Design and evaluation of braced touch for touchscreen input stabilisation

A. Cockburn[*,a], D. Masson[b], C. Gutwin[b], P. Palanque[c], A. Goguey[b], M. Yung[d], C. Gris[e], C. Trask[d]

[a] Computer Science, University of Canterbury, Christchurch, New Zealand
[b] Computer Science, University of Saskatchewan, Saskatoon, Canada
[c] ICS-IRIT, Universite Paul Sabatier Toulouse 3, Toulouse, France
[d] Ergonomics Lab, University of Saskatchewan, Saskatoon, Canada
[e] Airbus Operations, Toulouse, France

Keywords:
Touch interaction
Vibration
Turbulence
Target selection
Aviation
Vehicles

A B S T R A C T

Incorporating touchscreen interaction into cockpit flight systems offers several potential advantages to aircraft manufacturers, airlines, and pilots. However, vibration and turbulence are challenges to reliable interaction. We examine the design space for *braced touch* interaction, which allows users to mechanically stabilise selections by bracing multiple fingers on the touchscreen before completing selection. Our goal is to enable fast and accurate target selection during high levels of vibration, without impeding interaction performance when vibration is absent. Three variant methods of braced touch are evaluated, using doubletap, dwell, or a force threshold in combination with heuristic selection criteria to discriminate intentional selection from concurrent braced contacts. We carried out an experiment to test the performance of these methods in both abstract selection tasks and more realistic flight tasks. The study results confirm that bracing improves performance during vibration, and show that doubletap was the best of the tested methods.

1. Introduction

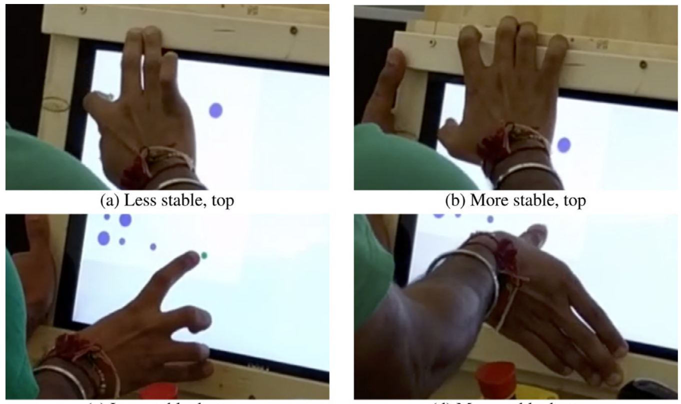
Commercial aircraft cockpits currently make extensive use of computer displays for system output to the pilot, and input is separately provided through a wide array of devices, including joysticks, trackballs, dials, switches, levers, and buttons. In contrast, through the use of touchscreens, input and output could be co-located, offering several potential advantages for aircraft manufactures and operators. In particular, cockpit flight systems could be updated by modifying the touchscreen user interface, without the prohibitive expense of reconfiguring and rewiring hardware cockpit panels. Other touchscreen advantages include reduced space and weight, as well as potential for eased operation. Consequently, many commercial and military aircraft manufacturers are investigating touchscreen interaction in the cockpit (ARINC661, 2016; Komer et al., 2013; Mark Fletcher, 2010; Zammit-Mangion et al., 2011).

Air turbulence and other causes of aircraft vibration, such as taxiway roughness, are a challenge for the potential use of cockpit touchscreens. When using physical controls, the pilots' hands are stabilised through contact or grip, but touchscreens do not offer equivalent means for mechanical stabilisation, causing errors. A previous study of touchscreen interaction during simulated turbulence showed that users relied on the bezel edge surrounding the touchscreen for hand stabilisation during vibration (Cockburn et al., 2017), as shown in Fig. 1. Users spanned their fingers to targets from the bezel, keeping some fingers on the bezel while one digit reached to the displayed content (typically the index finger or thumb). A firm grasp on the bezel improved accuracy, although this sometimes required awkward hand postures (e.g., Fig. 1d).

Although spanning the hand from the bezel edge can improve stabilisation, it has several important limitations. First, on large displays many areas of the touchscreen will be inaccessible via spanning. For example, if the fingers are placed on the top bezel edge as shown in Fig. 1b, then the thumb will be unable to reach targets that are further than ≈ 13 cm from the top of the display. Yet large displays are desirable in the cockpit to accommodate concurrent subsystem display (e.g., the F-35 Lightening II includes a 50×20 cm touchscreen, and larger sizes would be desirable in passenger aircraft). Second, stable bezel edge bracing often requires moving the hand into awkward postures (e.g., Fig. 1d). Third, users may be forced into completing selections with non-preferred and sub-optimal digits because their fingers/thumb are dedicated to stabilisation (e.g., Fig. 1b). Fourth, certain

* Corresponding author.
E-mail addresses: andy@cosc.canterbury.ac.nz (A. Cockburn), damien.masson@etudiant.univ-lille1.fr (D. Masson), gutwin@cs.usask.ca (C. Gutwin), palanque@irit.fr (P. Palanque), alix.goguey@usask.ca (A. Goguey), may085@mail.usask.ca (M. Yung), christine.gris@airbus.com (C. Gris), catherine.trask@usask.ca (C. Trask).

https://doi.org/10.1016/j.ijhcs.2018.08.005



(a) Less stable, top
(b) More stable, top
(c) Less stable, bottom
(d) More stable, bottom

Fig. 1. Bezel edge bracing at top and bottom of the display. Left, less stable grasps; right, more stable grasps.

forms of interaction are largely incompatible with bezel edge stabilisation – for example, pinch-to-zoom may be impractical when multiple fingers are grasping the display edge.

One obvious reason that users rely on the bezel for stabilisation is that it is not part of the touch-sensitive surface – users currently have no option for stabilisation other than to use areas off the touchscreen, because placing their fingers on the touchscreen would lead to unintended selections or interface actions. However, the multi-touch sensing capabilities of touchscreens could enable new forms of interaction that allow stabilisation through hand-bracing on the touch surface itself, as suggested in Fig. 2.

This paper describes the design and evaluation of new touchscreen interaction methods that allow the user to achieve mechanical stabilisation by bracing multiple fingers on the touchscreen before completing selection with further contact information. By allowing users to place stabilising fingers onto the display surface, we intend to overcome the four limitations described above – the full area of the touchscreen is available for interaction; the need for awkward postures is substantially reduced; the user is free to complete selections with whichever digit they prefer; and the full range of touch interactions are possible. Furthermore, the braced interaction methods that we describe are designed to be compatible with non-braced counterpart methods, allowing users to make selections that are mechanically stabilised during turbulence, while also allowing for unstabilised normal interaction during level flight.

After reviewing prior research on touchscreen selection methods, cockpit touchscreen systems, and vibration tolerance, we present a design framework analysing design considerations for braced touch, leading to a description of three candidate methods that differ in the criteria used to determine completion of a selection gesture – doubletap, dwell, and force threshold. We then describe our three experimental tasks, which were used to compare performance and preference with braced and unbraced selections with the three methods. All three tasks were conducted in conditions of no vibration and high vibration using a motion platform. The first task examined braced and unbraced performance during a batched sequence of target selection activities using a method similar to the ISO 9241-9 Fitts' Law standard Soukoreff and MacKenzie (2004). The second task examined performance during simulated in-flight tasks that involved responding to warnings concerning the auxiliary power unit (these tasks were adapted from the training manual of the Airbus A350). The third task again used abstract target selections, but with the selection hand returning to the flight stick between selections, and with subjects free to choose whether and how to brace their hand during selection.

Results showed that during vibration, bracing significantly reduced selection times in comparison to unbraced selections. The doubletap selection method was much faster, more accurate, and preferred to the dwell and force-threshold selection methods, and when using a bracing

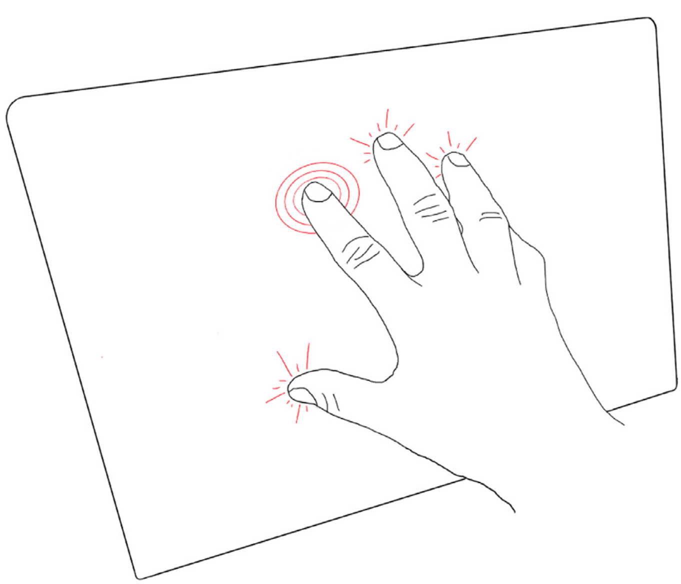


Fig. 2. Finger bracing. The hand is stabilised by placing multiple digits onto the touchscreen. Selection criteria such as doubletap or force threshold then determine the action required to select an object.

posture with doubletap wrong-target and false-negative errors were reduced in comparison to single finger selections. When subjects were free to choose between braced and unbraced selections, the strong majority (75%) chose to use bracing during vibration, and the same majority (75%) chose to use single finger selections when vibration was absent (as expected).

Our work makes three main contributions. First, we set out a design space for braced touch that covers the goals of minimising error rate, ensuring compatibility with standard touch techniques, working with any interface layout, and maximising coverage of the touchscreen. Second, we provide empirical evidence that braced touch can provide significant performance benefits during vibration, without unduly increasing effort or error rate. Third, we demonstrate differences between the selection methods, suggesting the superiority of doubletap.

2. Related work

Three main areas of previous research influence our work on braced touch – touchscreen selection methods, touchscreens in the cockpit, and methods to improve vibration tolerance during touchscreen interaction.

2.1. Touchscreen selection methods

Interface designers need to consider the criteria that will be used to determine a successful touchscreen gesture for selecting an item, and many different criteria are available, even for relatively simple tap-based selections. These criteria include the location of initial or terminating contact, the timing and/or repetition of actions, and the force or pressure applied during contact. For more complex stroke-based selections, further criteria might include gesture shape, movement speed or acceleration, and displacement distance. The studies reported in this paper are primarily directed at tap-based selections, and readers interested in issues associated with the design of stroke gestures are directed to a review by Zhai et al. (2012).

Early studies of touchscreen interaction compared user performance in target selection tasks when different terminating criteria were used, with alternatives including first-contact, slide-over, and lift-off (Potter et al., 1988; Ren and Moriya, 2000). These studies agreed that lift-off is an accurate method (with finger and stylus), partially because it allows the user to refine their contact location before the selection is completed.

More recently, multitouch capabilities have extended the range of interaction possibilities, allowing new forms of gestures to be recognised (e.g., Rekimoto, 2002). However, increasing the expressiveness of the gesture vocabulary also increases the potential for software to misinterpret the user's intention, potentially causing one type of gesture to be identified when another was intended. Among these problems are the risks that an unintended contact may alter or disable the meaning of a concurrent intentional contact – for example, when holding a mobile device, a finger might accidentally rest on the touch sensor, potentially causing the misinterpretation of a tap as being part of a pinch gesture; alternatively, when using a stylus the edge of the hand might accidentally contact the display, causing recognition errors. Methods to discriminate intentional contacts from unintentional ones are described in a variety of research papers (e.g,. Schwarz et al., 2014) and patents (e.g., Westerman, 2015).

Beyond accidental contacts, academic and industry researchers have also examined methods for identifying and tracking the digits associated with multiple concurrent contacts. Westerman's Ph.D. thesis (Westerman, 1999) provides an early analysis of problems and solutions in multi-touch, leading to many patent filings when he commercialised his work through FingerWorks (later acquired by Apple). The problems of identifying and interpreting the meaning associated with multiple concurrent contacts can be eased if the system has richer information about which hand/fingers are causing the contacts, and Wang et al. (2009) describe a method for extracting this information based on the orientation of contacts as they land on the touch surface. Multitouch frameworks such as Proton++ Kin et al. (2012) can provide further support for helping the designer to discriminate between multiple concurrent contacts from different users (e.g., on tabletop surfaces).

In recent work, Surale et al. (2017) experimentally analysed performance with several touch-based methods for varying selection mode; the analyses were conducted in sitting and standing postures. The analysed methods included long-press, confirmation gesture from the non-dominant hand, two-finger press, hard press, knuckle press and thumb-on-finger. Results showed that performance was similar whether sitting or standing, and that two-finger press was fastest and long-press slowest.

While these systems could assist the development of methods for recognising braced selections, they do not provide insights into whether bracing on the touchscreen surface is a viable method for touch interaction during heavy turbulence.

2.2. Cockpit touchscreen interaction

Proposals for the use of touchscreens in commercial cockpits, as well as general reviews of the issues associated with doing so, are presented by Hamon et al. (2014) and by Kaminani (2011). Several empirical studies have suggested that incorporating touchscreens into the cockpit environment could offer advantages over other input devices. Stanton et al. (2013) examined the comparative performance of four different types of input device (trackball, rotary controller, touchpad and touchscreen) for in-flight menu navigation, concluding that the touchscreen offered the best overall performance across a variety of measures. Thomas (2017) recently analysed pointing performance using a Fitts' Law methodology, comparing a hand-on-throttle-and-stick (HOTAS) isotonic pointing fingerstick with three input devices – trackball, trackpad, and touchscreen. Results suggested that the HOTAS had weaker performance than the other input methods, although he speculated that the HOTAS may have advantages during turbulence due to its support for mechanical limb stabilisation. Lewis (2015) examined left- and right-handed targeting performance using trackpad and touchscreen input devices in a cockpit setting, concluding that the touchscreen was faster. Barbé et al. (2012) examined ergonomic aspects of cockpit touchscreen placement, and Avsar et al. (2016a) reviewed ergonomics of touchscreen electronic flight bags in search and rescue helicopters. However, none of these studies examined the influence of turbulence or vibration on touchscreen interaction.

2.3. Touchscreen interaction during vibration

Uncontrolled vibrations during input may arise from external sources, such as aircraft turbulence, or from internal causes, such as nervous tremor. Wobbrock's EdgeWrite system used a mechanical means to help users with tremor to enter text on a mobile device Wobbrock et al. (2003). It allowed users to press a stylus against the raised edges or corners of a small square stencil-hole that was on the touchscreen surface. By dragging and pressing the stylus against a series of corners and edges, users with motor impairments could achieve faster and more accurate text entry than possible with other means.

Rather than using mechanical means to stabilise input, software methods can also be used. Kolbe Kolbe (2013) describes a method in which various heuristics are used to infer whether a touchscreen contact was intentional when the contact was preceded by a vibration. The heuristics include measures such as determining that the contact was unintentional if the contact area was greater than 1.5 times the area of a fingertip. Another approach involves posting a popup dialogue box for confirmation of intention when an interaction is immediately preceded by a vibration Williams et al. (2014). In another approach, Mott and Wobbrock Mott and Wobbrock (2014) used the kinematic characteristics of cursor movement to infer the intended target in a dense target environment.

Several patent applications have disclosed mechanical methods that are intended to reduce problems of cockpit touchscreen interaction during turbulence. Gannon (2012) describes a method in which the touchscreen is surrounded by a bezel that includes a recessed elastomeric ditch into which the fingers can be placed to stabilise the hand. Similarly, Thomas et al. (2017) describe a method in which the bezel is augmented with a raised and sliding 'bracing index' onto which the fingers or thumbs are placed. However, bezel-based approaches have limitations, including their constraint to small displays, as described earlier.

In a proposal more closely aligned with our own studies, Kawalkar (2012) describes a method for selectively rejecting any of several concurrently registered contacts. Part of their intention is to allow hand stabilisation by placing digits onto the display. Their method for determining which object the user intends to select includes the use of gaze direction (i.e., eye-tracking) – a contact that does not occur in combination with directed eye-gaze on the object would be rejected.

Relatively few published studies have empirically investigated touchscreen interaction during aircraft turbulence, although there have been some studies of touchscreen interaction in ships, which have much lower levels of motion-induced acceleration (Lin et al., 2010; Yau et al., 2008). Bauersfeld (1992) compared lift-off and confirm-on-contact target selection criteria during simulated aircraft turbulence, with results supporting earlier findings showing the superiority of lift-off (Potter et al., 1988). Avsar et al. (2016c) examined the impact of simulated constant high G-forces on touchscreen pointing performance, showing that pointing performance deteriorated when weighted bags were attached to subjects' wrists. Studies by Dodd et al. (2014) showed that when compared to no turbulence, moderate levels of simulated turbulence increased touchscreen data entry times, error rates, fatigue, and perceived workload. Finally, Cockburn et al. (2017) showed that during high levels of simulated turbulence, the accuracy of small target selection on touchscreens could be improved by using a stencil overlay on top of the touchscreen. The stencil, which prohibited contact registration in most areas, had holes cut through it to match the location of targets on the touchscreen. Although the stencil essentially prohibited missing targets, it also caused an increase in accidental contacts due to the finger 'bouncing' on the touchscreen as the finger was lifted off the surface.

3. Braced touch: goals and design

The primary design concept motivating this research, as depicted in Fig. 2, is that during vibration users will be able to stabilise touch input by concurrently placing multiple fingers onto the touchscreen surface, and that by doing so they will be able to achieve more accurate and faster selections. The design and evaluation of our braced touch interaction techniques was guided by four main design goals, described in the following subsection. We then describe some of the parameters that could be used within selection methods to attain these goals.

3.1. Design goals

Goal 1: Minimise error rate

Without stabilisation, touchscreen error rates will increase during vibration (Bauersfeld, 1992; Cockburn et al., 2017; Dodd et al., 2014). Errors during touchscreen interaction include the following three types, which are separately analysed in our studies.

Wrong target – the user selects a control that is different to the one intended. This will cause the system to enter an unintended state, and the intended action will not occur, both of which could have serious consequences during flight.

Right target, wrong action – the system registers an event on the intended target, but the event differs from the one intended. For example, the system registers a swipe event when the user intended a tap.

False-negative – the user's attempt to select an item accidentally occurs outside the boundaries of the intended target, falling on 'dead space' with no change to the system state.

Goal 2: Compatible braced and unbraced selection methods

Braced selections are only necessary to stabilise input during periods of vibration and turbulence, so during smooth flight, pilots should be able to interact with the touchscreen in a convenient manner, without bracing. It is therefore important that the selection methods used for braced selections should be similar to, and compatible with, those used for normal single finger unbraced selections. This similarity should ease the pilot's learning burden (due to method consistency) and reduce opportunities for the mode errors that might occur if the selection methods were different.

Goal 3: Agnostic to the UI state

The braced selection mechanisms should not depend on any assumed layout of the touchscreen user interfaces. Previous work for stabilising touch input has used methods such as physical stencils that were overlaid on top of the touchscreen, with holes cut through the stencil at the location of candidate interface items (Cockburn et al., 2017). While this approach reduced *false-negative* errors, the physical stencil layout could only match a single user interface layout, and a different stencil would be required if the user interface changed, as occurs in cockpit multifunction displays (MFD). Our design of braced touchscreen selection methods only considers solutions that are agnostic regarding the interface layout, therefore permitting interaction with any user interface within a cockpit MFD.

Goal 4: Maximise coverage of the touchscreen

As stated in the introduction, if the fingers are used to grasp a bezel, then the thumb can only reach targets within a limited span range into the display (approximately 13 cm). Furthermore, some areas of the display will be awkward to reach, particularly at the bottom of the display (e.g., Fig. 1d). The fourth design goal is therefore that braced selection methods should be usable across all regions of the touchscreen.

3.2. Selection parameters for braced touch

When successfully designed, touch-based interaction can appear simple, intuitive and 'natural' to the user (Shneiderman, 1987; Wigdor and Wixon, 2011). However, designing the gestures required for touch-based interaction is complex, involving consideration of multiple parameters, even for relatively mundane item selections. Among the important factors that a designer must consider are the following: (1) criteria for initiating a selection; (2) permissible actions between initiation and termination; (3) final criteria for completing the selection. Designing these requirements is particularly challenging when considering compatible braced and unbraced item selections.

3.2.1. Initiation: contact on target versus dragged entry

Touch selections can be permissive in allowing users to make contact with the display at a location that is initially off the ultimately selected item. Alternatively, a more strict selection criteria requires that the initial contact must lie within an item for it to be selected. Both of these policies are sometimes implemented within the same user interface component – for example, the iPhone virtual keyboard permits dragged entry for letter selection, but forbids it for selection of the backspace and return keys.

In a vibrating environment, permitting dragged entry has some appeal because users could initially place their finger onto the display (possibly off the target), then use that contact to gain pointing stability on the display, and subsequently drag their finger onto the intended target. However, dragged entry is also potentially risky in a safety-critical setting because the dragging action could represent an unintended movement off the desired target (potentially resulting in a 'wrong target' error). As our first goal is to minimise errors, all three of our candidate methods require that contact is initiated within the boundaries of the ultimately selected item.

3.2.2. Permissible actions: range of movement

As for initiation, a range of policies are possible regarding the range of movement permitted prior to completing a selection, and commercial applications demonstrate varied policies even within a single component. For example, icon selection on the iPhone 7 homescreen normally permits little movement, but if a low-level force threshold is exceeded, then dragging away from the item is permitted prior to selection.

For vibration-tolerant selections in the cockpit, a trade-off exists between the desire to allow some movement instability due to vibration and the need for stringent criteria to enhance safety-critical operation. As minimisation of errors is our first goal, all of our evaluated methods disallow any movement beyond the edge of the target.

3.2.3. Final criteria: release, duration, force, repetition

In considering the final criteria for confirming a selection, we wanted methods that would indicate a high degree of intention from the user (i.e., a very deliberate action that was unlikely to occur by chance during vibration). For each of the following criteria considered, we assumed that the event would have to occur within the bounds of the candidate item.

Release. Lifting off the touchscreen is probably the most widely used method for item selection. However, in a safety-critical vibrating environment, selection on release could create significant risks of accidental selection due to one or more fingers 'bouncing' on the display.

Duration. Another common method for reducing accidental selection is to require that an action be maintained for longer than a timeout period. For example, the iPhone's icon reconfiguration mode is only activated if the user maintains stationary contact with an icon for longer than $\approx$ 500 ms.

Force. Recent touchscreens, such as the iPhone 7, are capable of estimating the force applied by finger contacts. This could be used to complete selection only when a force threshold has been exceeded.

Repetition. Any of the above criteria for final selection could be combined with repetition to reduce accidental activation. For example, rather than finalising selection after a single release event, the user might need to repeat the action within a certain timeframe – for example, two releases (i.e., doubletap) within 300 ms, or two positive force pulses.

Finally, any of these selection criteria could be used in combination: e.g., a repeated and held force threshold.

3.3. Braced/Unbraced selection methods

Based on our design goals and considerations, we iteratively designed and tested several versions of compatible braced/unbraced selection methods. Our studies reported below focused on three alternative methods that differed only in the criteria used for finalising item selection – *doubletap* (release + repetition), *dwell* (duration + release), and *force* (force, without need for release). The criteria for initiating selection and the permissible actions before the final selection were identical for the three methods – the initial contact had to be made on the item, and any movement outside the bounds of the item cancelled the selection.

Fig. 3 shows a simplified state transition diagram for single finger and braced selections: states show the number of finger contacts on the display, and transitions show user actions and selection events. Single finger selections occurred when the only finger in contact with the display was released while over a target (at transition 2 in the figure).

Braced selections, at transition 6, could only be achieved after five or more fingers were placed on the display (after transition 5 in the figure), and only if the selection criteria were satisfied at transition 6 (described further below). All three variants of braced selection methods (doubletap, dwell and force) conformed to the state chart, and they all used identical heuristics for determining which digit was making the selection, as follows. When five or more contacts were concurrently on the display, the selection criteria for transition 6 were only applied to the most recently placed contact. The user could therefore place two or more digits on the display for stability and move them over the display without substantial risk of completing an accidental selection; only the last placed of five or more concurrent contacts on the display (normally the index finger) was used to determine whether the selection criteria for transition 6 were met. Subsequent braced selections could be made without lifting the other fingers from the display, allowing users to drag their fingers from target to target and complete selections by placing/tapping an additional finger (normally the 5th finger) on the display. Note that Fig. 3 is over-simplified in two ways. First, with the force method, releasing the finger was not necessary to satisfy the braced selection criteria at transition 6. Second, the figure shows transitions for each finger being separately lifted from the display (i.e., transitions 2, 4, 6 and 8); however, if the user was to lift all fingers at once (or a group of fingers) then the corresponding series of single finger transitions would occur.

To prevent accidental target selections at transition 2 when the final finger is lifted after an intentional target selection at transition 7, we implemented a minimum 1 s timeout between two successive selections of the same target. This timeout was also intended to reduce accidental selections during finger lift-off when vibration causes finger bounce on the display (observed in previous studies (Cockburn et al., 2017)).

The three methods evaluated in our studies were near identical in their use of these criteria. Their only differences were in the terminating selection criteria, as described below.

Doubletap. Two taps on an item within 500 ms of each other would select the item.

Dwell. Contact within an item for more than 500 ms, followed by release within the boundaries of the item, would select it. When the 500 ms timeout expired on an interface object, it was given green highlighting.

Force. Finger force measurements were registered through a force sensitive resistor (FSR) that was attached to the pad of the user's index finger using tape with the centre of its active region approximately 8 mm from the finger tip (see Fig. 4). The FSR was placed at this location to best register contacts that were made while bracing (in which the finger can be largely parallel to the touchscreen surface) as well as those that were made using a single finger posture (in which the finger is often more perpendicular to the surface). Taping the FSR to the finger in this manner was a suboptimal solution, partially because it altered the user's tactile sensation with the screen. However, pilot studies showed it to be superior to other methods we tried that involved mounting the touchscreen on pressure sensors, which failed for two main reason: first, we were unable to distinguish which one of multiple braced fingers was pressing hard; second, during vibration the touchscreen's accelerations induced substantial false readings on the pressure sensors.

Given the limitations of the force-sensing implementation, our experimental objectives with Force was to gain initial insights into the potential usability of the method during vibration, with the hope that any preliminary findings might generalise to actual multi-touch force-sensing technologies when they are developed for larger displays.

The series 400 FSR had an operating range of 0.02-2.0 kgf, an active area of 5.6 mm diameter, and a total diameter of 7.6 mm. Signals from the FSR were sent to the analog pin of an Arduino MKR1000 board, which reported force values to the computer running our experimental software at 1 KHz. Software then triggered selections when a force threshold of $\approx$ 700 g was exceeded (a noticeably hard press, similar to the 'deep click' threshold on recent Apple trackpads).

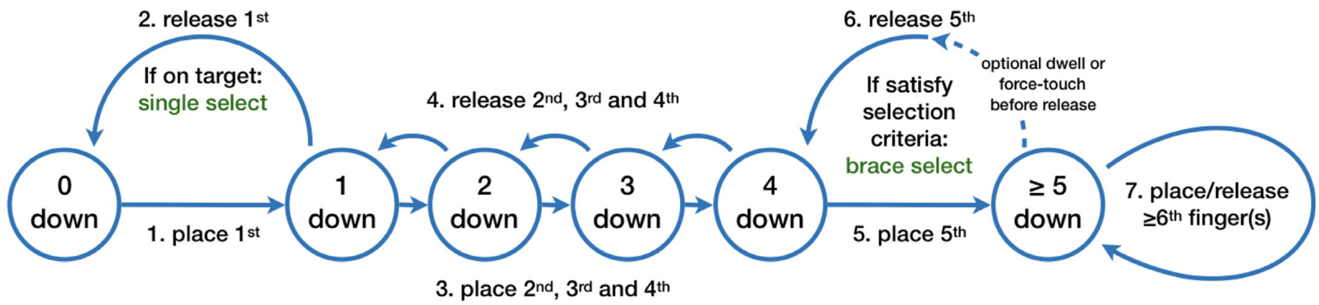


Fig. 3. Simplified state transition diagram for single finger selections (at transition 2) and braced selections (at transition 6) as fingers are placed and released from the display. Braced selections occurred when the selection criteria were satisfied by the last of five fingers placed on the display (note that force selections could be completed without releasing at transition 6).

4. Evaluation of braced/unbraced methods

We carried out a controlled experiment to assess the benefit of bracing over unbraced touch, and to investigate the differences between our three selection methods (doubletap, dwell, and force). We implemented the techniques described above and developed several tasks with different levels of realism for flight operations, including atomic selection actions, a realistic cockpit tasks from a commercial aircraft's training manual, and a selection task where subjects could freely choose whether to use bracing or not. The two main experimental hypotheses were as follows:

- *during vibration, braced touch selection methods reduce touchscreen selection times ($H1_t$) and error rates ($H1_e$).*
- *users will choose to complete selections using a braced posture during vibration* (*H2*).

Regarding the selection methods (doubletap, dwell and force), our research objectives were largely exploratory, with no *a-priori* expectation of a best design.

4.1. Experimental task types

The experiment proceeded through three sets of tasks.

4.1.1. Task 1: Batched target selections

Subjects selected a series of circular targets arranged in a circle, with each successive target highlighted blue and located on the opposite side of the circle (see Fig. 5a). This method was based on the ISO standard Fitts' Law task for evaluating pointing devices (Soukoreff and MacKenzie, 2004). Three different target widths were used (20, 27, and 33 mm), with the smallest size selected based on recommendations from Avsar et al. (2016b) for cockpit touchscreen interaction with an extended arm. The distance between target centres was constant at 265 mm.

For each selection method completed by each subject, Task 1 was repeated four times, comprising two levels of *vibration* (*static* and *vibration*) and two levels of *posture* (*single finger* and *braced*).

4.1.2. Task 2: In-flight APU warnings

Task 2 was intended to be more representative of cockpit interaction, with subjects using the joystick to maintain level flight while responding to a series of warnings associated with the Auxiliary Power Unit (APU) – although these tasks would normally be allocated to two different pilots, we merged their workload to better characterise intense touchscreen interaction. Standard APU operating procedures were updated for emulation through our touchscreen interface. For example, the physical 'APU Fire' button used in the A350 (shown in Fig. 6a) is covered with a protective shield that must be lifted before the button can be pressed. The touchscreen version of this button used in our experiment provided a visual indication of the shield (Fig. 6b), and tapping on the shield enabled the underlying button (Fig. 6c). Pressing the active Fire button then armed the extinguisher systems, which were discharged when the associated 'Squib' button was pressed (not shown).

Subjects used the joystick to correct random variations displayed in the Attitude Indicator (AI), shown at the right of Fig. 7. While doing so, a series of warnings would appear alongside the Centralised Aircraft Monitoring and Crew Alerting (CAMCA). When warnings appeared, subjects had to tap on the warning to display further information relating to the warning in the CAMCA, and take appropriate steps to address the warning before pressing Back in the CAMCA to return to the initial 'CRUISE' state (Fig. 7). They then dismissed the warning by tapping it again. Once each warning was dismissed, the subject continued to maintain level flight in the AI for 10 seconds, when the next warning was presented. The full set of display states, warnings, and required actions are summarised in Table 1, showing a total of 15 actions for one complete traversal through the tasks.

Each subject completed the full set of actions in Table 1 once for initial training, then four times for each of the selection methods they used, comprising both *single finger* and *braced* postures in *static* and *vibration* settings.

The experimenter acted as the 'pilot' and trainer throughout this

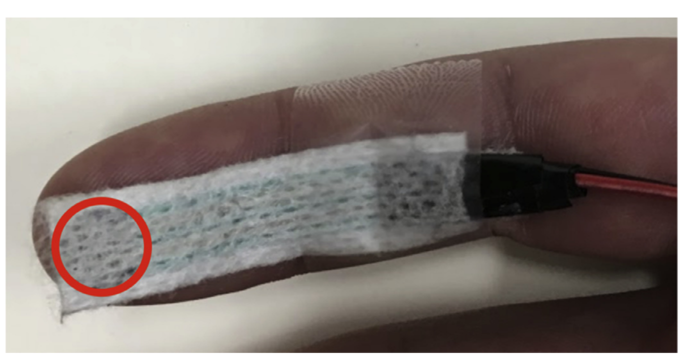
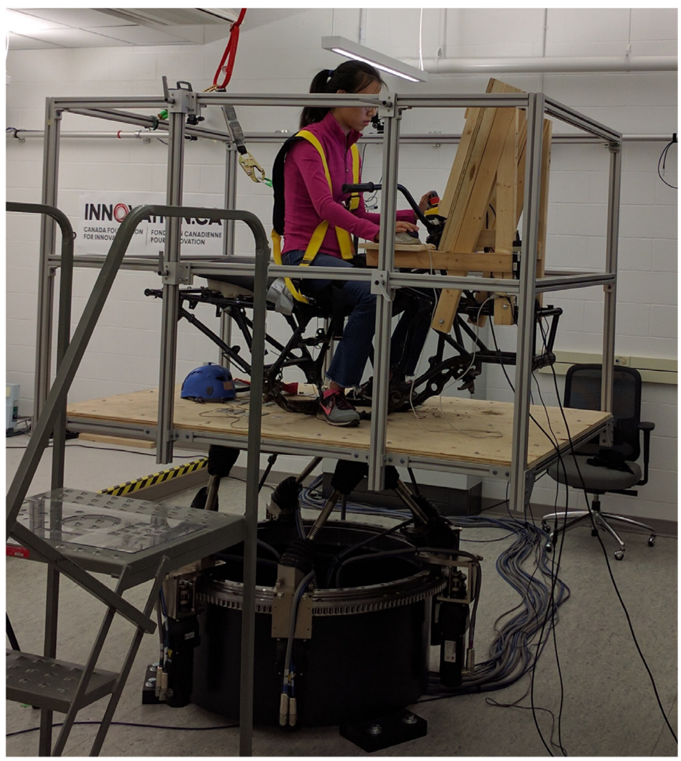


Fig. 4. A force-sensitive resistor was taped to the index finger for FSR tasks – sensor location highlighted.

(a) A subject completing Task 1 selections using a braced posture in the *force* condition. The joystick used for Tasks 2 and 3 is also visible.



(b) A Mikrolar R-3000 rotopod motion platform induced vibration.

Fig. 5. Experimental setup.

task, with the subject acting as co-pilot flying the aircraft and completing the actions. During the first training passage through the tasks, the 'pilot' gave full instructions on how to respond to the prompts. Subjects were also instructed to ask the 'pilot' for guidance at any point if they forgot the required actions. Some tasks also required subjects to read information from the CAMCA and report values to the 'pilot' (e.g., reporting fuel levels).

4.1.3. *Task 3: Control-stick-to-target selections, with free posture choice*

Like Task 1, subjects selected a series of targets arranged around a 265 mm diameter circle (all targets were 27 mm wide). However, unlike Task 1, subjects were required to move their hand to a joystick and click a button on it between each selection. The intention in requiring the hand to return to the joystick between selections was to better reflect normal in-flight selections – pilots seldom make a long series of interactions with buttons and dials, and instead make discrete selections with their hand returning to the control stick or armrest after each one. Importantly, subjects were free to complete selections using whichever *posture* they preferred (*single finger* or *braced*). Task 3 was completed in both *static* and *vibration* conditions. This task was completed last with each selection method, allowing the subjects' choice of braced or unbraced selection method to be based on their previous experiences.

(a) Physical button (b) Touch inactive (c) Touch active

Fig. 6. The APU Fire button: left, the physical button with its guard down; middle, a touchscreen emulation with the guard down; right, touchscreen version with the guard removed after tapping the button.

4.1.4. Procedure

For safety, subjects wore a body harness that was tethered to the ceiling, as shown in Fig. 5. They sat on an seat in front of a touchscreen, joystick, and emergency stop button that were all mounted in fixed locations on a motion platform. The experimenter sat beside the motion platform.

Each subject completed the three tasks using two of the selection methods; they also completed surveys and were invited to give general feedback on the methods. This took approximately one hour per subject and was rewarded with a payment of $10.

For each of the selection methods that a subject used, the following list shows the order of exposure to components of the experiment. Each element of the list uses a tuple of (*T, P, V*) to signify *Task* $\in \{1, 2, 3\}$, *Posture* $\in \{S(ingle), B(race), U(nassigned)\}$, *Vibration* $\in \{St(atic), V(ibrating)\}$, and *Survey* (completion of subjective feedback questions). The order was the same for all subjects, as follows: (1,S,St), (2,S,St), Survey, (1,B,St), (2,B,St), Survey, (3,U,St), (1,S,V), (2,S,V), Survey, (1,B,V), (2,B,V), Survey, (3,U,V). In other words, for each selection method, subjects first completed Task 1 with a single finger when static (1,S,St), then proceeded to Task 2 with a single finger when static (2,S,St), and so on. The *unassigned* posture during Task 3 means that subjects were free to choose whether to complete task selections using a single finger or braced posture.

All static conditions were therefore completed before any of the vibration conditions, and this order was chosen for two reasons. First, as our key hypotheses concern interaction during vibration, we believed it was desirable to provide subjects with fairly extensive experience with all of the tasks prior to introducing the potential distraction associated with vibration. Second, our hypotheses (*H*1 and *H*2) do not involve a direct comparison between static and vibrating conditions, so learning or fatigue effects across static and vibrating conditions are not a primary experimental concern.

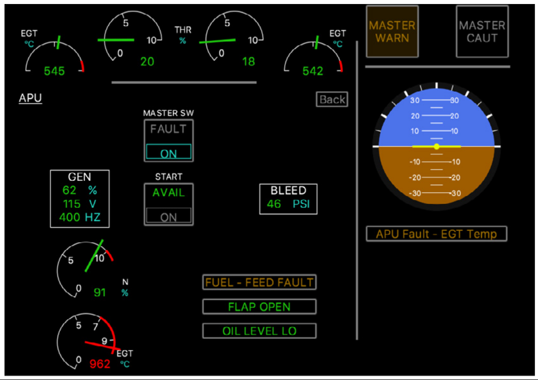
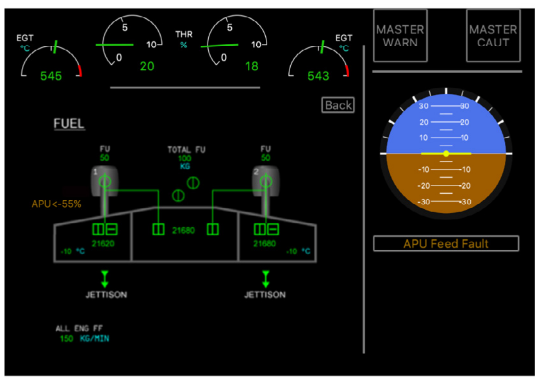
Although learning effects across static and vibrating conditions were not a major experimental concern, we also elected to have subjects complete single finger selections before completing braced selections, which leads to possible learning effects that could influence analysis of *H*1, which concerns reduction of selection times ($H1_t$) and errors ($H1_e$). Our rationale for using this order, despite possible learning effects, was as follows. First, users are familiar with single finger touchscreen interaction on traditional mobile devices, but not with the use of braced contacts on the touchscreen. We therefore felt it best that users first experience the tasks using the more familiar interaction method (single finger) before proceeding to braced conditions. Second, because learning effects tend to follow a power law (Newell and Rosenbloom, 1981), with early substantial improvements rapidly diminishing, we anticipate learning effects to have largely levelled before subjects began the vibration conditions. Regardless of these concerns, analysis of *H*2 is largely unaffected by potential learning effects because it only concerns the subjects' free choice of whether to use a bracing posture during the final set of tasks (3,U,V). We return to the potential influence of learning and fatigue effects in the Discussion.

4.1.5. Apparatus

Turbulence was simulated using a Mikrolar R-3000 rotopod motion platform. The motion profile sent to the platform produced non-periodic displacements with a mean frequency of 3.1 Hz (maximum 5 Hz).

Fig. 7. Task 2 interface, including touchscreen-adapted Centralised Aircraft Monitoring and Crew Alerting (CAMCA) and Attitude Indicator (AI, right).

Table 1
Visual states, warning messages, and required actions in Task 2.

Warning Information and Main Display	Required Actions
APU Fault - EGT Temp	
	• APU Fault - EGT Temp • Master SW - FAULT • Back • APU Fault - EGT Temp
APU Feed Fault	
	• APU Feed Fault • FUEL (read fuel aloud) • Back • Back • APU Feed Fault
APU Fire !	
	• APU Fire ! • Fire (remove shield) • Fire (arm extinguishers) • SQUIB (fire extinguishers) • Back • APU Fire !

RMS accelerations were 2.11 m/s^2 on the vertical axis, 0.72 m/s^2 on the lateral axis, and 0.07 m/s^2 on the longitudinal axis, giving a sum acceleration of 2.15 m/s^2. These values were confirmed using an accelerometer mounted on the seatpan. These levels of acceleration conform to the upper end of the 'very uncomfortable' range in the vibration discomfort index (ISO2631-1), and prior studies have shown that pilots' proficiency are reliably compromised at $\approx 0.2g$, which is 1.9 m/s^2 (Notess, 1961). Furthermore, non-periodic vibrations were used to eliminate subjects' ability to adapt to predictable sinusoidal motions (Notess, 1961). Aircraft industry representatives confirmed the general authenticity of the vibrations (for turbulence in fixed wing aircraft).

Touch input was received through a Dell S2240T21.5″ monitor running at 1920 × 1080 pixel resolution (2.03 px/mm). The display's placement (shown in Fig. 5) was configured to represent possible touchscreen positioning within an aircraft cockpit, specifically within arm's reach and below the user's eyeline to the windshield.

Additionally, a joystick (Logitech Attack 3) was available for use in Tasks 2 and 3. All software was written using multitouch support in JavaFX, running under the Windows 10 operating system.

4.1.6. *Subjects*

The eighteen volunteer subjects were all undergraduate and postgraduate students at a local university (age 19–45, mean 27.3, 8 female). All used their dominant hand for interacting with the touchscreen and joystick. None were pilots.

4.1.7. *Study design*

The study used a mixed factorial design with three factors: *posture* (braced or unbraced), *method* (doubletap, dwell, force-threshold), and *vibration* (none or high). A mixed design was used because completing

Tasks 1–3 and associated surveys in static and vibrating conditions and with braced and non-braced postures (except for Task 3) took approximately 30 m per selection method. Each subject therefore completed the tasks with only two of the selection methods, giving twelve subjects' data per selection method. The incomplete mapping between subjects and conditions precludes analysis with ANOVA's standard linear model. Our analysis therefore uses a Hierarchical Mixed Model (HMM), which provides a similar model yet allows for missing data from some subjects (Field et al., 2012). The analysis was carried in R using the *nlme* library, using subject as a random factor. The mixed model assumption that residuals are normally distributed was inspected using QQ plots.

5. Results

Results from the three tasks are presented for each of the main dependent measures: selection time, errors (wrong target selections and false-negatives), and proportion choosing to use a braced posture in Task 3.

5.1. Task time

All tasks were comprised of one or more item selections, and selection time was determined based on the total time to select the next intended target, including any time spent in error. Fig. 8 summarises the results for the three tasks, with charts showing mean selection times across the three selection methods. The charts for Tasks 1 and 2 also show selection times with single-finger and braced selections; in Task 3, subjects were free to choose braced or unbraced posture for completing the task. The left and right columns in the figure show selection times in *static* and *vibration* conditions respectively. Recall that direct comparisons across static and vibration conditions are not made – our hypotheses do not concern this comparison, any the comparison would be confounded by order effects (Section 4.1.4).

5.1.1. Task 1: ISO Fitts' law pointing

In the static (no vibration) version of Task 1, single finger selections were faster (mean 1202 ms, s.d. 680 ms) than braced selections (mean 2017 s.d. 2002 ms), as expected, giving a significant main effect of *posture*: $F_{1,1849} = 162.6$, $p < 0.001$ (see Fig. 8a). As the figure indicates, there was also a significant main effect of *method* ($F_{2,1849} = 62.3$, $p < 0.001$) as well as a significant *posture* × *method* interaction ($F_{2,1849} = 50.6$, $p < 0.001$), which can be attributed to the particularly slow performance with the *force* method when using a *braced* posture (mean 2834 ms), as discussed later. Posthoc pairwise comparison (Tukey tests) confirmed that doubletap was significantly faster than dwell and force (both $p < 0.0001$) and that dwell was faster than force ($p = 0.01$).

In the vibration version of Task 1 (Fig. 8b), there was a significant main effect of *posture* $F_{1,1849} = 7.09.$ 0, $p < 0.01$, with *braced* selections (mean 1784 ms, s.d. 1373) faster than *single-finger* selections (mean 1966 ms, s.d. 1720). There was also a significant effect of *method* $F_{2,1849} = 38.7$, $p < 0.001$ and a significant *posture* × *method* interaction ($F_{2,1849} = 12.0$, $p < 0.001$). The interaction is best attributed to a cross-over effect, with braced selections faster than single-finger selections when using *doubletap* and *dwell*, but slower when using *force*. Posthoc pairwise comparison (Tukey tests) confirmed that doubletap was significantly faster than dwell and force (both $p < 0.0001$), but there was no significant difference between dwell and force ($p = 0.99$).

5.1.2. Task 2: Simulated in-flight warnings from auxiliary power unit (APU)

Task time results in the static condition for Task 2 (Fig. 8c) are broadly consistent with those of Task 1. There was a main effect of *method* ($F_{2,1057} = 18.8$, $p < 0.001$), with *doubletap* fastest, followed by *dwell*, and *force* slowest. There was no significant main effect of *posture* ($F_{1,1057} = 1.68$, $p = 0.19$), nor was there a *method* × *posture* interaction ($F_{2,1057} = 0.88$, $p = 0.88$). The higher selection times in Task 2 compared to Task 1 can be attributed to the more cognitively challenging activities in the APU task (see Section 4.1.2). Posthoc pairwise comparison (Tukey tests) confirmed that doubletap was significantly faster than dwell and force (both $p < 0.01$), and that dwell was faster than force ($p < 0.01$).

In the vibration version of Task 2 (Fig. 8d), only the effect of *method* was significant ($F_{2,1057} = 4.33$, $p < 0.05$), with *doubletap* fastest (mean values are shown in the figure). *Posture* ($F_{1,1057} = 1.07$, $p = 0.30$) and *method* × *posture* ($F_{2,1057} = 0.49$, $p = 0.61$) showed no effect. Posthoc pairwise comparison (Tukey tests) confirmed that doubletap was significantly faster than dwell and force (both $p < 0.05$), but there was no significant difference between dwell and force ($p = 0.99$).

5.1.3. Task 3: Control-stick and target selection, with free posture choice

In Task 3 (Fig. 8e), subjects were free to select their preferred posture. Therefore, the only factor analysed for task time performance was *method*, which again results showed a significant difference in the static condition ($F_{2,370} = 27.9$, $p < 0.001$). Posthoc pairwise comparison (Tukey tests) confirmed that doubletap was significantly faster than dwell and force (both $p < 0.0001$), but there was no significant difference between dwell and force ($p = 0.56$).

Results for Task 3 also show a significant main effect of *method* in the vibration condition ($F_{2,370} = 9.5$, $p < 0.001$), with *doubletap* faster than dwell and force (Tukey $p < 0.01$ for both), but no significant difference between dwell and force ($p = 0.53$).

5.1.4. Task time summary for Hypothesis 1

Results from Task 1 generally support $H1_t$ (that bracing will reduce selection time) – during vibration, bracing was faster than single-finger selections (although not when using the *force* method). Results from Task 2, however, were inconclusive – mean times with *doubletap* and *dwell* were lower when using bracing than single-finger selections, but not significantly so. Force-based selections were much faster with a single finger than with bracing when static, and contrary to $H1_t$ they were also a little faster during vibration; reasons contributing to this are discussed later. The results from Task 3 do not have an effect on $H1_t$ because users were allowed to select their preferred posture (see discussion of *H*2 below). Finally, results show that doubletap was faster than dwell and force across all conditions and tasks.

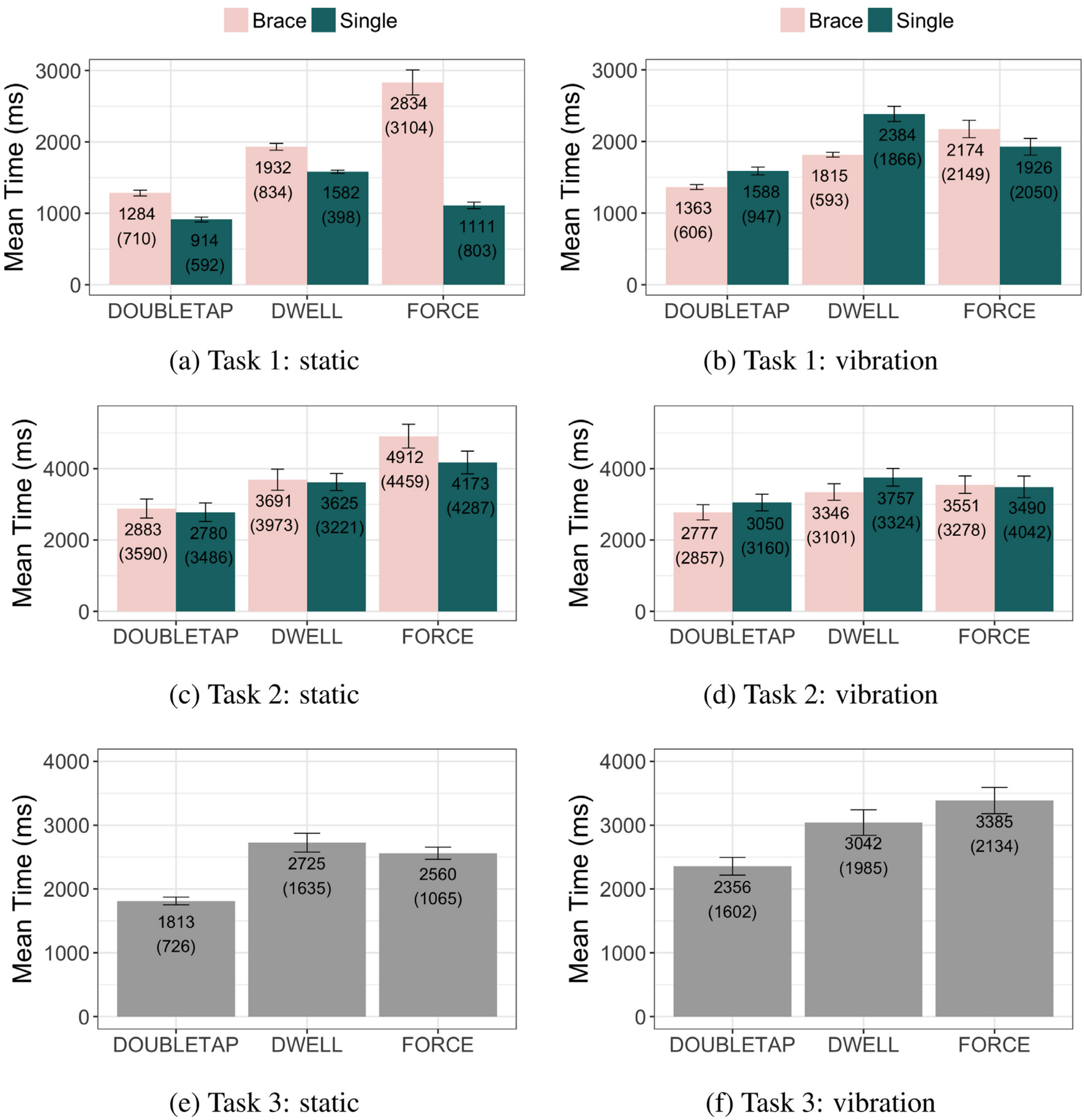
5.2. Errors: false-negative and wrong-target selections

Two types of errors were analysed: false-negative selections, in which subjects tried but failed to complete a selection; and wrong-target selections, in which a target other than the intended one was selected.

5.2.1. False-negative selections

False-negative selections represent a failure to select *any* item when a selection attempt is made. We used the following heuristics to infer the occurrence of a false-negative. For *doubletap*, a false-negative was inferred when two release events occurred within 500 ms of each other, and where both releases were within 50 px of the centre of the target (i.e., both releases were near to the target, but at least one was outside it). For *dwell* and *force* methods, a false-negative was inferred when a release event occurred within 50 px of the centre of the target and the release was preceded by a press event within 50 px of the target centre – this inference was intended to capture inaccurate finger placement and also failure to hold the contact for sufficient time or failure to reach the necessary force threshold.

False-negative selections were only analysed for Task 1. In Task 2, targets were of different sizes and shapes, making application of the heuristics that infer intention impractical, and in Task 3 users were free to choose their preferred selection posture, removing the experimental



(a) Task 1: static

(b) Task 1: vibration

(c) Task 2: static

(d) Task 2: vibration

(e) Task 3: static

(f) Task 3: vibration

Fig. 8. Selection time results for the three selection methods in static (left) and vibrating (right) conditions for the three tasks. Results for braced and single finger selections are also shown for Tasks 1 and 2. Error bars show ± 1 standard error. Results of statistical tests are shown below each chart, with results for *static* shown to the left of the double bar and results for *vibration* shown to the right.

control necessary to examine the comparative error rates of bracing and single-finger postures ($H1_e$) for those tasks.

Results of the false-negative analysis are summarised in Fig. 9, which shows the proportion of selections that included a false-negative, with the static condition on the left and vibration on the right. In general, false negative error rates were relatively high across all conditions – from 3% with single-finger, *doubletap* when *static* to 56% with single-finger, *force* during vibration.

In *static* conditions (Fig. 9a), the false-negative rate was higher with a *braced* posture (mean 0.21 errors per selection, s.d. 0.41) than with *single-finger* (mean 0.12 errors per selection, s.d. 0.32), giving a significant main effect of *posture*: $F_{1,1897} = 39.7$, $p < 0.001$. There was also a significant effect of *method* ($F_{2,1897} = 107.2$, $p < 0.001$), with *doubletap* having fewest errors (mean 0.04, s.d. 0.2), followed by *dwell* (mean 0.12, s.d. 0.33) and *force* (mean 0.33, s.d. 0.47). There was also a significant *posture* × *method* interaction ($F_{2,1897} = 8.4$, $p < 0.001$), which can be attributed to the small difference between postures with *doubletap*, in contrast to the larger differences across postures with *dwell* and *force*. Posthoc pairwise comparison (Tukey tests) confirmed that doubletap had fewer errors than dwell and force (both $p < 0.0001$) and that dwell had fewer errors than force ($p < 0.0001$).

$H1_e$ concerns comparative performance between braced and single-finger postures during vibration, with results summarised in Fig. 9b. During vibration, the error rate with a *braced* posture (mean 0.22, s.d. 0.41) was less than half of that a single-finger posture (mean 0.52, s.d. 0.5): $F_{1,1897} = 216.8$, $p < 0.001$. As for *static* conditions, there was also a significant effect of *method* ($F_{2,1897} = 37.6$, $p < 0.001$), with *doubletap* having fewest errors (mean 0.28, s.d. 0.45), followed by *dwell* (mean 0.33, s.d. 0.47) and *force* (mean 0.48, s.d. 0.5). There was also a significant *posture* × *method* interaction ($F_{2,1897} = 16.2$, $p < 0.001$), which can be attributed to the large difference between postures with *doubletap*, in contrast to the smaller differences across postures with *dwell* and *force*. Posthoc pairwise comparison (Tukey tests) showed no significant pairwise difference between doubletap and dwell ($p = 0.055$), but significant differences between doubletap and force and between dwell and force (both $p < 0.0001$).

The most important finding is that during vibration the rate of false-negative selections is lowest with a braced posture and *doubletap* – 7% of selections included a false-negative when braced, compared to 50% when using a single finger. These findings support $H1_e$ – bracing reduced the incidence of false-negative errors during vibration.

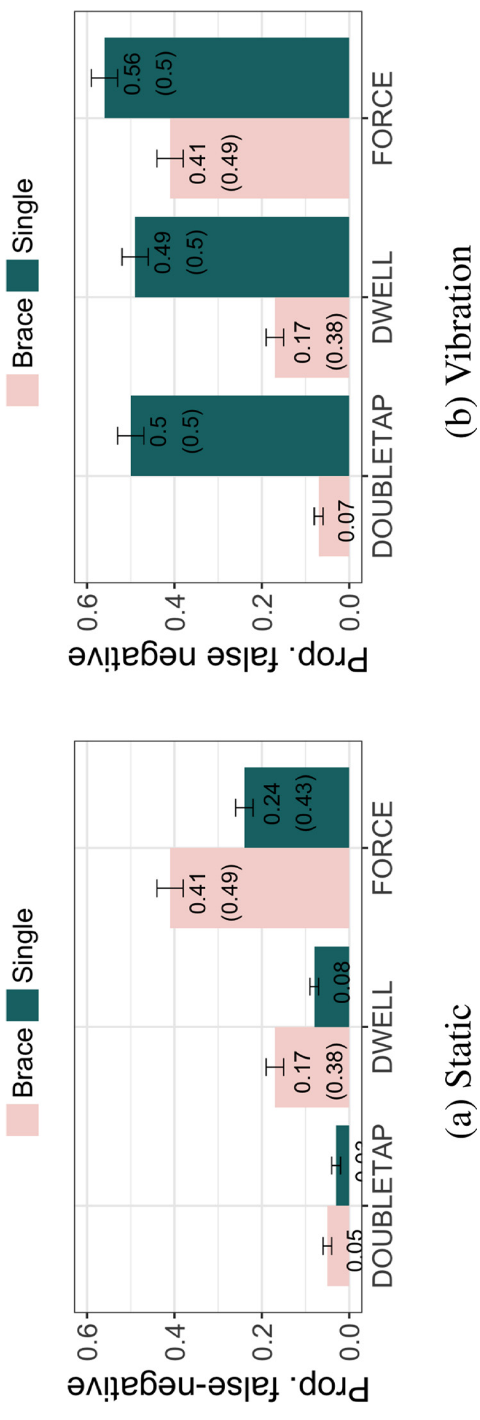


Fig. 9. Proportion of Task 1 selections that include a false-negative selection. Error bars ± 1 standard error.

5.2.2. Wrong-target selections

Wrong-target selections were inferred to have occurred when the selected target differed from the one expected. This could arise due to the user's misunderstanding (e.g., choosing to dismiss an alarm in Task 2, when the system expected the 'Back' button to be selected) or due to unintended contacts. In Task 2, subjects were engaged in moderately realistic flight tasks, concerning APU emergencies, and wrong-target error rates were relatively high (≈ 5%) and consistent across conditions. However, these errors are likely due to subjects misunderstanding the interaction steps required, rather than factors arising from braced postures. Our analysis therefore focuses on Tasks 1 and 3. Statistical analyses are omitted due to lack of data (e.g. zero errors in some conditions) and violation of linear mixed model assumptions (non-normal distribution of residuals).

Wrong-target results are summarised in Fig. 10, with the static condition on the left, and vibration right. In Task 1, wrong-target errors were rare, except when using the braced posture (up to 3% of selections included a wrong-target selection). Experimenter observation surmised that this was due to users rushing to complete the batch of selections without sufficient visual attention. The braced posture increased these errors because the upcoming target in the circle was often occluded by the hand (particularly when moving to a target in the bottom-right of the display); users therefore sometimes anticipated the location of the item and selected it without confirming its highlighting. In Task 3, where users were required to move their hand from the joystick to a cued abstract target, wrong-target selections were relatively rare, particularly with the doubletap method.

In summary, analysis of false-negative and wrong-target errors provides limited support for $H1_e$. Bracing reduced the incidence of false-negative errors during vibration with all of the methods, particularly with *doubletap*. However, in the batched series of tapping actions in Task 1, bracing increased the incidence of wrong-target selections.

5.3. Choice of posture and subjective responses

During Tasks 1 and 2, subjects were required to complete selections using the assigned posture (single finger or braced). This forced use was intended to provide insights into user performance with the postures across the different methods with and without vibration. In Task 3, however, users were free to complete selections with whichever posture they preferred, and they made this choice after having gained experience with both braced and single finger selections.

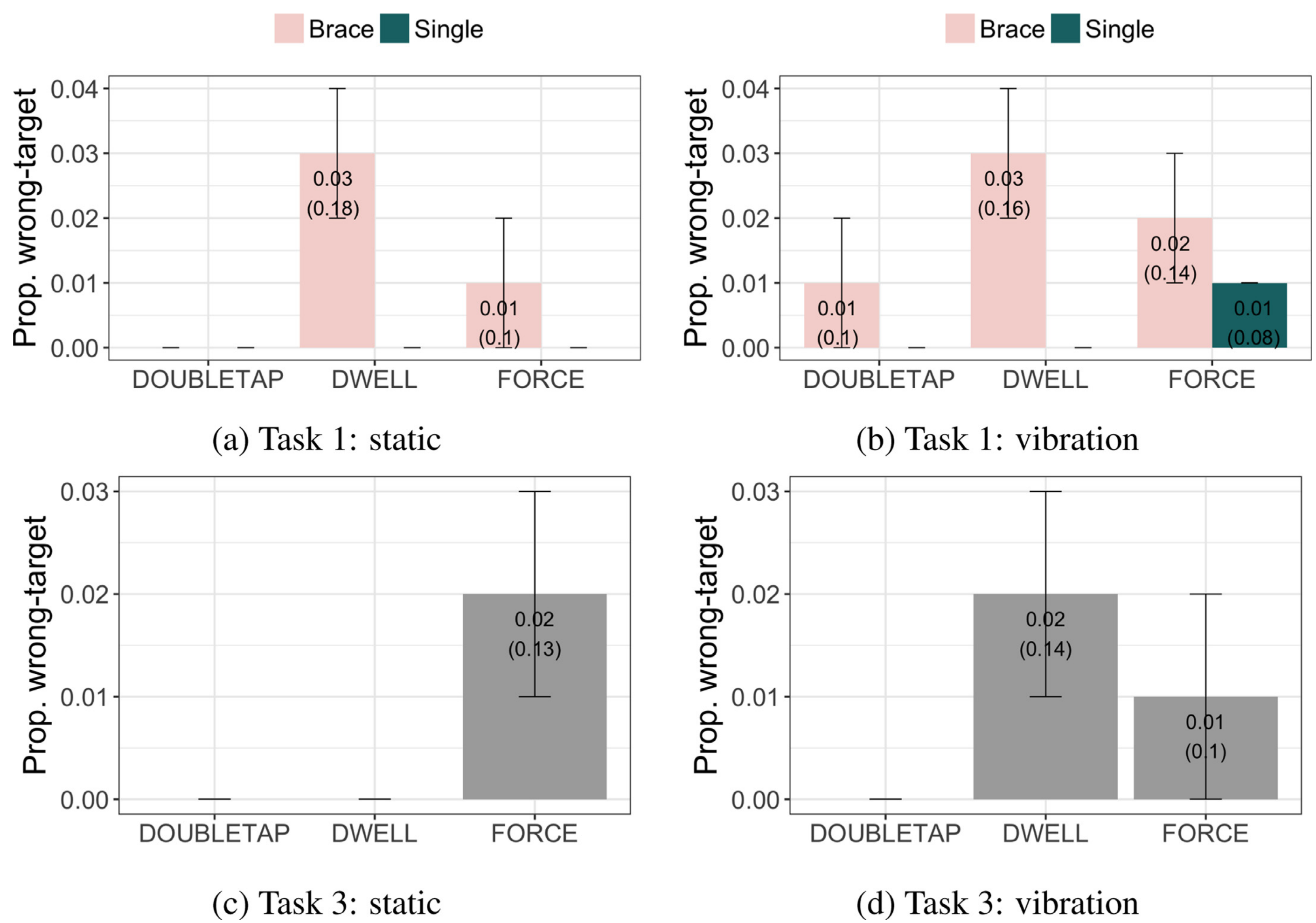


Fig. 10. Wrong-target results for the three selection methods in static (left) and vibrating (right) conditions by braced and single finger selections (Tasks 1 and 2). Error bars show ± 1 standard error.

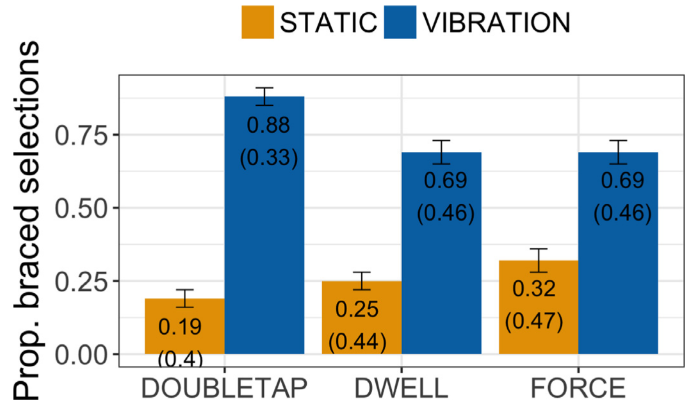


Fig. 11. Proportion of selections made using a braced posture (rather than single finger) during Task 3. Error bars ± 1 standard error.

Fig. 11 shows the proportion of selections that were completed using braced and single finger postures, clearly showing that when vibration was present the strong majority of selections were completed using a braced posture (75%) for stabilisation, while only 25% of selections used a braced posture during static trials (proportions test, $\chi^2 = 245.5$, $p < .0001$). Fig. 11 also indicates that subjects found the braced posture most effective during vibration when using doubletap (87.3% of selections). We therefore accept *H2*; with free choice, subjects elected to use braced selections during vibration.

Subjects' comments also suggested a strong preference for braced postures during vibration. In response to the question 'Did bracing your hand make things easier, harder or about the same compared to no bracing?', nearly all of the subjects stated that bracing made selections easier during vibration, although several qualified this by stating that bracing also made selections harder during static conditions: P1 *'it made it easier while vibration'*, P4 *'it was easier if vibration was present... challenging when there was no vibration'*, P6 *'It makes things harder when there is no vibrations but way easier when there is vibration'*, and P15 *'It's easier when there is vibration but less comfortable without vibration.'* We also asked subjects whether any of the selection methods were tiring, with several answers identifying *dwell* and *force* as requiring more effort, particularly when combined with bracing; subjects also noted that using a single finger during vibration was tiring. All of the subjects who used doubletap stated that it was their preferred method, explaining their preference due to various factors including comfort, ease, accuracy, and speed. One of these subjects (P15) disliked using doubletap with a braced posture, explaining that it was *'really painful and not comfortable'*; however, the sentiment of P18 was more common, who explained the benefits of braced doubletap as being *'natural'* and *'using this method put hand in place; it is very secure.'*

6. Discussion

To summarise the main results, bracing had the intended effect of stabilising input during vibration – first, subjects were generally faster with bracing than with single finger selections; second, with the *doubletap* method, subjects made substantially fewer false-negative errors when bracing; and third, when subjects were free to choose their selection posture, the strong majority used bracing. As expected, when vibration was absent, the strong majority of subjects used single finger selections. The doubletap selection method performed much better than *dwell* and *force*, both in static and vibration conditions, with comments and performance data suggesting that doubletap combined well with a bracing posture during vibration. The following sections first consider reasons contributing to the relative successes and failures of the methods and then review limitations of the current study, including directions for further research.

6.1. Successes and failures of doubletap, dwell, and force

Of the three methods evaluated, doubletap was superior in terms of task time, error rates and subjective responses. One of the few concerns raised about doubletap was P15's comment regarding discomfort when using a braced posture. The ergonomics of repeatedly lifting the index finger from a near-vertical display when using a braced posture could increase risks of carpal tunnel repetitive strain injuries due to high wrist flexion. These risks could be mitigated by tilting the display away from the operator to reduce the angle of risk flexion (ours was at an angle of 15° from vertical), however doing so could compromise visibility of items on the display. Although initial studies of cockpit touchscreen ergonomics have been reported (Avsar et al., 2016a; Barbé et al., 2012), further work on the ergonomics of braced touch is needed.

Dwell was probably the least successful method during vibration. In particular, the combination of a braced posture and *dwell* during vibration increased the incidence of wrong-target errors (Fig. 10b,f). This occurred when multiple braced fingers accidentally broke contact with the display during vibration; the user would then replace the fingers almost concurrently, and sometimes the last-placed finger was not the one the user intended to use for selection, causing an accidental dwell on an unintended object by a bracing finger. The need to maintain contact within the target while the timeout expired was also found to be "frustrating" when using a braced posture and "too inaccurate" when unbraced during vibration because of the difficultly of holding and maintaining a stable position for a prolonged period.

Despite these limitations of *dwell*, its feedback feature was appreciated by subjects – when the timeout expired, the selected item was highlighted green to confirm that releasing would finalise selection. Two subjects commented that this highlighting was useful: P5 *'I like waiting for the button to become green'*, P12 *'I liked the green color that popped out after holding ...it makes me feel like I've completed the task.'* *Dwell* was the only one of our methods to incorporate feedback within the button when partial selection criteria were fulfilled, and it is possible that related feedback could be incorporated into the other methods. For example, doubletap could be modified to include an initial tap to "arm" the item (causing it to be highlighted green), followed by a double tap to complete selection. Similarly, the force method could be modified to highlight the item when the force threshold is exceeded, with selection only completed by releasing the finger from the item.

Results for the *force* method were interesting, suggesting that it may be a viable or even desirable technique if the limitations of our implementation could be eliminated. Some subjects were efficient and accurate when using force, while others had difficulty attaining the required force threshold, leading to many false-negative errors (Fig. 9) and consequently slow performance. However, much of this problem can be attributed to our use of small finger-mounted FSRs for registering force, and the results could be substantially different if force was registered using a different technology.

The main cause of problems with our FSRs was related to their small size (5 mm diameter active area) combined with the different postures used for bracing and single finger contacts. We intentionally used small FSRs to facilitate comfortable placement on the subjects' fingers, but the small active area made it difficult for us to ideally place the FSR. When making a single finger selection users tend to use the tip of their finger, but when making a braced selection the finger-pad tends to be used. We took care to mount the FSR towards the tip end of the finger pad, and while some subjects found this worked well, others found that reaching the threshold force was difficult with at least one posture, leading to high false-negative error rates. Subject comments emphasised that pressing hard enough to exceed the force threshold was effortful and sometimes uncomfortable, but at least some of this high perceived effort and discomfort will have arisen from difficulties associated with our FSRs. Other limitations with our FSRs include the following: unlike doubletap and dwell, selections could only be completed with the index finger on which the FSR was mounted, and this constraint may have influenced the findings; the tape used to attach the FSR to the finger may have restricted movement; and the tape may have reduced the subjects' haptic perception of contact with the display.

Recent iPhones use capacitive methods to estimate finger force, and it is likely that finger force-sensing capabilities will be integrated into upcoming generations of larger touch displays. Future work should reevaluate braced touch during vibration when these displays are available.

6.2. *Opportunities for further work*

There are many opportunities for further work to build and generalise understanding of touchscreen interaction in vibrating environments. Among these are the need to extend our studies beyond the current subject pool, which did not include trained pilots, as well as the need to examine other forms of gestural interaction during bracing, such as dragging and pinching gestures. Five important areas for further work are highlighted below.

6.2.1. *Simulation fidelity and variety*

Our evaluations were primarily directed at gaining initial insights into the use of braced touch interactions for aircraft cockpits. Further studies could increase the fidelity of the cockpit environment, for example, by using real pilots as participants, seated in commercial aircraft simulators for greater ecological validity. Also, the range and type of vibrations examined could be broadened to better support results generalisation to conditions such as different vehicles (e.g., farm machinery such as tractors) and more extreme levels of in-flight turbulence. Finally, a variety of other methods have been proposed for mitigating the effects of vibration on touchscreen interaction (see Section 2.3), and future studies could compare the effectiveness of braced touch with these other methods.

6.2.2. *Learnability of bracing*

The widespread use of mobile touchscreens means that users are likely to be familiar with the need to avoid accidentally making contact with a touchscreen during interaction (because spurious contacts cause gesture recognition failure). Consequently, if braced selections were supported on a device such as a car's touchscreen, users would need to learn that this modality was available, and at least to some extent 'unlearn' their resistance to placing additional fingers on the display. This learning burden is relatively unimportant for pilots because they undergo frequent training, but there are interesting questions regarding how the general population would adapt to using braced selections in vehicles.

6.2.3. *Experimental learning effects*

All subjects in our experiments completed single-finger selections before completing equivalent selections using a bracing posture, and they completed all static conditions before completing vibrating conditions (see Section 4.1.4). We intentionally used this order to ease familiarisation with the bracing conditions, and to ensure that the harder and more important vibration conditions were conducted once subjects were familiar with the procedure. Regardless of the experimental design objectives, however, there are risks that learning effects may have contributed to some of the performance benefits observed for bracing over single finger selections during vibration.

We suspect that the contribution of learning effects to the observed benefits of bracing during vibration is small for two reasons: first, subjects were already familiar with the procedure having completed all static conditions for Tasks 1 and 2 before beginning the vibration conditions; second, when given free choice of single versus braced postures in Task 3, subjects chose to use a single finger for static conditions, yet they also chose to use the braced posture for the same task when vibration was present, suggesting that they deployed the methods appropriately as the vibration conditions changed. Regardless, however, further experimental work is necessary to confirm the role that learning effects may have played.

Another implication of the experimental design decision to have participants complete static conditions before vibration conditions is that we are unable to assess the degree to which vibration influenced task completion times – although we would expect vibration to result in slower performance that static conditions, we would also expect users to be slower in their initial (static) conditions due to their relative lack of familiarity with the experimental tasks. Indeed, Fig. 8 shows that mean task times were slightly faster during some vibration conditions than during the equivalent static condition. As previous studies have demonstrated the expected finding that vibration slows touchscreen interaction (e.g., Cockburn et al., 2017; Dodd et al., 2014), we felt that demonstrating this effect again was relatively unimportant. However, the fact that participants were clearly improving their performance during static conditions suggests that they were far from attaining the expertise that would be expected of real pilots in the cockpit. This emphasises the need for further studies with representative end users (e.g., pilots) in realistic settings.

Finally, there are interesting questions for further work regarding how users adapt to braced and unbraced selections at different levels of vibration, particularly as they become more familiar with the vibration and the braced selection methods.

6.2.4. *Issues of display orientation and location*

As mentioned earlier, the orientation and placement of the display has important ergonomic implications, including visibility of objects and strain due to wrist flexion. Another important issue of display orientation concerns the alignment between the display and the primary axis of acceleration arising from vibration. In aircraft, turbulence includes high vertical accelerations, smaller accelerations lateral accelerations, and low longitudinal accelerations (Notess, 1961). Consequently, with a vertical touchscreen orientation, users' fingers will tend to slip vertically on the display during turbulence, but if the touchscreen were mounted horizontally, the fingers would have a greater tendency to bounce on and off the display. Finding the ideal compromise between ergonomic requirements and vibration-induced error will require extensive further research.

Another issue related to display location that should be examined in future work concerns the role that finger/hand occlusion may have on the results. Some of the errors observed in our studies were likely due to the finger and hand occluding targets, and in the safety critical cockpit environment it is important to know whether bracing postures increases susceptibility to this type of error. Furthermore, prior findings show that humans adapt their hand postures as they move towards targets, in preparation for a suitable grip once contact is obtained (Klatzky and Lederman, 2012). In a similar vein, basic human factors research could examine how users move their hands towards target rich environments when a braced touch posture is intended.

6.2.5. Compatibility with other gestures

While static target selections, such as those used in our study, are an important part of many interactions, dynamic touchscreen contacts are also important, such as sliding, swiping, and movement with multiple concurrent contacts. There are therefore interesting and important questions about how bracing can be adapted to these forms of gestures. Although we have not yet conducted studies, we believe that bracing is compatible with dynamic gestures. For example, an object dragging gesture could be achieved by placing all digits of one hand the display, then lifting the index finger momentarily before placing it on the item to be dragged (selecting it in a manner that is similar to our doubletap method); the user could then move the whole hand while maintaining contact with all digits, dragging the item under the index finger. Similarly, a pinching gesture might begin with all five digits in contact with the display before lifting and replacing thumb and index finger to perform a pinching gesture. Rotational gestures could operate in a similar manner to pinching, with the whole hand rotating to ease displacement of the thumb and index finger.

7. Conclusion

In-flight turbulence is a challenge for the introduction of touchscreen interaction in commercial aircraft cockpits. Previous studies have shown that users can improve their touchscreen performance during simulated turbulence by grasping the bezel that surrounds the display to stabilise the finger completing selections. However this solution cannot be used to access many regions on larger displays, and it can force users to complete selections using awkward postures. To address these limitations we examined the design of various methods for braced touch, in which users stabilise their hands by placing multiple digits concurrently on the display. We evaluated the techniques using tasks that ranged from abstract target selections to more realistic in-flight activities. Results showed that bracing can be a successful strategy for fast and accurate touchscreen interaction during high levels of simulated turbulence, particularly when selections are finalised using a braced doubletap.

Acknowledgement

This work is partially funded by New Zealand National Science Challenge grant: UOCX1701. Thanks to the anonymous reviewers for their comments on the work.

References

ARINC661, 2016. Cockpit display system interfaces to user systems. ARINC Specification 661, supplement 6. airlines electronic engineering committee (AEEC).http://www.aviation-ia.com/cf/store/catalog_detail.cfm?item_id=2697. Last accessed: September 11, 2017.

Avsar, H., Fischer, J.E., Rodden, T., 2016. Designing touch-enabled electronic flight bags in SAR helicopter operations. Proceedings of the International Conference on Human-Computer Interaction in Aerospace. ACM, New York, NY, USA, pp. 14:1–14:11. https://doi.org/10.1145/2950112.2964591.

Avsar, H., Fischer, J.E., Rodden, T., 2016. Designing touch screen user interfaces for future flight deck operations. Proceedings of the IEEE/AIAA 35th Digital Avionics Systems Conference (DASC). pp. 1–9. https://doi.org/10.1109/DASC.2016.7777976.

Avsar, H., Fischer, J.E., Rodden, T., 2016. Future flight decks: Impact of +gz on touchscreen usability. Proceedings of the International Conference on Human-Computer Interaction in Aerospace. ACM, New York, NY, USA, pp. 3:1–3:8. https://doi.org/10.1145/2950112.2964592.

Barbé, J., Chatrenet, N., Mollard, R., Wolff, M., Bérard, P., 2012. Physical ergonomics approach for touch screen interaction in an aircraft cockpit. Proceedings of the Conference on Ergonomie Et Interaction Homme-machine. ACM, New York, NY, USA, pp. 9:9–9:16. https://doi.org/10.1145/2652574.2653402.

Bauersfeld, K., 1992. Effects of turbulence and activation method on touchscreen performance in aviation environments. Department of Psychology, San Jose State University Masters Thesis.

Cockburn, A., Gutwin, C., Palanque, P., Deleris, Y., Trask, C., Coveney, A., Yung, M., MacLean, K., 2017. Turbulent touch: Touchscreen input for cockpit flight displays. Proceedings of the CHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA, pp. 6742–6753. https://doi.org/10.1145/3025453.3025584.

Dodd, S., Lancaster, J., Miranda, A., Grothe, S., DeMers, B., Rogers, B., 2014. Touch screens on the flight deck. Proceedings of the Human Factors and Ergonomics Society Annual Meeting 58 (1), 6–10. https://doi.org/10.1177/1541931214581002. 10.1177/1541931214581002.

Field, A., Miles, J., Field, Z., 2012. Discovering Statistics Using R, 1st. Sage Publications Ltd., London.

Gannon, A., 2012. System and method for improving touch screen display use under vibration and turbulence. US Patent App. 12/952,846.

Hamon, A., Palanque, P., André, R., Barboni, E., Cronel, M., Navarre, D., 2014. Multi-touch interactions for control and display in interactive cockpits: Issues and a proposal. Proceedings of the International Conference on Human-Computer Interaction in Aerospace. ACM, New York, NY, USA, pp. 7:1–7:10. https://doi.org/10.1145/2669592.2669650.

Kaminani, S., 2011. Human computer interaction issues with touch screen interfaces in the flight deck. Proceedings of the IEEE/AIAA 30th Digital Avionics Systems Conference. https://doi.org/10.1109/DASC.2011.6096098.

Kawalkar, A., 2012. Touch screen and method for providing stable touches. US Patent App. 13/162,679.

Kin, K., Hartmann, B., DeRose, T., Agrawala, M., 2012. Proton++: A customizable declarative multitouch framework. Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology. ACM, New York, NY, USA, pp. 477–486. https://doi.org/10.1145/2380116.2380176.

Klatzky, R., Lederman, S., 2012. Touch. In: Weiner, I., Healy, A., Proctor, R. (Eds.), Handbook of Psychology, Experimental Psychology. Wiley, pp. 152–178. Handbook of Psychology

Kolbe, D., 2013. Method for determining valid touch screen inputs. US Patent App. 13/279,417.

Komer, J., Gepner, J., Hogan, R., Mabie, T., 2013. Avionics control and display unit having cursor control mode of operation. US Patent App. 13/438,613.

Lewis, R., 2015. The effect of handedness on use of touch screen versus touch pad. Proceedings of the 5th International Conference on Application and Theory of Automation in Command and Control Systems. ACM, New York, NY, USA, pp. 115–120. https://doi.org/10.1145/2899361.2899373.

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. https://doi.org/10.1080/00140130903528186.

Mark Fletcher, D.H., 2010. Panoramic cockpit displays for tactical military cockpits. Proceedings of the SPIE. 7690. pp. 7690–7697. https://doi.org/10.1117/12.853032.

Mott, M.E., Wobbrock, J.O., 2014. Beating the bubble: Using kinematic triggering in the bubble lens for acquiring small, dense targets. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA, pp. 733–742. https://doi.org/10.1145/2556288.2557410.

Newell, A., Rosenbloom, P., 1981. Mechanisms of Skill Acquisition and the Law of Practice. In: Anderson, J. (Ed.), Cognitive Skills and their Acquisition. Hillsdale, NJ: Earlbaum, pp. 1–55.

Notess, C., 1961. The Effects of Atmospheric Turbulence Upon Flight at low Altitude and High Speed. Cornell Aeronautical Laboratory, inc., Flight Research Department.

Potter, R.L., Weldon, L.J., Shneiderman, B., 1988. Improving the accuracy of touch screens: an experimental evaluation of three strategies. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA, pp. 27–32. https://doi.org/10.1145/57167.57171.

Rekimoto, J., 2002. Smartskin: An infrastructure for freehand manipulation on interactive surfaces. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA, pp. 113–120. https://doi.org/10.1145/503376.503397.

Ren, X., Moriya, S., 2000. Improving selection performance on pen-based systems: a study of pen-based interaction for selection tasks. ACM Trans. Comput. Hum. Interact. 7 (3), 384–416. https://doi.org/10.1145/355324.355328.

Schwarz, J., Xiao, R., Mankoff, J., Hudson, S.E., Harrison, C., 2014. Probabilistic palm rejection using spatiotemporal touch features and iterative classification. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA, pp. 2009–2012. https://doi.org/10.1145/2556288.2557056.

Shneiderman, B., 1987. Direct Manipulation: A Step beyond Programming Languages (Excerpt). In: Baecker, R., Buxton, W. (Eds.), Readings in Human-Computer Interaction: A Multidisciplinary Approach. Morgan Kaufmann, pp. 461–467.

Soukoreff, R., MacKenzie, I., 2004. Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI. Int. J. Hum. Comput. Stud. 61 (6), 751–789.

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. https://doi.org/10.1080/00140139.2012.751458.

Surale, H.B., Matulic, F., Vogel, D., 2017. Experimental analysis of mode switching techniques in touch-based user interfaces. Proceedings of the CHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA, pp. 3267–3280. https://doi.org/10.1145/3025453.3025865.

Thomas, L., Foster, M., Nikolic, M., 2017. Touch screen bezel design for use in aviation operations. US Patent App. 14/853,501.

Thomas, P.R., 2017. Performance, characteristics, and error rates of cursor control devices for aircraft cockpit interaction. Int. J. Hum. Comput. Stud. https://doi.org/10.1016/j.ijhcs.2017.08.003.

Wang, F., Cao, X., Ren, X., Irani, P., 2009. Detecting and leveraging finger orientation for interaction with direct-touch surfaces. Proceedings of the 22nd Annual ACM Symposium on User Interface Software and Technology. ACM, New York, NY, USA, pp. 23–32. https://doi.org/10.1145/1622176.1622182.

Westerman, W., 1999. Hand Tracking, Finger Identification, and Chordic Manipulation on a Multi-Touch Surface. Ph.D. thesis. Last accessed: September 11, 2017

Westerman, W., 2015. Selective rejection of touch contacts in an edge region of a touch

surface. US Patent 9,041,663.
Wigdor, D., Wixon, D., 2011. Brave NUI World: Designing Natural user Interfaces for Touch and Gesture, 1st. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.
Williams, J., Foster, S., Clark, J., Schwartz, S., Pilcher, A., 2014. Turbulence mitigation for touch screen systems. US Patent App. 13/652,104.
Wobbrock, J.O., Myers, B.A., Kembel, J.A., 2003. Edgewrite: A stylus-based text entry method designed for high accuracy and stability of motion. Proceedings of the 16th Annual ACM Symposium on User Interface Software and Technology. ACM, New York, NY, USA, pp. 61–70. https://doi.org/10.1145/964696.964703.
Yau, Y.-J., Hwang, S.-L., Chao, C.-J., 2008. Effects of input device and motion type on a cursor-positioning task. Percept. Mot. Skills 106 (1), 76–90. https://doi.org/10.2466/pms.106.1.76-90.
Zammit-Mangion, D., Becouarn, L., Aymeric, B., Fabbri, M., Bader, J., 2011. A Single Interactive Display Concept for Commercial and Business Jet Cockpits. Am. Inst. Aeronaut. Astronaut.
Zhai, S., Kristensson, P., Appert, C., Andersen, T., Cao, X., 2012. Foundational issues in touch-surface stroke gesture design: an integrative review. Found. Trends Hum. Comput. Interact. 5 (2), 97–205. https://doi.org/10.1561/1100000012.