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Testing usability and trainability of indirect touch interaction: perspective for the next generation of air traffic control systems

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This study aims to determine whether indirect touch device can be used to interact with graphical objects displayed on another screen in an air traffic control (ATC) context. The introduction of such a device likely requires an adaptation of the sensory-motor system. The operator has to simultaneously perform movements on the horizontal plane while assessing them on the vertical plane. Thirty-six right-handed participants performed movement training with either constant or variable practice and with or without visual feedback of the displacement of their actions. Participants then performed a test phase without visual feedback. Performance improved in both practice conditions, but accuracy was higher with visual feedback. During the test phase, movement time was longer for those who had practiced with feedback, suggesting an element of dependency. However, this 'cost' of feedback did not extend to movement accuracy. Finally, participants who had received variable training performed better in the test phase, but accuracy was still unsatisfactory. We conclude that continuous visual feedback on the stylus position is necessary if tablets are to be introduced in ATC.

Practitioner Summary: We investigated the possibility of integrating a tablet computer as an input device in air traffic control. While we found that practice globally improved pointing performance, we concluded that the presence of continuous visual feedback on the stylus position is necessary to guarantee selection efficiency.

Keywords: air traffic control; tablet computer; aiming movements; visual feedback; training; control strategies

Introduction

Context

Air traffic controllers play a central role in managing air traffic control (ATC) and improving their interactions with systems is a key challenge to reduce errors (Chang and Yeh 2010). In a traditional ATC setting, controllers use paper flight strips to keep track of changes in flight parameters and maintain an accurate mental representation of the flight space. However, it is likely that these paper strips will soon become outdated as controllers are increasingly interacting directly with the radar screen to make flight modifications (e.g. the mouse and a drop-down list, or even the potential for eye gaze inputs; Alonso et al. 2012). Because such a system is instantaneously updated, not only can it prevent false alarms that often occur in more traditional systems – for example, receiving an alert when the controller has already changed an aircraft's flight parameters – but it also allows a more efficient and proactive management of potential conflicts and false alarms. This study aims to determine whether a computer tablet can be used to interact optimally with graphical objects displayed on another screen in an ATC setting. With this system, the controller might select the label of a flight displayed on the radar screen and change its parameters using a handwriting recognition device. The recent rise of touch screens or stylus-based screens seems to support this choice and the many hopes that such technologies can replace paper (Conversy et al. 2011).

The conventional tablet computer is an 'on-display' touch input device as the touch surface is coincident with the display surface. Whereas such devices provide excellent control–display compatibility along with direct coordination between hand and eye, they may not be optimal for air traffic controllers. In fact, 'off-display' touch input devices – where the touch surface is separate from the display surface – have potential advantages that could better suit the ATC context than on-display devices. Indeed, the separate positioning of the display (e.g. a radar screen) and touch surfaces could promote optimal viewing while minimising effortful arm movement or reaching towards the radar screen. Off-display devices can also prevent the hand from obscuring part of the display, and perhaps dangerous potential loss of information, when using the touch surface (Whitfield, Ball, and Bird 1983). In this sense, Alapetite et al. (2013) have shown that the use

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of a bottom deported touch screen together with a screen in front of the participant compares favourably against trackballs or head-down interactions. In addition, rather than an indirect input device (such as a mouse), the use of a direct input device (e.g. touch screen) involves a multisensory experience and more cerebral activities, leading to richer information encoding and consequently better information retrieval from memory (Sénécal et al. 2013). They showed that individuals with a higher need for touch are able to better recognise the stimulus encountered during their navigation using a touch screen instead of a mouse. The authors also revealed that the activity in the posterior parietal cortex, a brain region associated with multisensory experience, was affected by the type of input device (direct vs. indirect) in these participants during memory retrieval and stimulus recognition.

Tablet computers can emulate the behaviour of a mouse, but unlike the mouse, they can also be used to display useful information. Hence, the use of a touch surface separated from the radar screen could allow the display of additional information relevant to the controller such as meteorological conditions or digital strips. Yet, these benefits of off-display devices may not be sufficient to overcome the reduced control–display hand–eye coordination compatibility compared to on-display devices. Another potential drawback of off-display devices is the possibility that the controller may need to frequently shift gaze between the radar display and tablet, especially if relevant information is presented on the latter. This necessity could be problematic since switching gaze over a dynamic display may lead to undetected critical changes on that display (e.g. Boot et al. 2006; Vachon et al. 2012). In an empirical comparison of on- and off-display input devices, Whitfield, Ball and Bird (1983) demonstrated that the use of off-display devices carried no particular costs over their on-display counterpart, suggesting that the choice of the type of touch input device should be guided by the characteristics of the task to be performed.

The introduction of an off-display input device in ATC involves a new organisation of the work space and likely requires an adaptation of the sensory-motor system. Indeed, the controller must perform movements on the horizontal plane (the tablet on the desktop) while also assessing them on the vertical plane (the radar screen). This configuration potentially leads to greater difficulty in planning and controlling spatial aiming movements as compared to a more direct aiming movement situation (Alonso et al. 2009). Yet, previous work suggests that such decrease in performance may be limited by training, at least to a certain extent, even in situations where there is a discrepancy between the information provided by the visual system and what is perceived by the kinaesthetic system (e.g. if the touch screen is smaller than the radar screen; Ferrel et al. 2000). The availability of hand movement feedback relating the input device (i.e. the tablet) to the display seems to also improve pointing performance (Alonso et al. 2009). In addition, according to McLaughlin, Rogers and Fisk (2009), direct devices are not always easier to use than indirect ones. It depends on the overlap between device attributes and input requirements and the nature of the task (required level of precision, necessity or not to perform repetitive actions, etc.). All this literature suggests that a careful analysis of the effects of introducing a new input device is required, in particular in a safety-critical context such as ATC.

Impact of visual feedback and variable training on motor learning

Spatial aiming movements, in general from a home position to a target position, consist of two main phases: an initial impulse phase and a correction phase. The initial impulse is planned and assumed to move the limb into the vicinity of the target, while a correction phase guides the limb in a more controlled manner using visual and proprioception feedback. Classical studies have reported that performing variable movements – rather than repetition of the same type – improves the different phases of aiming movement and generally leads to more effective parameter specification in retention or transfer tasks (Schmidt and Bjork 1992; van Rossum 1990). Van Rossum (1990) suggested that practicing a variety of movements with an analogue motor programme – composed of elements with common invariant characteristics such as timing, relative force and sequences of actions – would enhance the development of rules for specifying future parameter requirements. In other words, varying the movement during practice helps the individual choose better parameters to execute the final movement.

It seems that the availability of visual feedback while performing an action also improves the different phases of movement. According to Saunders and Knill (2005), humans use continuous visual feedback from the hand to control and adjust both the direction and distance of pointing movements. Analyses of reaction time (RT) and kinematic movements (Bennett and Davids 1996; Carson et al. 1990) confirm the existence of different strategies depending on the sources of sensory information available (Khan and Franks 2000). Initial impulse planning is programmed more quickly when visual feedback is available, and this advantage can also help compensate for approximate planning at the initial impulse stage. However, the specificity-of-practice hypothesis (Proteau et al. 1987) suggests that practice with vision leads to dependence on visual feedback to control movements. For instance, Khan and Franks (2000) showed that the removal of vision between the acquisition phase and the test phase led to a decrease in performance as a function of the numbers of trials performed during training. On the other hand, when visual information was not available during training, individuals spent more time preparing their movement and became less dependent on the visual element (Khan et al. 2002). Interestingly, a more recent

study by Franklin et al. (2007) suggested that visual feedback of the hand's movement is not necessary for the adaptation to novel movements; rather, vision appears to be mainly used to fine-tune corrections of hand trajectory at the end of reaching movements.

Finally, a recent study with an iPad device investigated the amount of visual guidance required by users for precise back-of-device interaction (i.e. pointing on the back of the tablet without direct view on the hand). They showed that the removal of visual feedback (a dot on the visible face of the tablet) did not lead to significant quantitative or qualitative degradation in performance (Wolf et al. 2012). In this study, it seems that proprioception overcame the lack of visual feedback in back-of-device interaction as explained by the Sensorimotor Adaption Model (van Beers, Wolpert, and Haggard, 2002). It is noteworthy, however, that in Wolf et al.'s (2012) study there was no spatial translation between the target and the movement to perform, i.e. that participants' actions on the vertical and horizontal planes of the tablet directly mapped onto what was observed on the screen.

Present study

The development of next generation ATC systems will be associated with an increasing level of interaction between human operators and technology (Chiappe, Vu, and Strybel 2012), most likely to the detriment of tangible artefacts such as paper strips. While several solutions are envisaged to reduce controllers' mental workload and accident rate, ranging from increased automation authority (Prevot et al. 2012) to electronic strips (Mertz, Chatty, and Vinot 2000), to systems mixing augmented paper and digital pens (Hurter et al. 2012; Letondal et al. 2013), we explore here the possibility to introduce a touch screen device to interact with the radar screen. Before such a device can be introduced, it is necessary to study the impact that it might have upon all aspects of the task. The current study takes a cognitive systems engineering (CSE) perspective whereby the information system and its human operator are viewed as a single unit: the joint cognitive system (see Rasmussen, Pejtersen, and Goodstein 1994). The introduction of new technology should therefore team together with the operator to optimise overall performance, such that any benefit in one domain does not incur costs in another (e.g. Lafond et al. 2010).

In order to gain a comprehensive understanding of the effects of introducing a tablet computer to the air traffic controller, it is necessary to have an empirical assessment of the impact of the system on performance. We focused this study on pointing target selection, a recurrent activity for controllers (e.g. menu/aircraft-selection operations) that may benefit from touch screen usage. The use of such an interaction device must be assessed with regard to precision, velocity and safety requirements, essential to ATC activities. To gain insight into the conditions in which the introduction of such a technique should be done, in particular the type of practice to learn the aiming movements and the possible use of visual feedback, controllers used a tablet computer to perform pointing movements to reach targets displayed on another monitor, placed vertically in front of them. Each participant performed five blocks of training stimuli. One group performed movements in the 'full-vision' condition, in which a cursor representing the movements of the stylus above the tablet was displayed on the radar monitor. The other group made movements in the 'partial-vision' condition, in which no feedback on the stylus position was available on the radar monitor, but participants could have an approximate idea of the stylus position due to their peripheral vision. For both vision conditions, half of the participants practiced 'variable' movements with three distances and four directions, and the other half made 'constant' movements with only two directions and a constant distance. In the final test phase, all four groups performed novel aiming movements in the partial-vision condition only.

Hypotheses

Regarding the training phase, we expected better accuracy in the full-vision condition, but improved performance across the five blocks of stimuli for both groups. We also expected longer RTs in the partial-vision group (more time to plan movement) but shorter movement times (MTs) (no final fine tuning that requires vision). During the test phase, we hypothesised better performance for those who had practiced variable movements during training and poorer performance in the full-vision group, as the availability of visual feedback was removed between the training and test phases (Khan and Franks 2000). More generally, we examined whether accuracy in both groups would be compatible with the levels of efficiency required for ATC activity.

Method

Participants

Thirty-six controllers, all ENAC (Ecole Nationale de l'Aviation Civile) employees, participated in the study (mean age = 35.4 years, SD = 4.1). Although they were not professional air traffic controllers, they all had theoretical knowledge

of ATC activity and were familiarised with the ATC operational activity in a high-fidelity simulator. They were all right-handed and unaware of the purpose of the experiment. Participants were randomly assigned to one of the four experimental groups: (1) constant training/full vision, (2) constant training/partial vision, (3) variable training/full vision and (4) variable training/partial vision. This work received the ethics committee approbation CERUL 2010-028. Participants were not paid for their participation in the experiment.

Material

Participants were seated facing a video monitor at a distance of 80 cm (see [Figure 1](#)). They used a “Wacom Cintiq 18sx” tablet computer to perform horizontal pointing movements at targets displayed on the vertical monitor. An OptiTrack FLEX3 camera placed at 80 cm above the workspace analysed the trajectory of the pointing movements by means of a dot placed on the tip of the stylus. The camera provided real-time visual feedback (60-Hz refresh rate) about the movements of the stylus above the tablet, which was represented by a cursor on the monitor. The tablet and screen were the same size (18”) and the zoom lens camera was calibrated to lead to a scale equal to one: A stylus displacement of 1 mm was represented as a 1-mm shift of the cursor on the screen. It should be noted that even without the use of a camera, the Wacom tablet does allow the display of real-time visual feedback regarding the movement of the stylus above the tablet before it makes contact. Nevertheless, this detection is possible only when the stylus is very close to the tablet (about 1.5 cm) and, therefore, it does not display the feedback early enough. Alternatively, using the camera allows a display of feedback from the beginning of the movement. Given the financial and technical costs associated with implementing continuous visual feedback on the stylus position, we tested whether providing such feedback is mandatory to ensure selection efficiency in ATC or not.

Procedure

Participants were asked to use the stylus to perform aiming movements as quickly and accurately as possible on the horizontal touch screen to select graphical objects displayed on another screen (the horizontal radar screen). Nothing was displayed on the touch screen. Participants were instructed to look at the radar screen only (which was continuously verified by the experimenter). At the beginning of each trial, participants placed the tip of the stylus on the home position, the centre of the touch screen, which corresponded to a 2-cm square in the centre of the radar screen. Feedback about the stylus position on the tablet was displayed on the radar screen in all conditions (i.e. even in the partial vision) at this stage to help the participant to place the stylus in the home position before each trial. Contact on the home position for 200 ms triggered a 2-cm diameter target circle on the radar screen that participants had to select as fast as possible with the stylus on the digitised tablet. A target was marked as selected as soon as the stylus physically touched the tablet.

There were two distinct sessions during the experiment: a training phase and a test phase. During the training phase, after each selection, the target turned green if the participant correctly hit the target area, and red if he/she missed it. No such colour-change feedback was provided during the test phase. During the training phase, for the variable movement condition, the targets were located at 4, 8 or 16 cm from the home position, and at four different angles: 45°, 135°, 225° and 315° (clockwise, see [Figure 2](#)). For the constant condition, the targets were located 8 cm from the home position and at 45° or 135°. During the test phase, the targets were located at 12 cm from the home position and at an angle of 337.5°. For both groups we decided not to hide the tablet so that the controller could use peripheral vision during movements in order to have an approximate idea of the stylus position, representative of a normal operational context. Peripheral vision is known to play a role in rapid aiming movements (Bard, Hay, and Fleury 1985; Bard et al. 1990).

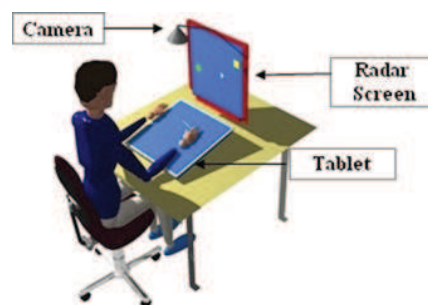


Figure 1. Illustration of the experimental set-up. The participant locates the target on the radar screen by pointing on the tablet with the stylus. The camera displayed the position of the stylus above the tablet on the radar screen in real time (full-vision group only).

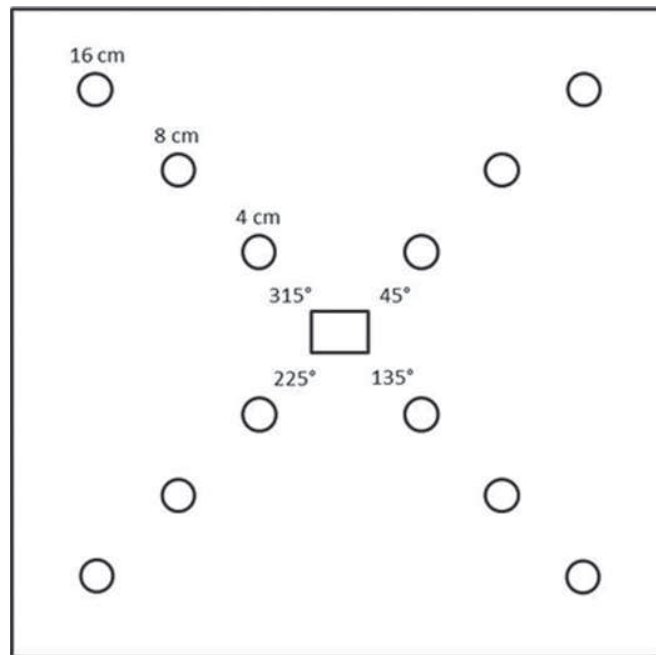


Figure 2. Illustration of the 12 possible target positions during the training phase according to the three distances and the four angles.

During the training phase, for the full-vision group, the camera displayed a cursor representing the position of the stylus on the tablet. In the partial-vision condition, the cursor was not displayed during movement, but appeared on the screen when the stylus touched the tablet in order to make participants aware of their errors and proximity to the target. In the test phase, all participants performed new aiming movements in the partial-vision condition only. All participants completed a total of 600 training trials, which were divided into five blocks of 120 trials. Each block included 12 groups of stimuli (3 distances \times 4 directions) of 10 trials for the variable condition and two blocks (1 distance \times 2 directions) of 60 trials for the constant condition. For the test phase, participants completed 10 trials, all with identical distance and direction parameters. The order in which all the stimuli were presented was randomised.

Dependent variables

The performance measurements were RT, MT and spatial error (SE). RT was the time between the appearance of the target and lifting the pen. MT was the time between the lifting of the stylus and the first contact with tablet. SE was calculated as the distance (in cm) between the endpoint of the aiming movement and the centre of the target (see Figure 3). These variables were selected because they are good indicators of selection efficiency using a tablet computer, which can directly impact ATC safety, especially when workload is high (e.g. when there are a large number of aircraft to manage). Indeed, a low level of spatial accuracy using a device could mean an increased number of attempts to select the correct aircraft or even worse, selection of the wrong aircraft. In addition, long RTs and MTs could be problematic in the case of conflicting aircrafts, where very prompt action must be undertaken.

Results

All data were analysed using Statistica 10 (StatSoft). For the training phase, we examined separately the partial-vision group and the full-vision group. The alpha level was set at 0.05.

Training phase

Reaction time

Figure 4 presents mean RTs obtained in both constant and variable training conditions as a function of vision condition and practice block. For each training condition, RTs were submitted to a 2 \times 5 mixed ANOVA with Practice (Blocks 1–5) as a

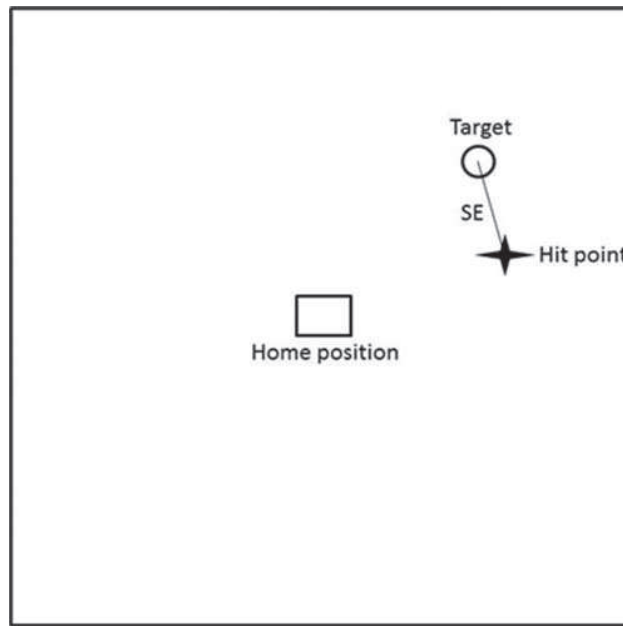


Figure 3. Illustration of spatial error. In this example, the participant achieved a very low accuracy.

within-subject factor and Vision condition (full vs. partial) as a between-subjects variable. In terms of constant training, the RT analysis yielded a main effect of Practice, $F(4, 56) = 4.13, p = 0.005, \eta^2 p = 0.23$, indicating a decrease in the time spent planning the aiming movement with practice. Paired-comparison tests revealed that RTs in Block 1 were significantly slower than in the other blocks (LSDs < 0.05). The main effect of Vision condition was also significant, $F(1, 14) = 8.30, p = 0.012, \eta^2 p = 0.37$, indicative of faster RTs in full vision (0.387 s) than in partial vision (0.489 s). We found no interaction between the two factors ($p = 0.126$).

The 2×5 ANOVA performed on RTs in variable training showed significant main effects of Practice, $F(4, 56) = 13.18, p < 0.001, \eta^2 p = 0.49$, whereby RTs decrease with practice, and of Visual condition, $F(1, 14) = 35.88, p < 0.001, \eta^2 p = 0.72$, revealing more rapidly initiated movements in the full-vision condition (0.344 s) than in the partial-vision condition (0.545 s). A significant Practice \times Vision condition interaction also emerged, $F(4, 56) = 5.19, p = 0.001, \eta^2 p = 0.27$, because the practice effect was limited to the partial-vision condition. More specifically, Block 1 RTs were

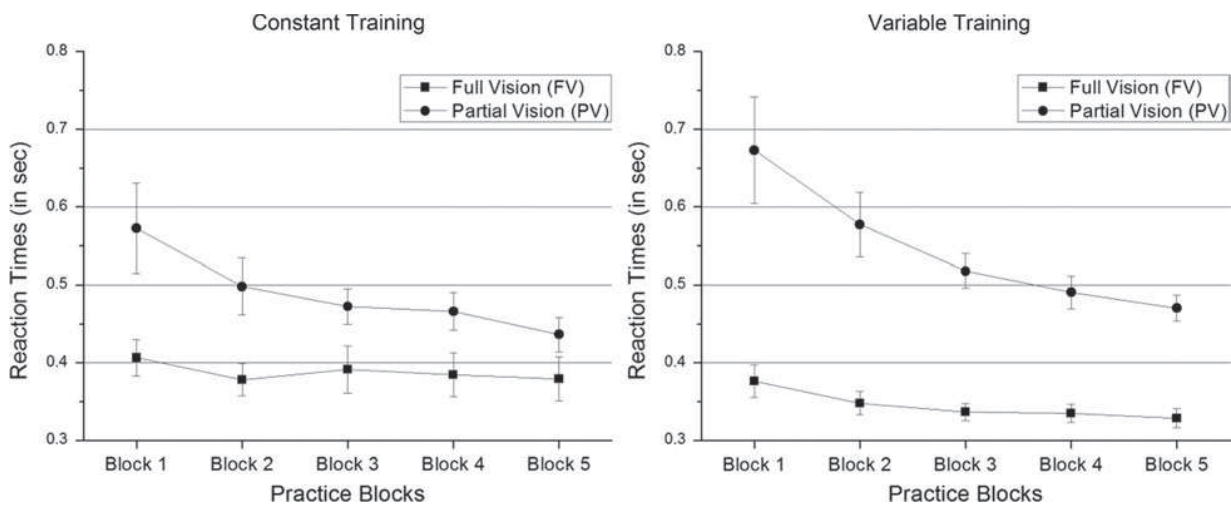


Figure 4. Mean reaction time (in s) in the full-vision and partial-vision conditions as a function of the five practice blocks for constant (left panel) and variable training (right panel).

significantly slower than the four other blocks (LSDs < 0.001) while Block 2 RTs were significantly longer than in Blocks 3–5 (LSDs < 0.050).

Movement time

Mean MTs presented in Figure 5 were submitted to the same 2×5 mixed ANOVA separately for both forms of training. For constant training, the analysis revealed a significant main effect of Practice, $F(4, 56) = 21.28, p < 0.001, \eta^2 p = 0.60$, suggesting that MTs speeded up with practice. The main effect of Vision condition was also significant, $F(1, 14) = 32.97, p < 0.001, \eta^2 p = 0.70$, because MTs were slower in full vision (0.698 s) than in partial vision (0.397 s). The two-way interaction was not significant ($p = 0.085$).

For variable training, the ANOVA also yielded significant main effects of Practice, $F(4, 56) = 7.88, p < 0.001, \eta^2 p = 0.36$, and Visual condition, $F(1, 14) = 9.41, p = 0.008, \eta^2 p = 0.40$. These results indicate that MTs decreased with practice and were faster in the partial-vision condition (0.480 s) than in the full-vision condition (0.707 s). The Practice \times Vision condition interaction was significant, $F(4, 56) = 3.00, p = 0.025, \eta^2 p = 0.18$, because the practice effect on MTs was limited to the full-vision condition. Further analyses in this condition showed that Block 1 MTs were significantly slower than in the later blocks (LSDs < 0.001), while Block 2 MTs were significantly longer than Block 5 MTs (LSD < 0.050).

Spatial errors

Mean SEs presented in Figure 6 were submitted to the same 2×5 mixed ANOVA separately for both forms of training. Regarding the constant training, the analysis yielded a significant main effect of Practice, $F(4, 56) = 4.84, p = 0.002, \eta^2 p = 0.26$, revealing that SEs diminished with practice, especially after Block 1 (LSDs < 0.050 with all four other blocks). The main effect of Visual condition was also significant, $F(1, 14) = 44.26, p < 0.001, \eta^2 p = 0.76$, because participants in the full-vision group had lower average SEs (0.552 cm) than the partial-vision one (0.878 cm). No interaction was found between the two variables ($p = 0.082$).

For variable training, the analysis of SEs also yielded significant main effects of Practice, $F(4, 56) = 16.09, p < 0.001, \eta^2 p = 0.53$, and Visual condition, $F(1, 14) = 145.21, p < 0.001, \eta^2 p = 0.91$. As for constant training, these results indicate that SEs decreased with practice and that the partial-vision condition was more prone to SEs than the full-vision condition. More importantly, the ANOVA revealed a significant Practice \times Vision condition interaction, $F(4, 56) = 8.74, p < 0.001, \eta^2 p = 0.38$, whereby the improvement found with practice was limited to the partial-vision group only. Further analysis of this condition showed that errors in Block 1 were significantly greater than in the four other blocks (LSDs < 0.001), errors in Block 2 were significantly larger than in Blocks 4 and 5 (LSDs < 0.005) and errors in Block 3 were significantly greater than in Block 5 (LSD < 0.010).

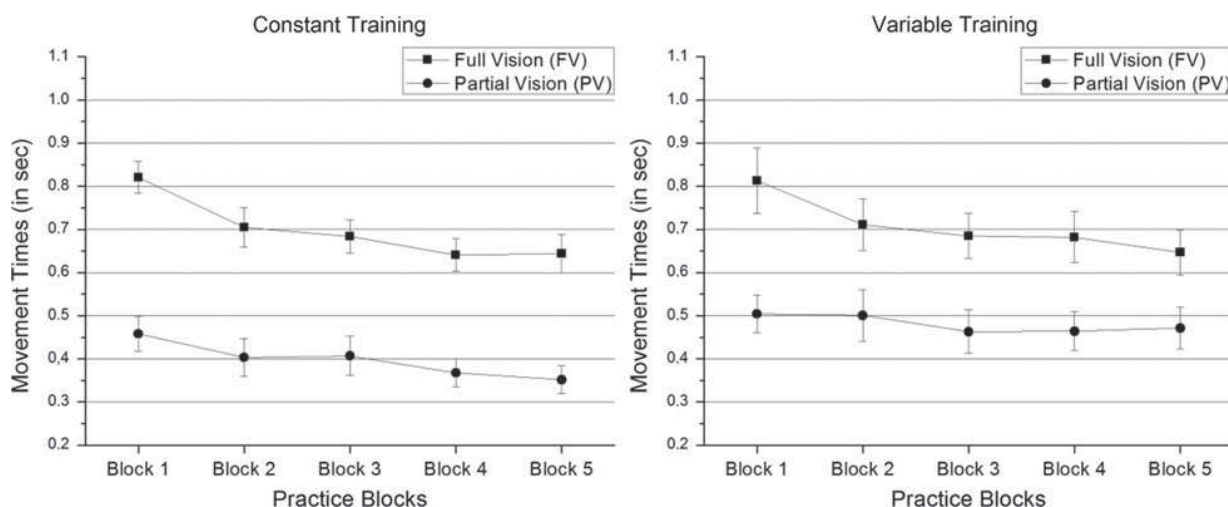


Figure 5. Mean movement time (in s) in the full-vision and partial-vision conditions as a function of the five practice blocks for constant (left panel) and variable training (right panel).

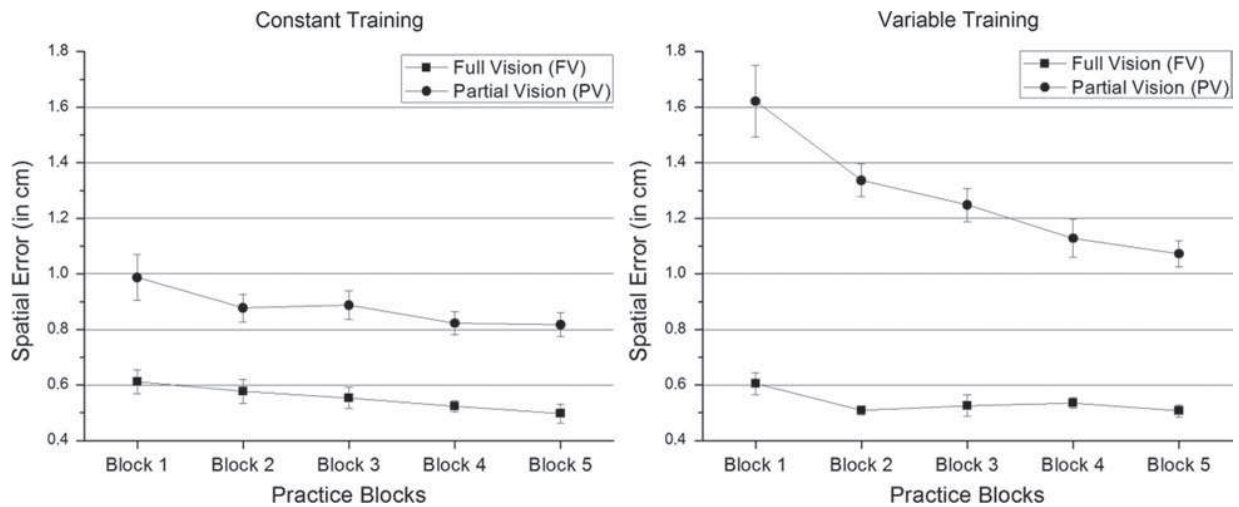


Figure 6. Mean spatial errors (in cm) in the full-vision and partial-vision conditions as a function of the five practice blocks for constant (left panel) and variable training (right panel).

Test phase

Reaction time

Figure 7 presents mean RTs observed in the test phase as a function of the type of training (constant vs. variable) and the vision condition (full vs. partial). The 2×2 ANOVA performed on these data revealed a main effect of Training type, $F(1, 28) = 4.28, p = 0.047, \eta^2 p = 0.13$, because RTs were faster for participants who performed variable training than for those who completed the constant training (0.386 s vs. 0.451 s, respectively). There was no main effect of Vision condition ($p = 0.859$) and no significant interaction ($p = 0.272$).

Movement time

MTs obtained during the test phase are plotted in Figure 8 as a function of training type and vision condition. The ANOVA carried out on these data revealed a significant main effect of Training type, $F(1, 28) = 6.72, p = 0.014, \eta^2 p = 0.19$, indicating that MTs were longer for the participants who performed variable training in comparison to the constant training group (0.596 s vs. 0.454 s, respectively). The main effect of Vision condition was also significant, $F(1, 28) = 4.32, p = 0.046, \eta^2 p = 0.13$, showing that MTs were longer in the full-vision group than in the partial-vision group (0.558 s vs. 0.466 s, respectively). However, no interaction was found ($p = 0.743$).

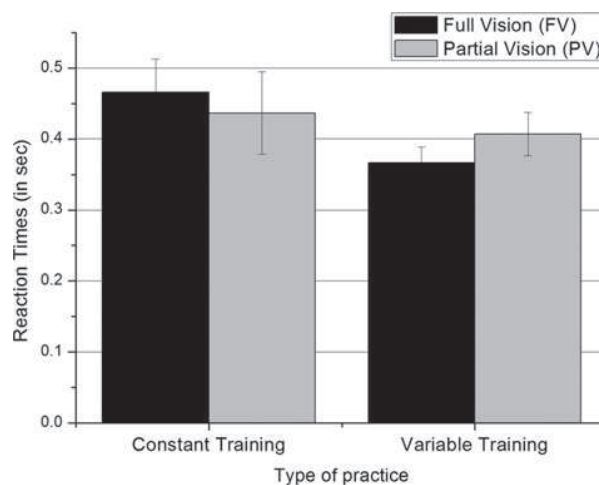


Figure 7. Mean reaction times (in s) in the test phase as a function of training type and vision condition.

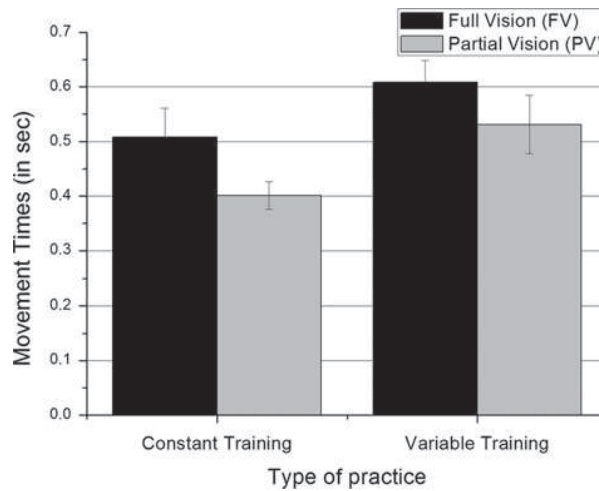


Figure 8. Mean movement times (in s) in the test phase as a function of training type and vision condition.

Spatial errors

Figure 9 presents mean SEs obtained by the four groups during the test phase. The 2×2 ANOVA performed on these data yielded a significant main effect of Training type, $F(1, 28) = 11.10, p = 0.002, \eta^2 p = 0.28$, indicative of smaller SEs with variable training than with constant training (1.80 cm vs. 2.71 cm, respectively). However, neither the main effect of Vision condition ($p = 0.386$) nor the two-way interaction was significant ($p = 0.427$).

Summary of results

To summarise, results from the training phase revealed that performance in terms of RT, MT and SE improved quickly through practice. More importantly, the presence of feedback about the position of the stylus improved RTs and spatial accuracy but lengthened MTs regardless of the type of training. Yet, this impact of continuous visual feedback was particularly marked in the first blocks of variable training. With regard to the test phase, in which no feedback was provided, the results showed that participants who completed the variable training were faster to react (i.e. RT) and more precise at selecting targets (i.e. SE) while being slower at producing aiming movements (i.e. MT) than those who performed constant training. The impact on performance in the test phase of having access to continuous feedback during training was limited only to changes in MTs. Indeed, training with visual feedback tended to slow down the production of aiming movements when such feedback was no longer available in the test phase.

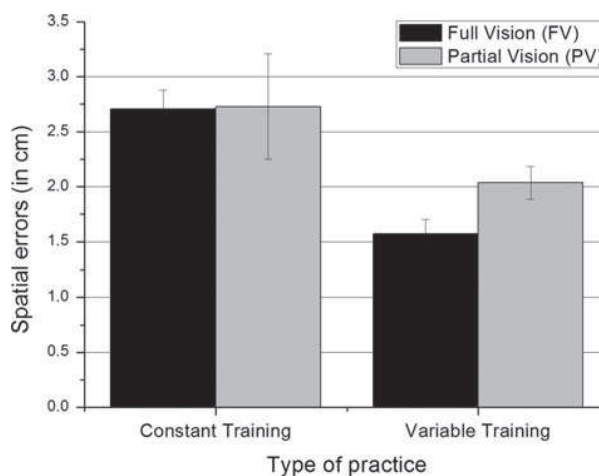


Figure 9. Mean spatial errors (in cm) in the test phase as a function of training type and vision condition.

Discussion

This study aimed to determine whether a tablet computer could be used to interact with a graphical object displayed on another screen in an ATC context. Since removing visual feedback about the stylus position would allow the use of cheaper standard tablet computers, we assessed whether it is possible to use a tablet without a camera providing visual feedback on the movements made. A secondary goal was to examine the effects of different types of training (involving either constant or variable movements) on performance during a test phase with no feedback and requiring novel movements.

The analysis of the training phase provides evidence that practice (across the five blocks) globally improved performance for each dependent variable (RTs, MTs and SEs). This outcome was significant regardless of the type of training. With regard to the feedback about the position of the stylus, the results demonstrated that receiving continuous visual feedback resulted in faster initiations of the aiming movement (i.e. shorter RTs) but in longer production of the aiming movement (i.e. longer MTs) than in the absence of explicit feedback. This result is in line with Khan et al. (2002) who showed that individuals spend more time preparing movement when visual information is not available; when this information is available, individuals spend less time preparing and depend instead on visual feedback to perform the movement. Consistent with this, Franklin et al. (2007) suggested that visual feedback is useful for fine-tuning hand trajectory corrections at the end of reaching movements. In fact, visual feedback has been shown to provide a signal for correction of the hand trajectory even under conditions where the hand is not visible (e.g. Goodale, Pelisson, and Prablanc 1986; Prablanc, Pelisson, and Goodale 1986) as in the present experimental set-up. This explanation can account not only for the increase in MT but also for the better spatial accuracy observed in the full-vision condition. Indeed, participants in the full-vision group had lower average SEs than the partial-vision one during the training phase. With visual feedback of the stylus position, the estimated state of the hand/limb would be improved (cf. Franklin et al. 2007), resulting in reduced endpoint variability, hence better precision towards the end of the movements. This improved spatial accuracy is contrary to the results obtained by Wolf et al. (2012) who showed that the removal of visual feedback (a dot on the visible face of the tablet) did not lead to significant quantitative or qualitative degradation in performance. However, unlike in the present research, their study did not require spatial translation between the target and the movement to perform (i.e. between horizontal and vertical planes). Thus, the present findings suggest that removed off-display touch input devices that do not map actions exactly onto what is observed on the screen, such as the one in the present study (e.g. that require translating an upward action into a forward motion), would strongly benefit from continuous visual feedback.

During the test phase which had no visual feedback, participants who had received variable training were more accurate than those in the constant training condition. This result supports the hypothesis that variable training is more effective to develop motor programmes, leading to better transfer to new movements (van Rossum 1990). Interestingly, variable training resulted in faster RTs but longer MTs in the test phase than constant training. It suggests that faster motor programming (i.e. RT) needs to be counterbalanced by more pronounced online motor control (i.e. MT). However, it appeared that total movement time (RT + MT) for both full- and partial-vision groups was nearly equivalent for constant and variable training (0.905 s vs. 0.955 s, respectively), which confirms that the type of training has no major impact on the total velocity with which the movements are performed. In line with the specificity-of-practice theory (Proteau 1992), which predicts that training with visual feedback would eventually lead to dependence on such feedback to control movements, the full-vision group took longer to produce aiming movements (i.e. MT) in the test phase (i.e. in the absence of visual feedback) than the partial-vision group. However, such a 'dependency' upon feedback was restricted to the time required to produce the movements, while movement accuracy in the no-feedback test phase was similar whether participants trained with or without continuous feedback. In any case, the beneficial contribution of visual feedback to participants' performance revealed earlier calls for providing such feedback at all time. Hence, we recommend that to introduce the tablet computer in the field of ATC, controllers should be trained *and* work with such an input device always in the presence of continuous visual feedback about the stylus position.

The iterative approach in the development of human-machine interfaces (HMI) involves the validation of design choices in terms of both aspects of design and means of interaction. In the case of complex interfaces, to conduct evaluations of such choices can be very difficult and expensive. The increasing level of computerisation will inevitably result in more interaction between human operators and computers in ATC. Methodologically, we used a simplified reproduction of the envisaged ATC system and focused our investigations on the possibility to introduce a touch pad as a new pointing device. We believe that this platform represents a first step to evaluate innovations as it provides an optimal balance between ecological validity and experimental control. This approach enables ergonomists and engineers to evaluate ATC HMI solutions in a simplified and controllable environment (Parise et al. 2012). This simplified set-up is the first step before using the more elaborate context of an ATC microworld and represents an interesting stage along the CSE continuum of applied research (Rasmussen, Pejtersen, and Goodstein 1994). Our simulation used the recurrent ATC selection task and was sufficiently engaging and relevant to the participant, but requires fewer human resources than implementing more

complex simulations. Its flexibility for different configurations and manipulations means that it is possible to develop and evaluate different designs with short iterative cycles, in order to establish a clearer relationship between variables within a realistic context. At a more advanced stage it would be necessary to validate the effects obtained with our environment in a more complex simulation, and then an operational setting using professional controllers.

Conclusion

The goal of the study was to assess whether a tablet computer could be used as an input device for air traffic controllers with enough efficiency. In the final block of the training phase, aiming movements deviated an average of 0.544 cm from the target in the presence of continuous feedback, whereas the average SE was about twice as large (1.079 cm) in the absence of such feedback by the end of the training. Given the safety-critical nature of ATC, this outcome clearly indicates that visual feedback remains necessary. This conclusion is bolstered by the finding that when visual feedback is no longer provided – i.e. during the test phase – aiming movements tended to deviate even further from the target (mean SEs of at least 1.6 cm), regardless of the type of training received. Indeed, in an ATC context, controllers interact with rather small graphical objects, and we assume that such an accuracy level would not be sufficient to guarantee safety, even with more extensive training. Another benefit of providing visual feedback is to avoid displaying the radar screen on the tablet and, thus, preventing frequent gaze switching between the radar and the tablet. Such gaze switching over a monitoring display can increase the tendency to miss critical events (e.g. Boot et al. 2006; Vachon et al. 2012), which, in turn, could lead to disastrous consequences (see Varakin, Levin, and Fidler 2004).

Of course, the presence of feedback did not come without any drawbacks. Beyond the financial and technical costs of introducing continuous feedback, it appears that aiming movements tended to take longer to produce when participants relied on feedback to perform the task. However, we judge that this time penalty was not large enough (about 0.225 s, on average) to affect the timeliness of air traffic controllers' actions. Nevertheless, when considering the trade-off in ATC between the necessity of minimising human error and the advantages of producing faster responses, the present findings clearly indicate that the benefits of providing continuous visual feedback on the movement of the stylus in terms of accuracy overcome the drawbacks associated with implementing this technology. Therefore, we conclude that the presence of continuous visual feedback on the stylus position is required to use a digitised tablet for ATC.

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