using screens in each of the three screen locations: centre (screen 1), side (screen 2) and overhead (screen 3) whilst being subjected to each vibration condition.

Four levels of turbulent mimicking vibration were assessed: control: no movement; light chop: 2-6Hz filtered random vertical motion r.m.s. weighted magnitude 0.37 $m.s^{-2}$; light turbulence: 1-6Hz filtered random vertical (magnitude 0.25 $m.s^{-2}$), roll (magnitude 0.03 $m.s^{-2}$) and pitch (magnitude 0.02 $m.s^{-2}$) motion, r.m.s. weighted magnitude 0.26 $m.s^{-2}$, pitch centre 1.5m behind seat; moderate turbulence: 1-6Hz filtered random vertical (magnitude 0.51 $m.s^{-2}$), roll (magnitude 0.06 $m.s^{-2}$) and pitch (magnitude 0.04 $m.s^{-2}$) motion, r.m.s. weighted magnitude 0.52 $m.s^{-2}$, pitch centre 1.5m behind seat. Vibration levels were weighted to provide an overall directional measure of vibration exposure, as described in British Standard 6841 (BSI, 1987). Each participant undertook the group of tasks within each condition in a balanced randomised order, followed by each of the questionnaires. This was repeated twelve times (also in a balanced, randomised order): once for each of the three screens in each of the four vibration conditions.

For all participants, prototype 17.3" widescreen Liquid Crystal Display (LCD) units were positioned in side (screen 2) and overhead (screen 3) positions (see Figure 1). Projected Capacitive Touchscreen (PCT) sensors were optically bonded to the LCD units to provide touch force sensing capability; the bonding method being selected to achieve negligible relative movement between the PCT and LCD under vibration conditions. For all but four of the participants, a third prototype 17.3" PCT screen with touch force sensing as described above, was positioned in the centre (screen 1) position (see also Figure 1). In order to compare performance of different touchscreen technologies, for the remaining four participants, a (non-force sensing) 15" infra-red touchscreen (IRT) was positioned in the centre (screen 1) position. The PCT and IRT displays were visually different and participants using the IRT in the screen 1 position were informed that as the centre screen did not have force sensing capability, they would not be asked to complete the force sensing MDTT task on that screen.

Measured variables included response (movement) time, number of erroneous touches and touch accuracy, all captured from the touchscreen data input record, for both force sensing and non-force sensing tests. For the force sensing tapping tests, a touch would only register where it had a minimum unit specific force value of 50 (a force of 1 N, typical of an intentional touchscreen finger press). Whilst a minimum TSU specific unit of 50 was required to trigger a successful press, the PCT was sensitive to increments of just 1 TSU specific unit (0.02N). The number of touches below the force threshold with corresponding force values were therefore also recorded, along with the location of press.

Data Reduction & Analysis

Data were recorded for each task and statistical analysis and processing undertaken using an in house developed Matlab algorithm. The average (median) results are illustrated graphically for each test (figures 2 – 8), dependent variable and screen type. Whilst results from the IRT were illustrated graphically for comparison with PCT, no statistical effects are described, due to the small sample size (n=4). For tasks completed using the PCT screen, a factorial repeated-measures ANOVA was used to analyse the parametric scale measures: time and error rate/accuracy (as appropriate); a Friedman's ANOVA to analyse ordinal level, non-parametric measures: workload, usability and discomfort variables. All statistical effects are reported as significant at a minimum level of $p < 0.05$.

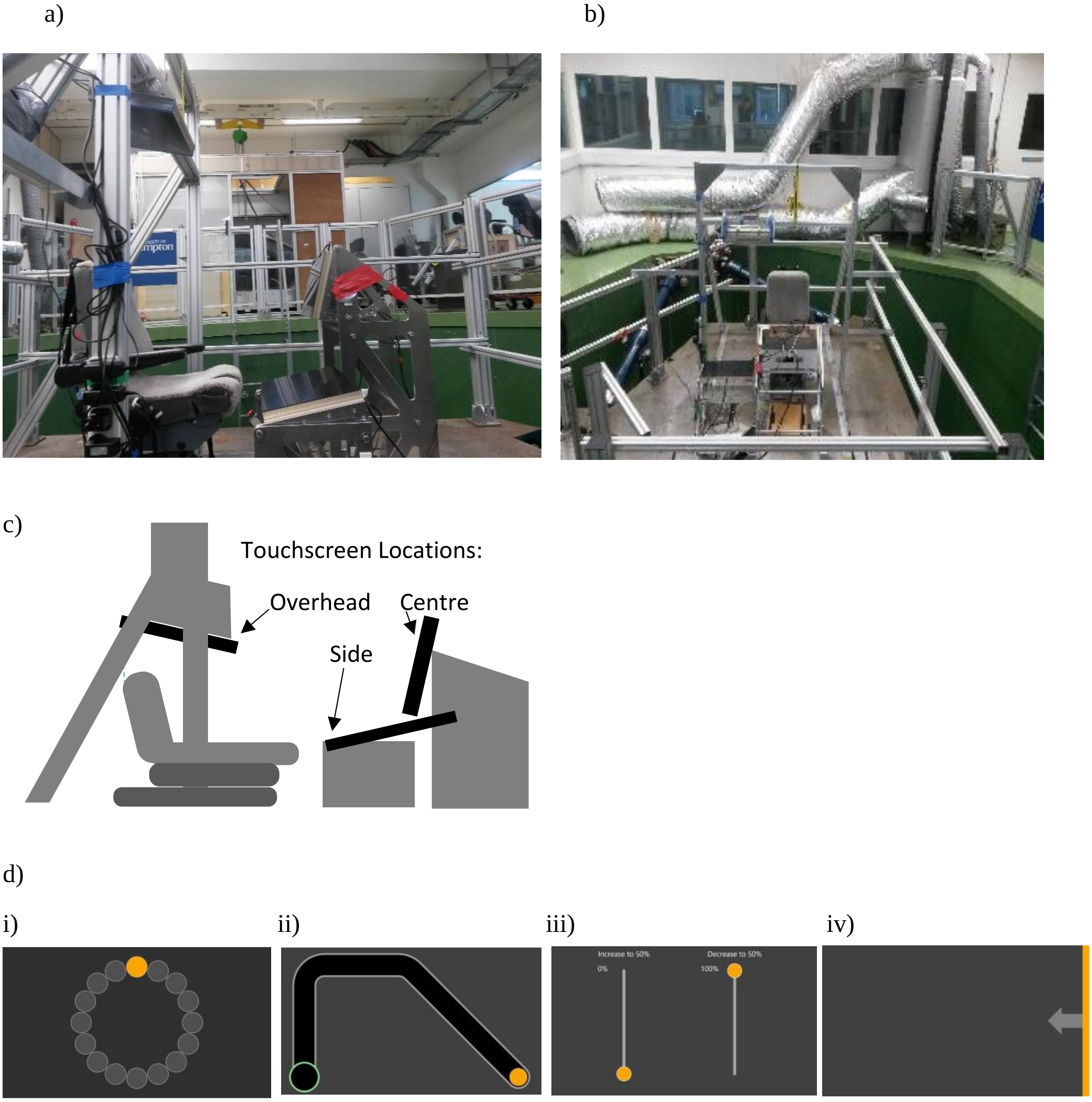


Figure 1 (a) side and (b) front photographs and (c) side schematic of the test setup. The overhead and side touchscreens were positioned at 10° from the horizontal and the centre touchscreen at 15° from the vertical. The centre touchscreen was mounted centrally in line with the seat. The side touchscreen was mounted to the side such that the left hand side of the screen was positioned 6cm laterally from the right hand edge of the seat. The overhead screen overlapped the right hand edge of the seat. (d) Sample screenshots of the tasks: (i) Force and non-force –sensing MDTT, (ii) ghost ball tracking, (iii) slider function and (iv) edge swipe

Results

Multi-directional Tapping Tests (MDTT)

Figure 2 shows the mean movement times to successful press and mean number of erroneous presses for all tested conditions. Both the mean movement times and the mean number of erroneous presses increased with decreasing button diameter (for all conditions and all screens) and increasing vibration level for all button sizes and all screens). For the side and overhead touch screens, there were also some error presses for the smaller buttons where the participant was pressing the location of the previous button without realising that they had successfully pressed it and there were also several accidental presses on the edge of the screen where participants were using the edge of the screen to anchor their hand.

There was a significant effect of vibration condition on (i) movement time when force sensing was employed, for centre ($F(3, 20) = 23.2$, $p < 0.0001$), side ($F(3, 24) = 53.3$, $p < 0.0001$) and overhead ($F(3, 24) = 21.94$, $p < 0.0001$) PCT screens and on (ii) the number of erroneous presses for centre ($F(3, 20) = 15.39$, $p < 0.0001$), side ($F(3, 24) = 29.9$, $p < 0.0001$) and overhead ($F(3, 24) = 6.26$, $p < 0.005$) PCT screens. For the force sensing tests, the mean number of error presses where the force was below the threshold, but in the correct location, are also shown in Figure 3 a along with the corresponding force of those presses in Figure 3b. An observation was made that for the non-force sensing tapping tests, there were more erroneous presses on the side screen (screen 2) than the centre screen, at the smaller button diameters for the moderate turbulence mimicking vibration, thought to be due to the reduced relative angle between the finger and the screen for this configuration, leading to larger finger contact area and reduced ability to accurately press location. There was a significant effect of vibration condition on movement time for centre ($F(3, 20) = 47.6$, $p < 0.0001$), side ($F(3, 24) = 38.1$, $p < 0.0001$) and overhead ($F(3, 24) = 35.8$, $p < 0.0001$) PCT screens and on the number of erroneous presses for centre ($F(3, 20) = 27.2$, $p < 0.0001$), side ($F(3, 24) = 27.7$, $p < 0.0001$) and overhead ($F(3, 24) = 17.3$, $p < 0.001$) PCT screens.

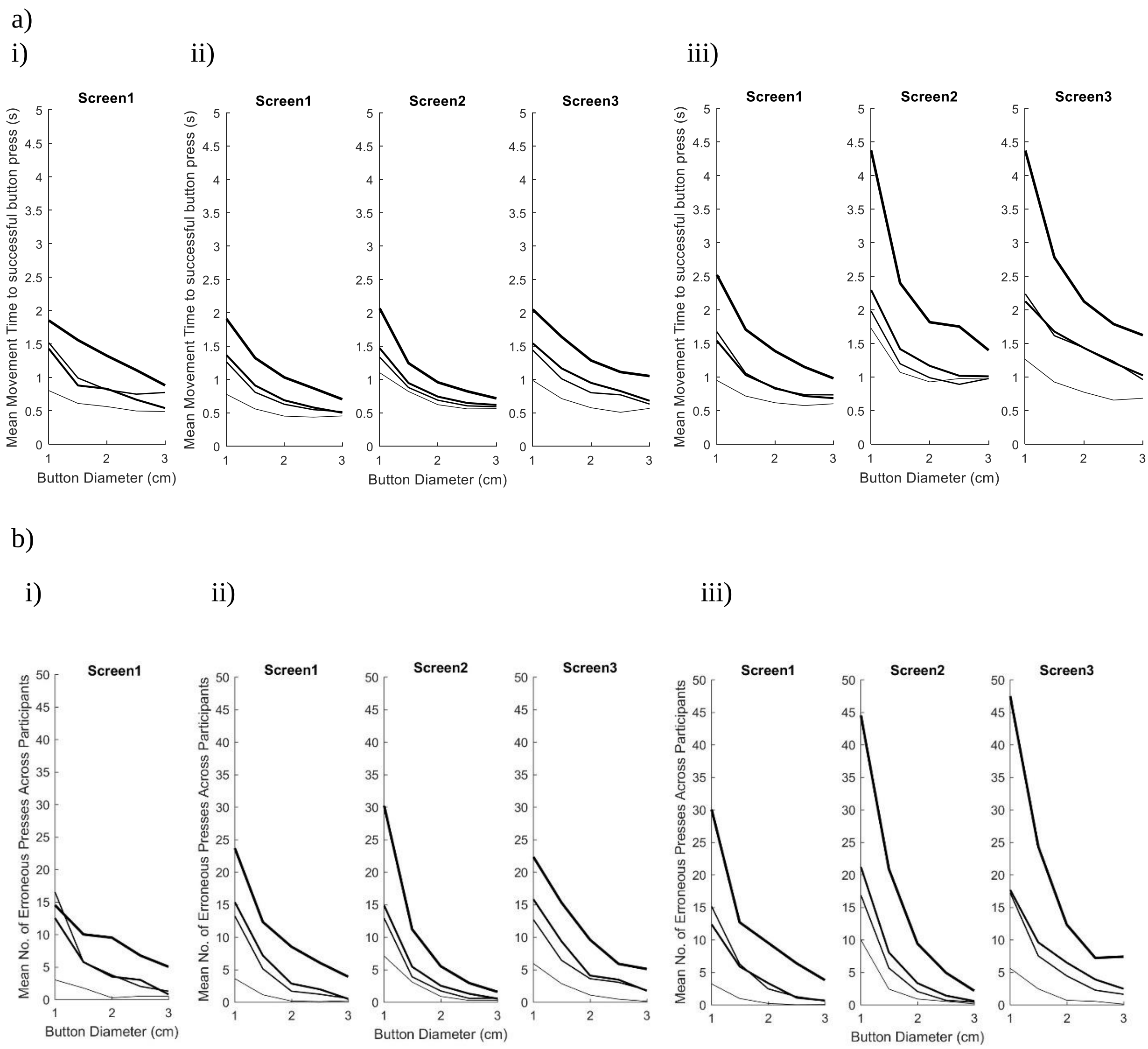


Figure 2 Comparison of (a) mean movement times and (b) mean number of erroneous presses, in MDTT, across different button diameters (cm) and vibration conditions (control, light chop, light turbulence and moderate turbulence, shown with increasing line thickness) for (i) IRT, and PCT for (ii) non-force sensing and (iii) force sensing (IRT data indicative only due to small sample size).

a) b)

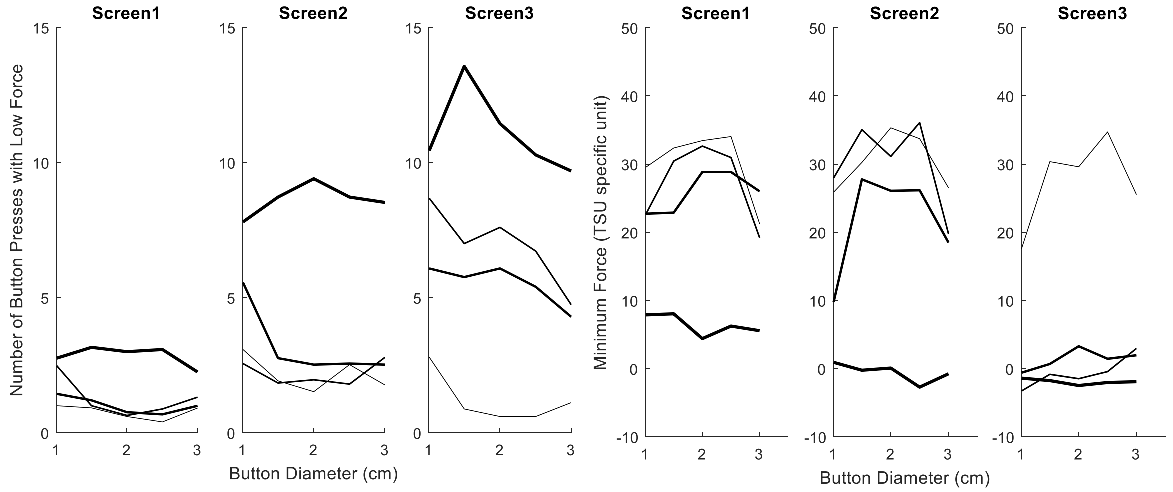


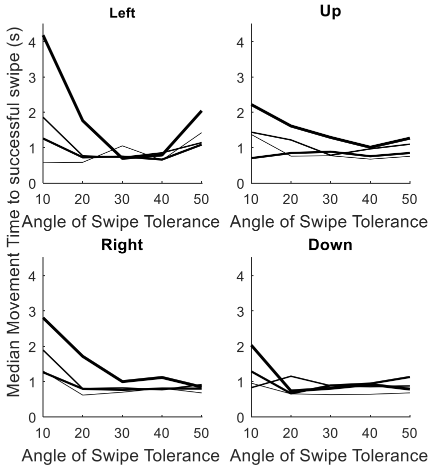
Figure 3 Mean (across participants) of (a) number and (b) corresponding minimum force, of presses with force below the pre-determined threshold, but correct location, in MDTT across different button diameters (cm) and vibration conditions (control, light chop, light turbulence and moderate turbulence, shown with increasing line thickness) for force sensing PCT screen.

Gesture Tasks

Swipe Task

Figure 4 shows the median movement time for each screen for each swipe direction: left, up, right and down. In general, each successful swipe incurred a median movement time in the order of 1 second. For the left swipe at 50° tolerance angle, movement times were higher for the first swipe of each test set. Following this, the movement times remained similar as the test progressed and the tolerance angle decreased until 10° tolerance angle, where the movement time increased. Movement time increased with increasing vibration condition, most noticeably for the left and upwards swipes, particularly for the overhead screen and a significant effect of vibration level was observed for both centre ($F(3, 20) = 7.11$, $p < 0.005$) and overhead ($F(3, 24) = 6.93$, $p < 0.005$) screens but not for the side screen ($F(3, 24) = 1.75$, $p = 0.18$).

a)



b)

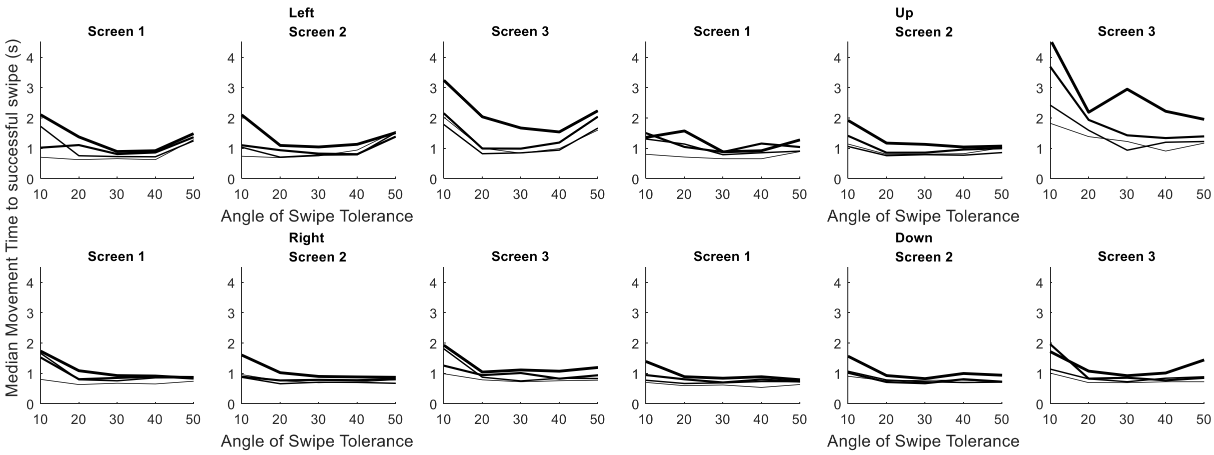


Figure 4 *Comparison of median movement times in swipe tests, across 5 subtests (where required swipe angle tolerance gradually decreased) and vibration conditions (control, light chop, light turbulence and moderate turbulence, shown with increasing line thickness) for (a) IRT centre screen and (b) PCT centre, side and overhead screens (IRT data indicative only due to small sample size).*

Ghost Ball Task

Figure 5 (a) and (b) show median movement time and accuracy respectively. Movement times were dependent on the track of the ghost ball, which moved at a constant speed along the track, starting as soon as the participant touched the screen. For the PCT screen (see Figure 5 ii), median movement times differed between vibration conditions to the greatest extent in the overhead screen ($F(3, 24) = 11.98$, $p < 0.0001$), but also to a significant extent in the side ($F(3, 24) = 4.54$, $p < 0.05$) but not for the centre ($F(3, 20) = 2.93$, $p = 0.06$) screen. The final segment of the task was also investigated; from the time the ball touched the final circle, to positioning the ball within the final circle. There was a significant effect of vibration level in movement time for final ball positioning, for centre ($F(3, 20) = 3.51$, $p < 0.05$), side ($F(3, 24) = 3.32$, $p < 0.05$) and overhead ($F(3, 24) = 9.22$, $p < 0.001$) screens. There is a clear learning effect in the first subtest, where movement times were higher for all screens (see Figure 6). For subsequent subtests, a shorter and fairly consistent time of approximately 2 seconds, is taken to position the ball in the end circle, for all vibration levels, therefore it is likely that the large variation found in the overall movement times between vibration levels in the overhead screen (of the order of 3 seconds, see Figure 5 a ii) predominantly arises from the main track following part of the task.

The median accuracy of the ball position from the ghost ball is in the order of 1cm, for all conditions and all screens, except for the moderate turbulence vibration condition in the overhead screen. In this case accuracy was poor at a median of 3cm for subtests involving a '∩' shaped track (where the start and end points of the track were at the bottom of the screen), and 4.5cm for subtests involving a '∪' shaped track (where the start and end points of the track were at the top of the screen). There was a significant effect of vibration condition on accuracy across centre ($F(3, 20) = 4.54$, $p < 0.05$) and overhead ($F(3, 24) = 22.14$, $p < 0.0001$) PCT screens, but not for the side ($F(3, 24) = 2.61$, $p = 0.07$).

In addition, the mean (note: not median) number of touches to complete the ghost ball task were also calculated as a measure of how frequently the user accidentally removed their touch away from the screen during a continual movement task. Figure 7 shows how the number of touches increased significantly with increasing vibration for all PCT screens: centre ($F(3, 20) = 9.61$, $p < 0.001$), side ($F(3, 24) = 11.31$, $p < 0.0001$) and overhead ($F(3, 24) = 18.98$, $p < 0.0001$) positions.

Slider Task

The results for the slider tests are shown in Figure 8, for both IRT and PCT screens. For each of the four types of slider, there were two sliders presented, the first slider was presented at the 0% position and the second slider was presented at the 100% position at the start of the test. For the PCT screen, the first slider appears to have a consistently increased movement time, possibly due to a delay in starting to interact with each type of slider as the new screen appeared. As previously, the movement time increased with increasing vibration level for the first slider in the centre ($F(3, 20) = 5.22$, $p < 0.01$), side ($F(3, 24) = 4.87$, $p < 0.01$) and overhead ($F(3, 24) = 4.21$, $p < 0.05$) screens and the second slider in the centre ($F(3, 20) = 4.68$, $p < 0.05$), side ($F(3, 24) = 5.14$, $p < 0.01$) and overhead ($F(3, 24) = 6.20$, $p < 0.01$) screens.

Ergonomic Comfort Questionnaires

The median scores for the questionnaire are shown in figure 9. Regions with median values of zero i.e. no discomfort at all, were not displayed in the figure: upper back, elbow (right), lower back, forearm (right), hand (right) - median nerve, hand (right) - ulna nerve, thumb (right), palm (metacarpals), palm (thumb metacarpal), palm (carpal bones) and dorsal surface (over metacarpals). There was a marked increase in frequency of discomfort, ache and pain for all vibration conditions in the regions of the right shoulder and upper arm and the overhead screen in the neck. All other regions had a median value of no discomfort, except for the wrist in the moderate turbulent mimicking vibration condition for the overhead screen. These findings were similar for severity of discomfort and interference with the task.

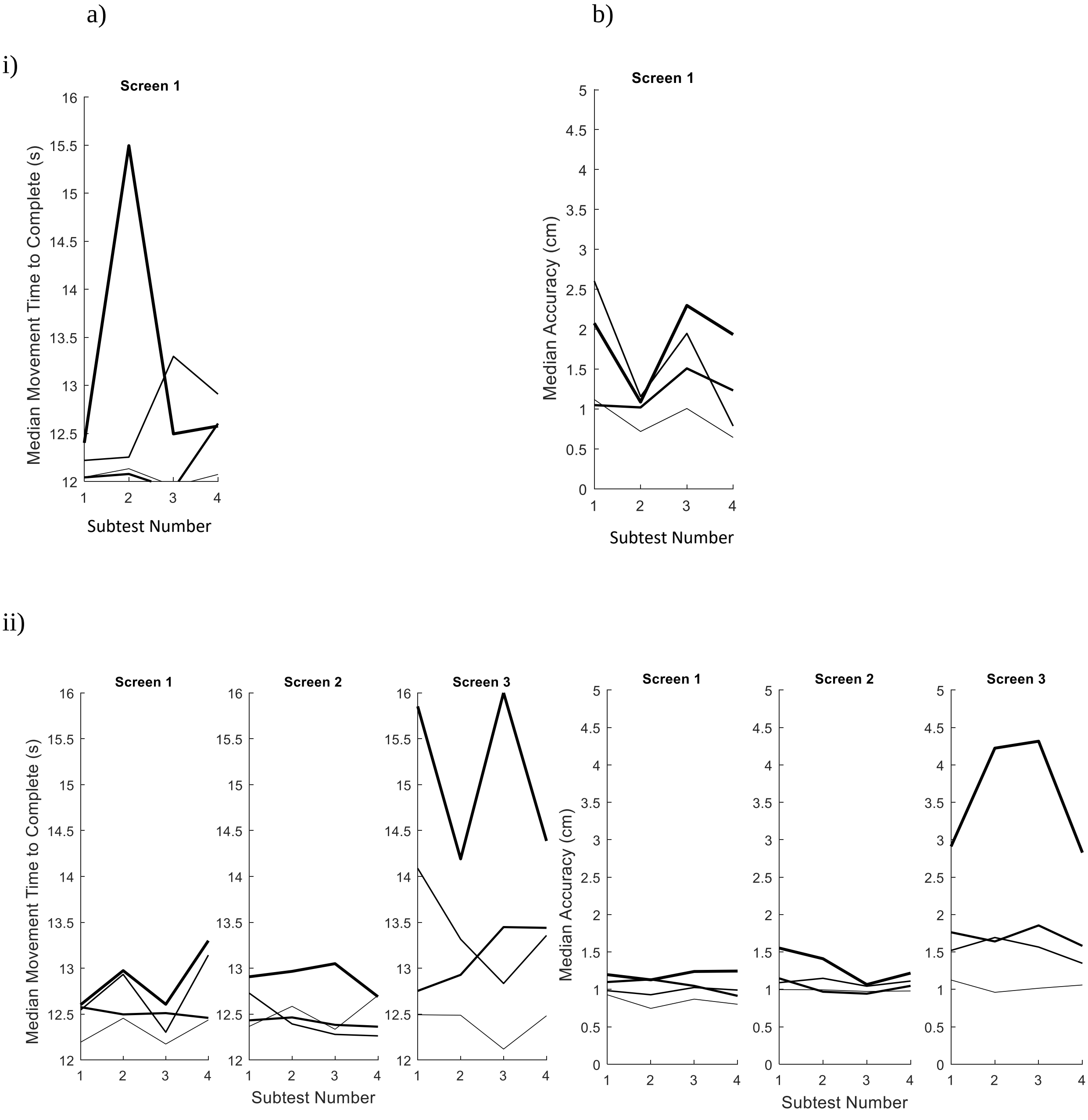


Figure 5 Median (a) movement times and (b) accuracy in ghost ball drag tests, across 4 subtests (where tracks were flipped horizontally and vertically to start and finish in alternate corners) and vibration conditions (control, light chop, light turbulence and moderate turbulence, shown with increasing line thickness) for (i) IRT centre screen (n=4) and (ii) PCT centre, side and overhead screens (centre n=21, side and overhead n=25) (IRT data indicative only due to small sample size).

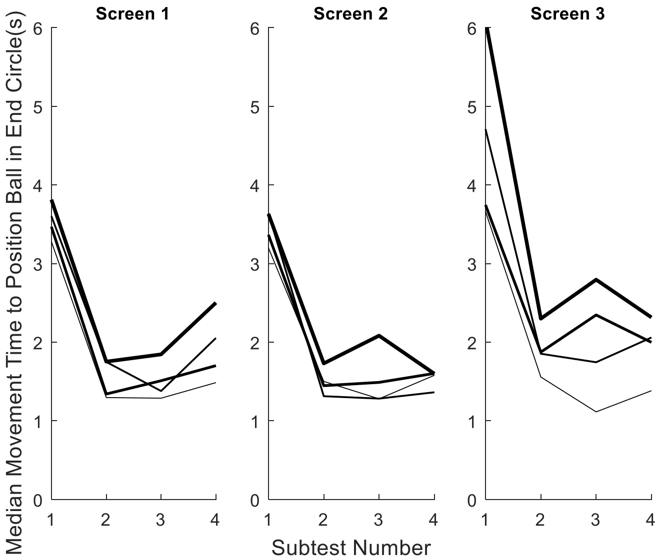


Figure 6 Median movement time between ball contact with the end circle and correctly positioning the ball within the final end circle, in ghost ball drag tests, across 4 subtests (where tracks were flipped horizontally and vertically to start and finish in alternate corners) and vibration conditions (control, light chop, light turbulence and moderate turbulence, shown with increasing line thickness) for PCT centre, side and overhead screens (centre n=21, side and overhead n=25).

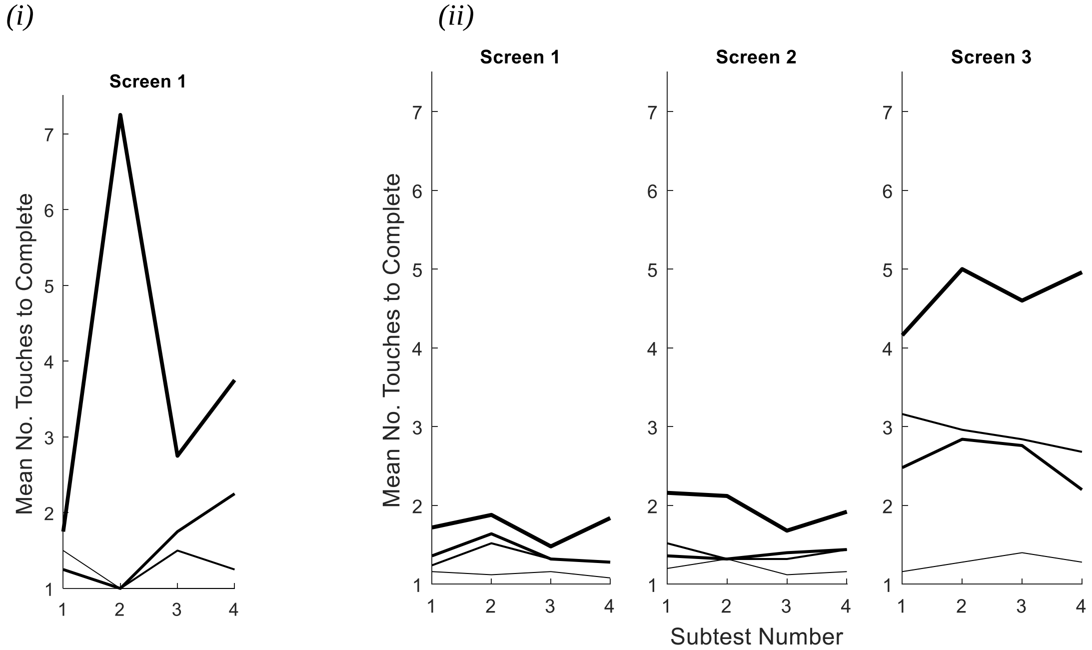


Figure 7 Mean number of separate touches required to complete ghost ball drag tests, across 4 subtests (where tracks were flipped horizontally and vertically to start and finish in alternate corners) and vibration conditions (control, light chop, light turbulence and moderate turbulence, shown with increasing line thickness) for (i) IRT centre screen (n=4) and (ii) PCT centre, side and overhead screens (centre n=21, side and overhead n=25) (IRT data indicative only due to small sample size).

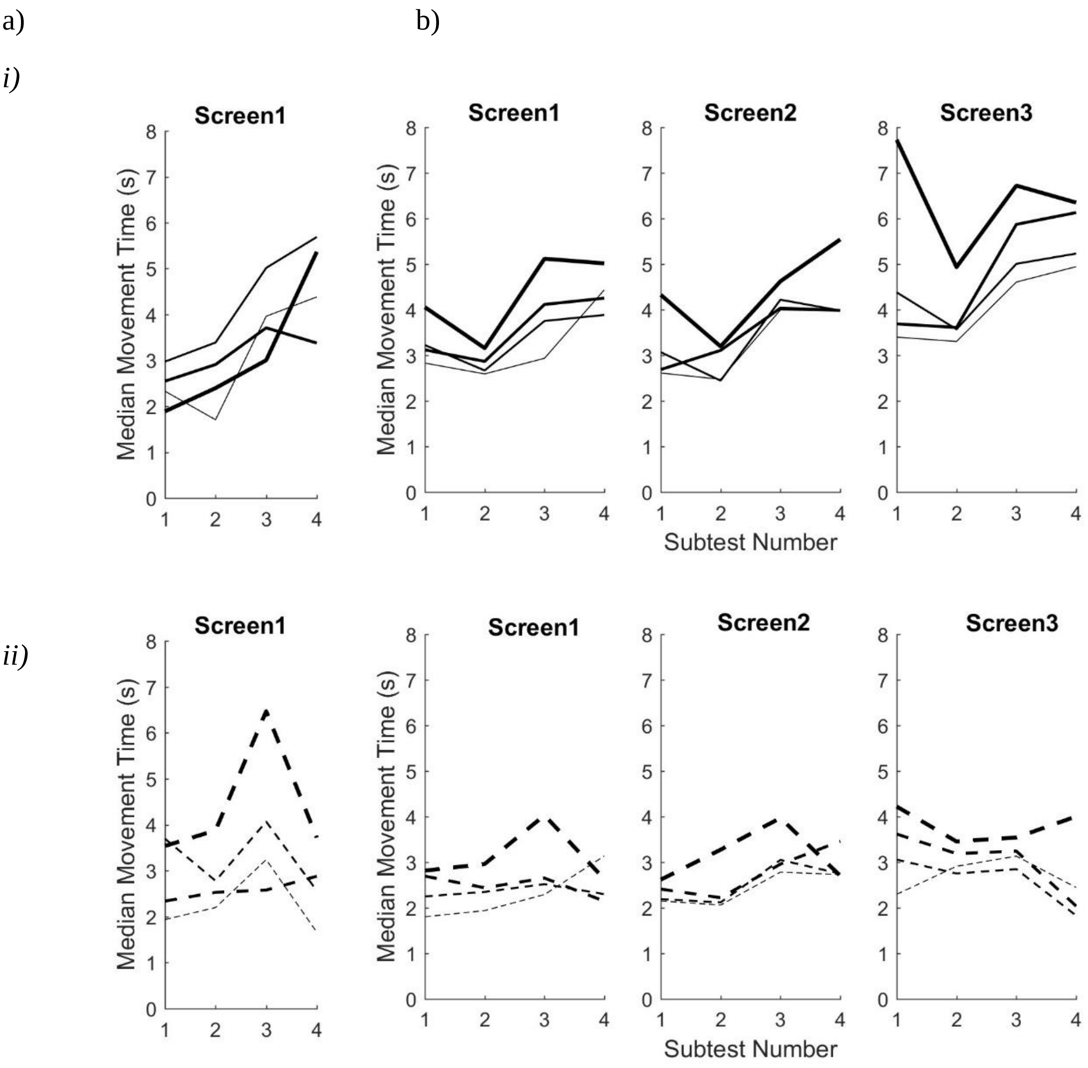
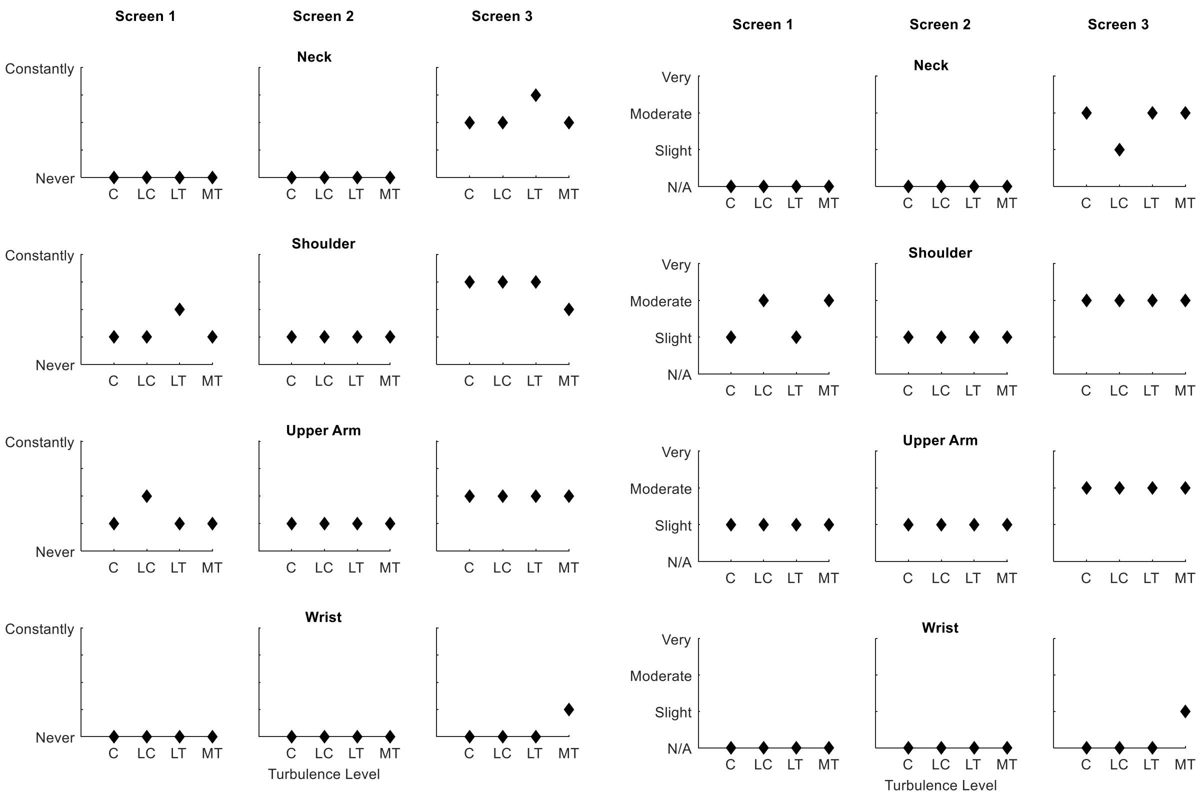


Figure 8 Comparison of median movement times in slider tests, across 4 subtests: vertical, horizontal and circular sliders and two finger pinch zoom and vibration conditions (control, light chop, light turbulence and moderate turbulence, shown with increasing line thickness) for (a) IRT centre screen and (b) PCT centre, side and overhead screens. Two sliders were presented for each slider type (i) 1st slider, starting in the 0% position, (ii) 2nd slider, starting in the 100% position (IRT data indicative only due to small sample size).

(a) (b)


Screen 1
Screen 2
Screen 3
Neck
Shoulder
Upper Arm
Wrist
Constantly
Never
Very
Moderate
Slight
N/A
C
LC
LT
MT
Turbulence Level

(c)

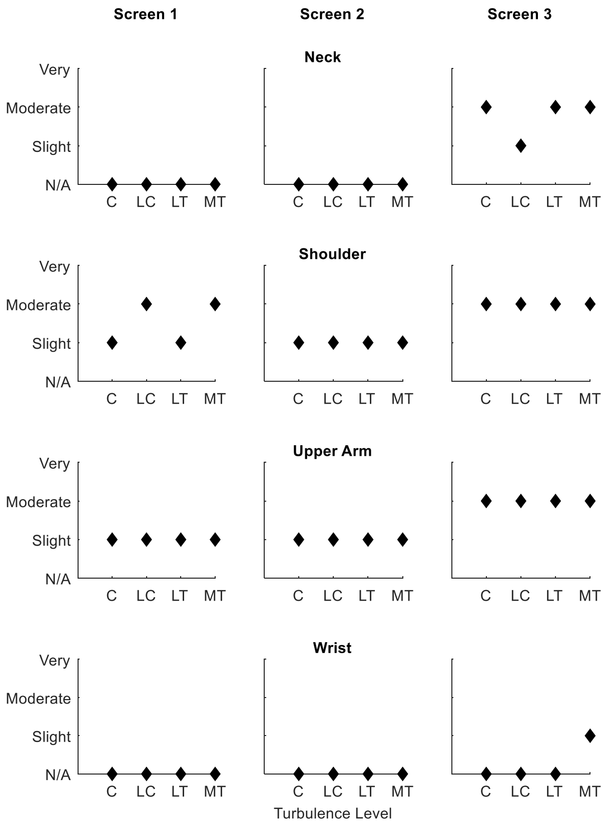


Figure 9 Median questionnaire scores (across participants) for (a) frequency of discomfort, ache and pain, (b) severity of discomfort, ache and pain, and (c) interference with the task (regions with median score of 'never' are not shown) for different levels of turbulence (C=control, LC= light chop, LT=light turbulence and MT=moderate turbulence)

<u>*System Usability Scale*</u>

Figure 10 shows the System Usability Scores for each touchscreen position for each vibration condition. There were no significant differences within each screen across vibration levels or across screens in the control (no movement) condition, however there was a significant effect of screen location for light chop ($F(2, 20) = 6.45$, $p < 0.01$), light turbulence ($F(2, 20) = 5.10$, $p < 0.05$) and moderate turbulence ($F(2, 20) = 5.17$, $p < 0.05$) conditions.

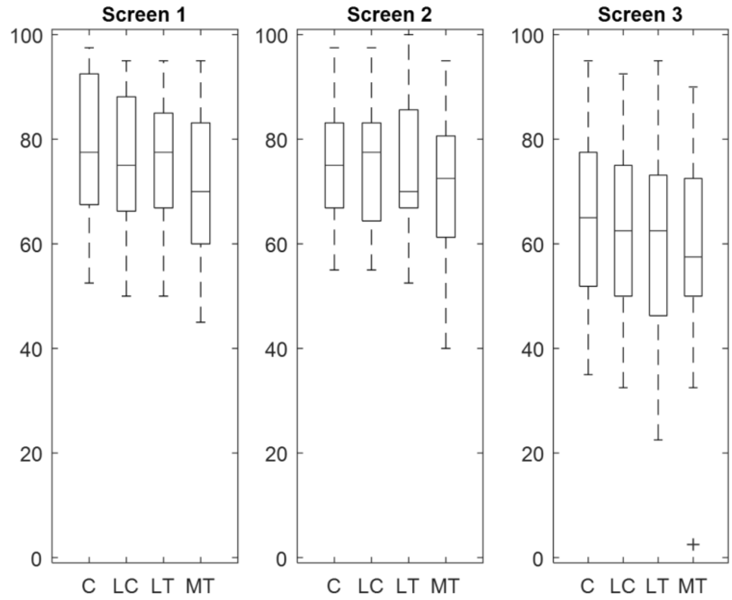


Figure 10 Box and whisker plot for System Usability Scale scores (across participants); C – control, LC – light chop, LT – light turbulence MT – moderate turbulence, for centre (screen 1), side (screen 2) and overhead (screen 3) screens

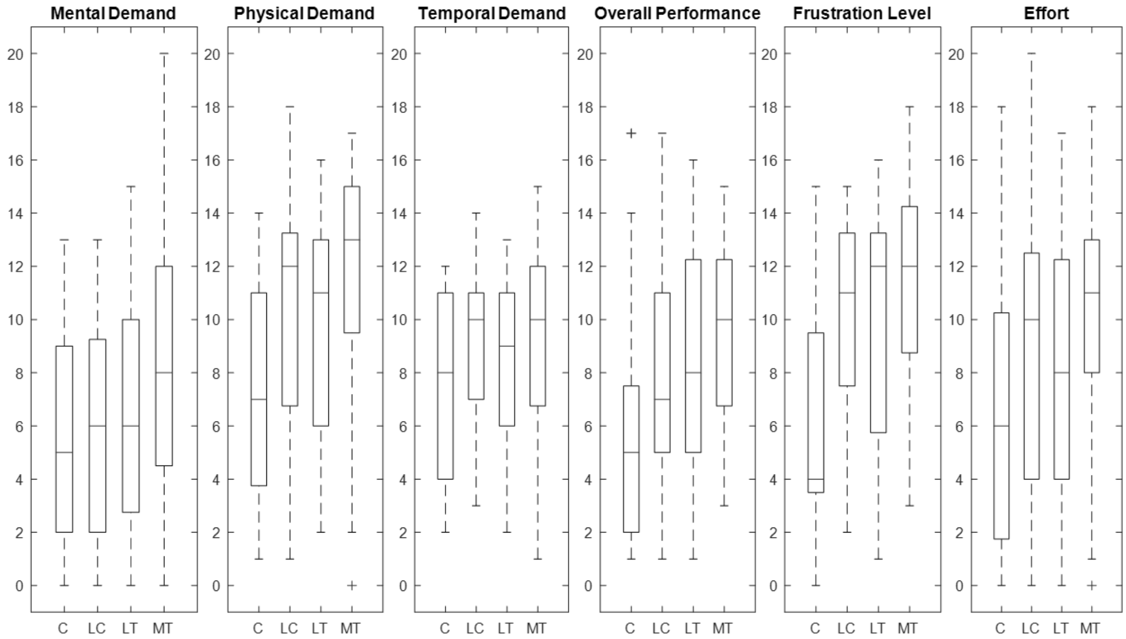
<u>*NASA-TLX*</u>

The NASA-TLX scores for each participant for each vibration condition on each screen are shown in Table 1 and Figure 11. There was a significant effect of vibration condition in the overhead ($F(3, 24) = 3.34$, $p < 0.05$) PCT screen, but not for the centre ($F(3, 20) = 2.84$, $p < 0.07$) or side ($F(3, 24) = 2.58$, $p = 0.08$). There was no significant effect of screen location for the control (no movement) condition, however there was for light chop ($F(2, 20) = 5.49$, $p < 0.05$), light turbulence ($F(2, 20) = 7.33$, $p < 0.005$) and moderate turbulence ($F(2, 20) = 6.81$, $p < 0.01$) conditions.

		Mental	Physical	Temporal	Performance	Effort	Frustration	Overall Workload
Centre	C	5	7	8	5	4	6	38
	LC	6	12	10	7	11	10	55
	LT	6	11	9	8	12	8	53
	MT	8	13	10	10	12	11	67
Side	C	5	8	6	5	9	5	45
	LC	5	12	8	7	10	6	52
	LT	6	11	9	8	11	7	57
	MT	6	12	9	10	12	12	65
Overhead	C	7	15	10	10	13	10	67
	LC	9	15	10	10	14	13	73
	LT	10	15	10	10	14	14	73
	MT	10	17	12	12	17	15	81

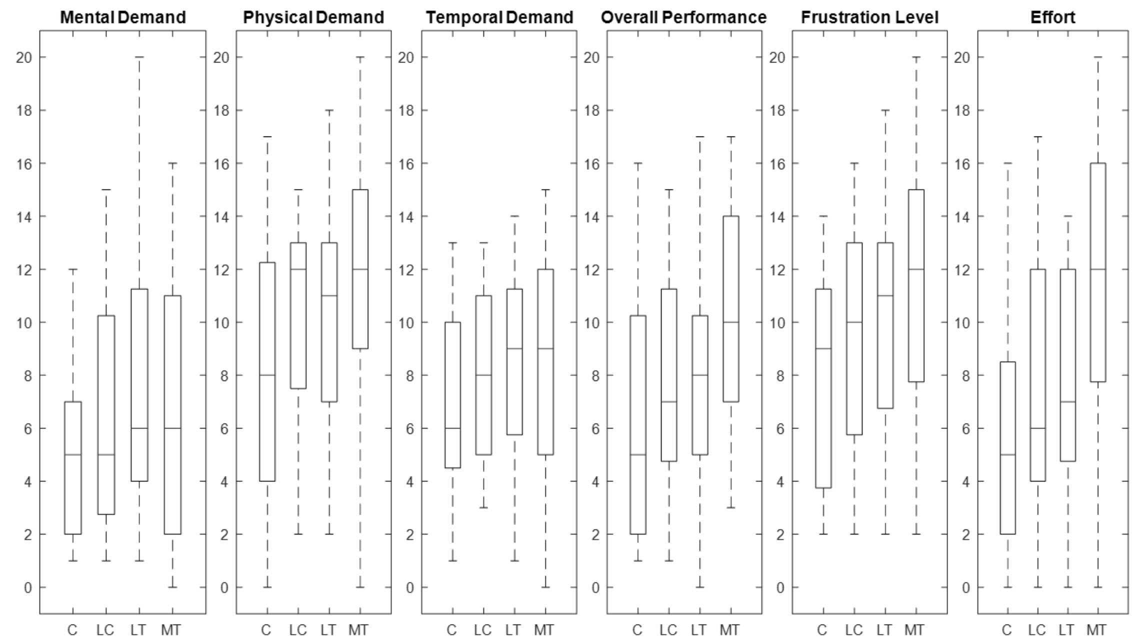
Table 1 Median NASA-TLX scores (across participants); C – control, LC – light chop, LT – light turbulence MT – moderate turbulence.

a)



Mental Demand
Physical Demand
Temporal Demand
Overall Performance
Frustration Level
Effort
0
2
4
6
8
10
12
14
16
18
20
C
LC
LT
MT

b)



c)

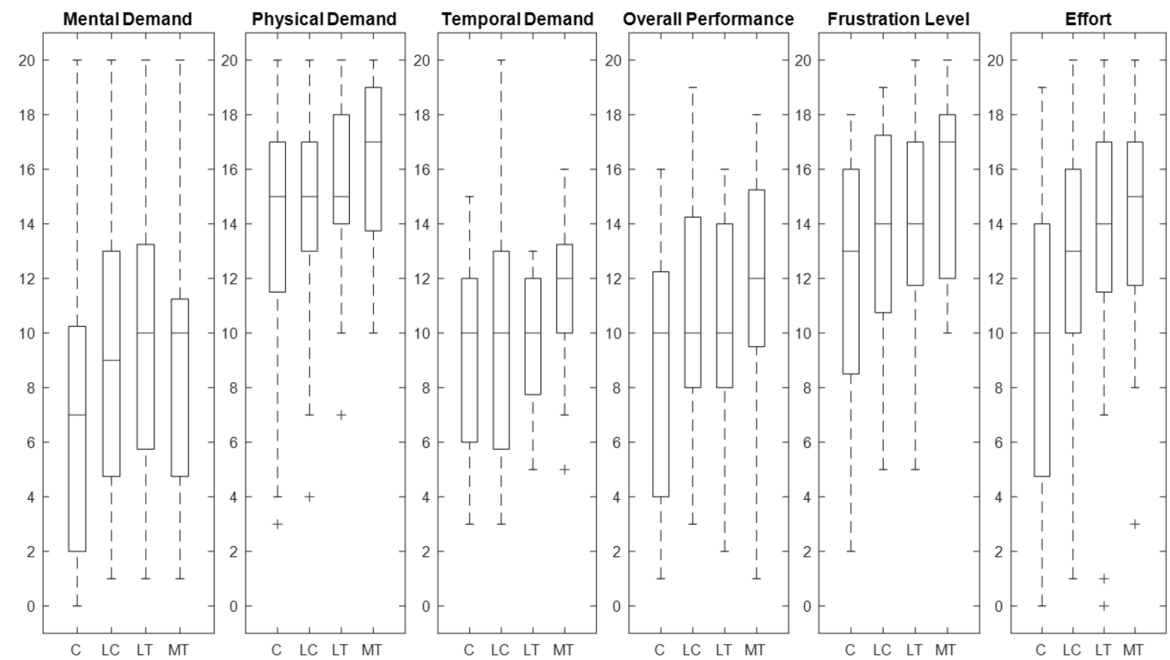


Figure 11 Box and whisker plot for NASA -TLX scores (across participants); C – control, LC – light chop, LT – light turbulence MT – moderate turbulence, for a) centre, b) side and c) overhead screens

Discussion

The aim of this study was to expand current understanding of touchscreen performance when subjected to turbulent mimicking vibration environments. For the dependent variables measured (movement time, accuracy and error rate) across the range of tasks assessed, as found by Cockburn et al. (2017), turbulence mimicking vibration has a significantly detrimental effect on performance. In particular the six hypotheses detailed in the introduction were tested and these are discussed in turn below. Fitts' law was further expanded, into a specific movement related law for aircraft vibration, also taking account of button size and proximity and its effect on error rate.

Hypothesis: Touch interaction in an operational flight deck can be implemented with an acceptably low interaction error rate

For all screens, locations and tasks: movement times and error rate generally increased and accuracy decreased significantly with vibration level, with the exception of the ghost ball accuracy on the side screen. Times and error rates for the light chop condition tended to be similar to the light turbulence condition which may reflect the similarity in range of vibration frequencies and magnitude and suggests that direction of movement is not as critical as the magnitude of the movement. Performance on the MDTT with small button sizes was generally poor, especially for both side and overhead screens, where it is likely the participants often did not realise they had successfully pressed the smaller buttons and should have moved onto the next one, possibly due to their finger obscuring the button. Errors were eliminated at larger button sizes where no movement was occurring. For the three non-stationary vibration conditions, error rate was reduced rather than eliminated by the use of larger button sizes and was still of the order of 10%, even in the centre and side screens. Touchscreen technology should not be implemented without confirmation for critical tasks, and possible effects on secondary task workload should be considered carefully before implementation.

A frequent observation by participants that did not show in the results was that on occasion presses would not always register on the side screen. The authors hypothesise that the issue may have arisen due to angle of the screen mounting; where a smaller angle would have been subtended for the side screen between the finger and the screen and would result in a larger finger press area on the screen, compared to a fingertip press for the other two screens. Whilst the overhead screen was mounted at the same angle, the issue was not apparent as the pressing finger was in a vertical rather than horizontal orientation. The performance on the side screen may improve if this issue was resolved and use of smaller button sizes should be more carefully considered for screens where there are smaller relative angles between finger and screen.

For the MDTT, there were several accidental presses on the edge of the screens where participants were using the edge of the screen to anchor their hand, however these erroneous presses are easily identifiable and can be rejected automatically in future software.

In summary, for non-stationary vibration conditions, interaction error rate was found to be generally high; therefore confirmation for critical tasks would be recommended when implementing in an operational flight deck.

Hypothesis: Touch interaction error rate in a turbulent flight deck environment can be reduced with the use of force sensing to confirm interactions

To determine whether unintentional presses could be minimised with the new force sensing technology in the PCT screen, the MDTT test was repeated with and without the requirement of the force threshold for successful tap (in addition to the requirement to press in the correct location). Participants quickly learnt the level of press required, and pressed above that force level for the majority of presses. Some erroneous presses were recorded where force was below the threshold, as shown in Figure 3, however despite these presses being automatically removed, the number of location incorrect erroneous presses was greater, for all conditions and screens, compared to non-force sensing MDTT tests (see Figure 2 b (ii) and (iii)). This suggests that the intentional increase in press force may lead to decreased accuracy of press location. Consequently, the force sensing function would appear to hinder user's performance rather than aid it, at the force level set for this study. Further investigation is recommended, to confirm whether this finding holds true for different force thresholds.

Hypothesis: The prototype implementation of force sensing on the touch is immune to the effects of vibration

Figure 3 (b) shows how the minimum force measured is fairly constant across different button sizes and tends to decrease with increasing level of vibration. The author's hypothesise that as force level only varies with vibration and not button size, the negative force values recorded are likely to be arising due to malfunction of the touchscreen unit, rather than differences in human performance. The surface layer of the screens have been found to bow under high levels of motion induced stress. Further investigation is required to ascertain the extent to which this is interfering with the system's ability to record press force accurately. This may in turn also be leading to the poor general performance in the force sensing tests and must be thoroughly investigated before any further optimisation tests are conducted using the systems force sensing capability.

Hypothesis: With a suitably positioned display, and with suitable hand anchor points, users can operate the touchscreen in representative vibration conditions without suffering undue arm fatigue or discomfort

An important consideration of this study was the location of the touchscreen in relation to the user. Increased levels of discomfort can arise where the user's arm needs to remain outstretched to interact with displays and it is was hypothesised that this discomfort would be elevated when operating under turbulent conditions. In comparison to the no movement control condition, there were no significant differences in discomfort found across turbulence mimicking conditions, indicating that discomfort was not further elevated where vibration was present, except for the wrist in the moderate turbulent vibration condition for the overhead screen. In general, discomfort was consistently reported for all vibration conditions (including the control condition) in the regions of the right shoulder and upper arm and the overhead screen in the neck. All other regions had a median value of no discomfort.

Discomfort was generally higher in the overhead screen compared to the centre and side screens. This arose due to experimental design, where the current system was not able to switch automatically between screens. This meant that the participants had to complete all tests and questionnaires in one go, for each screen in each vibration condition. For the overhead screen this was particularly challenging and difficult where workload increased (particularly physical demand, frustration and effort) and usability decreased and meant typically maintaining an arm up position for ten minutes or more. In a realistic flight deck situation, use of an overhead screen would usually be limited to use in the order of seconds rather than minutes. The authors would recommend that any future studies take account of this and a different configuration of test battery be set, to that of the other screens.

Hypothesis: Single tap gestures will be performed with lower error rates than drag or multi-touch gestures in a turbulent flight deck environment

The increasing number of touches required to complete the ghost ball task with increasing vibration (see Figure 7) indicates that it is difficult to maintain screen contact to undertake drag type tasks for a prolonged period whilst under turbulence mimicking vibration. The movement times for the slider task were generally higher than other tasks (see Figure 8), therefore single press tasks should be used where possible (such as tap or swipe tasks), rather than drag type touches (such as ghost ball and slider tasks, especially those requiring excessive time to accurately reach a final position), in order that movement times are kept to the order of 1 second and error rates are of the order of 25% or lower. The authors would also recommend an additional on-screen pop-up confirmation button be used where high turbulence is detected to ensure critical task selection is confirmed before the system acts on the input.

Expansion of Fitt's Law for Motion (e.g. Turbulence)

Similar to the findings of Dodd et al. (2014), error rate increased with turbulence mimicking vibration and rate of increase was greater as the touch target size was reduced. Therefore, for time critical tasks the authors would recommend that larger button sizes are employed. For non-time critical tasks, the authors investigated the potential of deriving an expanded version of Fitts' law (Fitts, 1954) that could be used to aid choice of button size in non-static conditions. Fitts' law was originally derived for static use, therefore the non-force sensing MDTT data recorded from this study were used to assess how the parameters within Fitts' law varied with different levels of motion. For this study, turbulence mimicking motion was recorded as r.m.s. weighted magnitude in $m.s^{-2}$.

Fitts' law states that the movement time (MT) will depend directly on the distance to be moved (D) and inversely with the size of the button (W) as shown in equation 1. Constants a and b are derived empirically.

$$MT = a + b \cdot log_2\left(\frac{2D}{W}\right) \quad \text{Equation 1}$$

For the MDTT used in this study, D was equal to 16cm and W varied from 1 to 3 cm. A new parameter, V, represents the r.m.s. weighted magnitude of the turbulence mimicking vibration in $m.s^{-2}$. Empirically derived values for 'a' and 'b', were then plotted against V (using data from all three touchscreens). A least squares linear fit was then used to derive Equations 2 and 3, allowing the variation of both a and b across different levels of motion to be calculated using:

$$a = -2.5\,V - 0.56 \quad \text{Equation 2}$$

$$b = 0.88\,V + 0.29 \quad \text{Equation 3}$$

The novel expansion of Fitt's law in Equation 4 includes the effect of motion on movement time and may be useful in several transport modalities, given the widespread recent prevalence of touchscreen use. Data from control and light and moderate turbulence conditions were used to develop this function, with light chop data excluded due to its different (uni-directional) behaviour, however the intention is that the accuracy of this expanded law may be further improved, as further empirical data becomes available.

$$MT = (-2.5V - 0.56) + (0.88V + 0.29) \cdot log_2\left(\frac{2D}{W}\right) \quad \text{Equation 4}$$

Conclusions

Previous studies have found that fixed touchscreen use tends to be more physically demanding and lead to more bodily discomfort (Stanton et al. 2013; Harvey et al. 2011) and suffer from higher error rates (Avsar, Fischer and Rodden 2015, Cockburn et al., 2017) than other input devices such as trackballs and touchpads (Lin et al., 2010; Yau, Chao and Hwang, 2008, Cockburn et al., 2017). However despite this, in a flight deck context, for all vibration conditions, the usability and workload appeared comparable to those reported from other input devices, for both the centre and side screens. Faster movement times and lower error rates were observed for the centre screen across all vibration conditions and the screen position causing least discomfort to use was the side screen.

Further study of touchscreen use in flight decks appears worthwhile, given their potential for integrating a large number of functions into a single system, enabling more efficient use of space and consistency of information presentation. A major disadvantage of touchscreens is that-slower interaction styles are likely to increase discomfort and touchscreens are therefore more suitable for tasks with high time pressure that are required to be performed quickly. The study has shown that it is possible to interact using short single presses with reasonable accuracy and low error rate, even under turbulent mimicking vibration conditions and longer interaction styles such as slider bars should be avoided. It may be possible to devise a combination of the two, for example allowing users to single press on specific slider bar locations, as an alternative to a sliding gesture, to allow the user to interact on a shorter time scale, should they choose. In addition to the recommendations for areas of further exploration in the context of aircraft flight decks made by the authors, whilst non-pilot participants were appropriate for the basic tasks assessed in this study, future study should be conducted with qualified pilots undertaking more realistic tasks, for example engine health or in flight checks, requiring multiple screen interaction.

The study supports results published by Cockburn et al. (2017), showing that touchscreens have potential in a flight deck environment, where performance under single presses with larger button sizes should be chosen over those with small button sizes or requiring prolonged contact; overhead screen use should be minimised and the mounting angle of the device should be optimised for both optimal viewing angle and finger orientation, to minimise contact area; confirmation of input selection should be required for all critical tasks especially at high levels of turbulence where errors are more prevalent; and finally, force sensing capability has potential to eliminate this input confirmation requirement, but its mechanical function and limitations under vibration must first be further investigated, especially to determine the optimum minimum force threshold level.

References

Avsar H, Fischer J, Rodden. "Target size guidelines for interactive displays on the flight deck." 34th Digital Avionics System Conference, Sep 2015.

Baldus, T., & Patterson, P. (2008). "Usability of pointing devices for office applications in a moving off- road environment." Applied Ergonomics, 39(6), 671-677. doi:10.1016/j.apergo.2008.01.004

Bender, G., T., 1999, "Touch Screen Performance as a Function of the Duration of Auditory Feedback and Target Size", PhD Dissertation, Wichita State University.

Bhalla, A. V. and Bhalla, M. R. 2010. "Comparative Study of Various Touchscreen Technologies." International Journal of Computer Applications, 6 (8), 12-18.

Bjorneseth, F. B., Dunlop, M. D., & Hornecker, E. 2012. "Assessing the effectiveness of direct gesture interaction for a safety critical maritime application." International Journal of Human Computer Studies, 70(10), 729-745. doi:10.1016/j.ijhcs.2012.06.001

Brooke, J. 1996. “SUS: A ‘Quick and Dirty’ Usability Scale.” In Usability Evaluation in Industry, edited by P. W. Jordan, B. Thomas, B. A. Weerdmeester, and I. L. Mcclelland. 1st ed., 189–194. London: Taylor and Francis.

BSI (British Standards Institution), 1987. “BS 6841: Measurement and evaluation of human exposure to whole – body mechanical vibration.” London.

Cockburn, A, Gutwin, C, Palanque, P, Deleris, Y, Trask, C, Coveney, A, Yung, M and MacLean, K. 2017. “Turbulent Touch: Touchscreen Input for Cockpit Flight Displays.” In Proceedings of the 2017 CHI, Conference on Human Factors in Computing Systems (CHI '17). ACM, New York, NY, USA, 6742-6753. DOI: https://doi.org/10. 1145/3025453.3025584

Dodd, S, Lancaster, J, Miranda, A, Grothe, S, DeMers B & Rogers B. “Touchscreens on the Flight Deck: The Impact of Touch Target Size, Spacing, Touch Technology and Turbulence on Pilot Performance.” Proceedings of the Human Factors and Ergonomics Society 58th Annual Meeting, 2014.

Dul, J., & Weerdmeester, B. 2001. “Ergonomics for Beginners: A Quick Reference Guide.” 2nd ed. London: Taylor and Francis.

Eichinger, A., & Kellerer, J. 2014. “Between laboratory and simulator: A cognitive approach to evaluating cockpit interfaces by manipulating informatory context.” Cognition, Technology and Work, 16(3), 417-427. doi:10.1007/s10111-013-0270-y

Federal Aviation Administration. 2011. “Advisory Circular 20-175 (AC 20-175). Controls for Flight Deck Systems. Aviation Safety” – Aircraft Certification Service, Aircraft Engineering Division. Washington, DC.

Fitts, P.M. 1954. “The information capacity of the human motor system in controlling the amplitude of movement.” Journal of Experimental Psychology 47 (6), 381–391.

Goode, N., Lenne, M. G., & Salmon, P. 2012. “The impact of on-road motion on BMS touch screen device operation.” Ergonomics, 55(9), 986-996. doi:10.1080/00140139.2012.685496

Graham-rowe, D., 2011. “Vibrating touchscreens that give you a push back” https://www.newscientist.com/article/mg21128216-000-vibrating-touchscreens-that-give-you-a-push-back/

Hancock, P. A., & Caird, J. K. 1993. “Experimental evaluation of a model of mental workload.” Human Factors, 35(3), 413-429.

Happich, J. 2015. “Force sensing touchscreen leverages projected capacitive technology” http://www.eenewseurope.com/news/force-sensing-touchscreen-leverages-projected-capacitive-technology

Hart, S. G., & L. E. Staveland. 1988. “Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research.” In Human Mental Workload, edited by P. A. Hancock, and N. Meshkati, 239–250. Amsterdam: North Holland Press.

Harvey, C., Stanton, N. A., Pickering, C. A. McDonald, M. & Zheng, P. 2011. “To twist or poke? A method for identifying usability issues with the rotary controller and touch screen for control of in-vehicle information systems.” Ergonomics, 54 (7), 609-625.

Hedge, A., Morimoto, S., & Mccrobie, D. 1999. “Effects of Keyboard Tray Geometry on Upper Body Posture and Comfort.” Ergonomics 42 (10): 1333–1349.

Hoffman E.R. & Sheikh, I.H. 1994. “Effect of varying target height in a Fitt’s movement task.” Ergonomics. 36(7), 1071-1088.

Kaminani, S. 2012. “Human Computer Interaction Issues with Touch Screen Interfaces in the Flight Deck”. 31st Digital Avionics Systems Conference, October 14-18.

ISO (International Organization for Standardization) 2010. ISO 9241 Ergonomics of human system interaction - part 210: Human-centred design for interactive systems. Tech. rep. Switzerland.

Lin, C. J., Liu, C. N., Chao, C. J., & Chen, H. J. 2010. “The performance of computer input devices in a vibration environment.” Ergonomics, 53(4), 478-490. doi:10.1080/00140130903528186

Lin, M.-L., Radwin, R. G., & Vanderheiden, G. C. 1992. “Gain effects on performance using a head-controlled computer input device.” Ergonomics, 35,159–175.

NASA (National Aeronautics and Space Administration). 1986. “NASA Task Load Index (NASA-TLX), Version 1.0: Paper and Pencil Package.” Moffett Field, CA: NASA-Ames Research Center, Aerospace Human Factors Research Division.

Noyes JM & Starr AF. 2007. “A comparison of speech input and touch screen for executing checklists in an avionics application.” The International Journal of Aviation Psychology, vol 17 (3).

Orphanides, A. K., & Nam, C. S. 2017. “Touchscreen interfaces in context: a systematic review of research into touchscreens across settings, populations, and implementations.” Applied ergonomics, 61, 116-143.

Pope, S. 2009. “Garmin G3000 Brings Touch Screen Tech to Flight Deck”, Avionics Magazine.

Rockwell Collins. 2016. “Boeing 777X to feature touchscreen flight displays from Rockwell Collins.” https://www.rockwellcollins.com/Data/News/2016-Cal-Yr/CS/FY16CSNR51-777x.aspx

Rogers, W. A., Fisk, A. D., McLaughlin, A. C. & Pak, R., 2005. “Touch a Screen or Turn a Knob: Choosing the Best Device for the Job.” Human Factors 47 (2): 271–288. http://www.ingentaconnect.com/content/hfes/hf/2005/00000047/00000002/art00005, http://dx.doi.org/10.1518/0018720054679452

Schwartz, N. & Adam, E. 1988. “Panoramic cockpit control and display system (PCCADS).” In Proceedings of the Joint GCP/FMP Symposium on Man-Machine Interface in Tactical Aircraft Design and Combat Automation, p.13-1 – 13-10. AGARD.

Shin, G., & X. Zhu. 2011. “User Discomfort, Work Posture and Muscle Activity while using a Touchscreen in a Desktop PC Setting.” Ergonomics 54 (8): 733–744.

Soukoreff, W., R., & MacKenzie, S., I., 2004. “Towards a Standard for Pointing Device Evaluation, Perspectives on 27 Years of Fitts’ Law Research in HCI”, International Journal of Human Computer Studies, 61, 751-789.

Stanton, N. A., Salmon, P. M., Walker, G. H., Baber, C. & Jenkins, D. P. 2005. “Human Factors Methods: A Practical Guide for Engineering and Design.” 1st ed. Aldershot: Ashgate.

Stanton, N. A., Harvey, C., Plant, K. L. & Bolton, L. 2013. “To Twist, Roll, Stroke or Poke? A Study of Input Devices for Menu Navigation in the Cockpit.” Ergonomics, 56 (4), 590-611.

Wang, X., & J. Trasbot. 2011. “Effects of Target Location, Stature and Hand Grip Type on In-Vehicle Reach Discomfort.” Ergonomics 54 (5): 466–476.

Wickens, C.D. Lee, J.D., Liu, Y., & Becker, G., S.E. 2004. “An Introduction to Human Factors Engineering.” Pearson Prentice Hall, Upper Saddle River, NJ.

Williams, P.D. 2017. “Increased light, moderate, and severe clear-air turbulence in response to climate change”. Advances in Atmospheric Sciences, Volume 34, Issue 5, 576–586

Yau, Y., Chao, C., & Hwang, S. 2008. “Effects of input device and motion type on a cursor-positioning task.” Perceptual and Motor Skills, 106(1), 76-90. doi:10.2466/PMS.106.1.76-90.