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The influence of augmented reality interaction design on Pilot's perceived workload and situation awareness

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ABSTRACT

This work explored the potential for Augmented Reality (AR) rendering information superimposed over the flight deck to increase a pilot's situation awareness (SA). This emerging technology introduced novel human-computer interaction paradigms that would have impact on pilot's cognitive demands. The objective of this research was to evaluate both the pilot's perceived workload and SA while interacting with an AR device using different interactive modes. Participants performed traditional landing checklists as a baseline to compare with the AR gesture-command and voice-command checklists. The research results showed that gesture-commands created additional cognitive and physical demands. Conversely, voice-command checklists could constitute a significant improvement in terms of reducing participants' perceived workload and maximising SA performance. The findings provided evidence that the interactive modes of AR user interface design could influence participant's cognitive information processing and perceived workload in flight operations. However, there were some limitations with AR applications that included latency on response time, narrow field of view, accuracy of voice recognition, calibration within dynamic environment and inexplicable movements of the head position that required further investigation. An AR device can be a great tool for training at the initial stage to increase cost-efficiency in flight operations. Furthermore, the implementation of an AR design may provide part of the potential solution for single pilot operations in the future.

1. Introduction

The increasing sensory information in the flight deck may result in a cognitive burden and reduce pilot's situation awareness (SA). Highly automated cockpit has evolved to encapsulate a plethora of human-computer interaction (HCI) issues. This raises questions around the efficiency of interactions with automated systems on the flight deck (Dorneich et al., 2016). Emerging head-mounted AR technologies can display rich textual and graphical imagery overlaid upon the operational environment and permit intuitive interaction through gestural and voice modes (Gardony et al., 2018). The development of pilot aids such as augmented visualization and augmented reality (AR) devices shall be considered for the initial stage of flight deck design (Dorneich et al., 2017). HCI research on the impact of AR on the user's perception and cognition has gained importance in recent years due to the advancing technology (Spicer et al., 2017). AR renders 3D content superimposed over the real-world by allowing the user to remain conscious of changes within the surrounding environment to maintain SA. This contrasts with immersive Virtual Reality (VR) which removes the user from the surrounding environment-drastically reducing situational awareness and inducing spatial disorientation (Knibbe et al., 2018). Human perception is constructed in real time by integrating different sensory modalities which consist of vision, auditory, haptics and somatosensory. The multisensory integration mechanism is critical to perception, cognition, and adaptive behaviours. The most common feedback on HCI interface design is visual and auditory during interaction with technology (Obrist et al., 2016). Current AR applications have a potential impact on operator performance and perceived workload in safety-critical systems (Stanton et al., 2016) in differing ways. Therefore, the application of innovative AR technology in the flight deck requires further investigation for validation and certification purposes.

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2. Related work

2.1. Benefits of applied augmented reality in industries

AR aims to alter the operator's perception of reality and provide support to users through integrated digital content and enhanced perception with the real world. These characteristics have increased researchers' interest to explore the system usability, monitoring performance and cognitive loads related to AR applications (Beitzel et al., 2016). Moreover, with the development of visual technology, the display resolution of AR device continues to improve, making AR devices far more relevant to real-world applications (Aromaa et al., 2020). AR has been applied in many fields to benefit the cognitive process, increasing task performance, speeding up the completion time and decreasing the cost of operation process (Carmigniani et al., 2011). Furthermore, AR technology could support pilots by making meaningful connections between virtual representations of SOPs and specific levers and gauges in the physical environment (Cecilia and Marti, 2005). The use of augmented visualization on head up displays (HUD) have extended from military aviation to become prevalent in civil aviation on aircraft such as the Boeing 787 and Airbus A350 (Yeh et al., 2003). Virgin Atlantic has implemented a similar AR application to train flight crew members (Virgin, 2018).

Flight operations require real time information to be perceived, analysed, and filtered for pilots to make in-flight decisions under time pressure. Pilots have to process large amounts of information resulting in a high mental workload (Dorneich et al., 2016). The presentation of augmented visualization allows pilots to update their mental model and enhance SA on a momentary basis (Grabowski et al., 2018). The most prevalent AR device is the Microsoft HoloLens with applications in aerospace, manufacturing, automobile, medical, and entertainment industries (Carey, 2018). Boeing has tested the use of HoloLens in its procedure for installing wiring on 767 and 747 production lines for a reported 90% reduction in "first time error rate" and a 30% improvement task completion time (Boeing, 2018). Starting the Auxiliary Power Uni (APU) task by AR device has also shown a significantly faster task completion time and notably more fluency and ease in the ability to locate and procedurally "flow" through checklist items required (Borgen et al., 2021). It is also predicted that the use of the AR device will reduce the training time for flight operation per trainee by approximately 75% compared to traditional methods of classroom instruction and practical application (MacPhedran, 2018).

2.2. Cognitive process on HCI

It is often observed that there are sequential multitasking activities confronting pilots (Wickens et al., 2003). This sequential multitasking in flight operations includes how the pilot scans the aircraft instrument panel and may serve different sub-tasks, such as the control of heading, altitude, or the display of navigational hazards. The cognitive process of task switching described requires a high level of SA to make appropriate decisions in safety critical and dynamic systems. An AR can be shown to support information processing mechanisms, since the virtual objects did not require any continuous interaction and could instead provide augmented support to enhance the operator's SA (Aromaa et al., 2020). SA was described by Endsley (1988) as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future". The dynamic cues provided by augmented visualization on AR devices could lessen pilots' cognitive loads by following visual cues that facilitate attention distributions and SA on the flight deck (Li et al., 2020).

AR devices can allow the operator to attain requisite variety for multiple methods of interaction including gesture-command and voice-command. AR devices can mitigate the problems by projecting visual feedback on the interface and auditory feedback through device speakers, hence improving operator's SA performance and decision-making (Rowen et al., 2019). The application of AR in flight deck Head-up displays (HUDs) provides operational benefits on SA and workload for the flight crew (Kramer et al., 2009). The interface designs relating to the effectiveness of HCI could also affect the level of physical demand, mental demand and lack of comfort while performing safety-critical tasks due to the burdensome weight on head-mounted display (Kim et al., 2019). Alternatively, AR could reduce the cognitive workload by integrating multiple sources of information (Neumann and Majoros, 1998). AR technology provides a highly supported operational environment that replaces traditional instructions and procedural descriptions with multimedia data. Operators not only can complete tasks quicker but also reduce mental workload to comprehend the presented information, thus improving the operational efficiency and task performance (Chu and Ko, 2021). It has been demonstrated that the use of AR has helped engineers to reduce the cognitive workload on comprehension time and their overall efficiency in maintenance tasks (Yang et al., 2019).

2.3. Evaluation of cognitive demands on an AR application

The correct assessment of AR application linked to pilot's workload and SA is of critical importance in safety and human factors in aviation. The NASA-TLX and SART-10D are popular subjective measurements of cognitive demands which measure an operators' perceived workload and SA on completion of a task (Taylor, 1990; Hart and Staveland, 1998; Endsley et al., 1998). Workload is normally self-evaluated and reflects an individual perception of a multidimensional concept, covering mental and physical effort, frustration, or time constraints that go beyond the objective task difficulty and demands (Fernandes and Braarud, 2015). The evaluation of cognitive workload often leads to variations in multiple dimensions and disentangling each respective impact remains complex. However, an intensive cognitive activity may yield a high level of workload without eliciting a high level of stress, and thus a high level of stress might occur even when the workload is low (Hidalgo-Muñoz et al., 2018). There are three main methods to measure cognitive workload: subjective surveys, performance metrics and assessing physiological response - each method has strengths and weaknesses when applied to real-world research (Hart and Staveland, 1988).

Pilots' cognitive process in the flight deck is both environment and subject dependent. It changes amongst different operational stages, complexity of tasks and the design of automated systems. Pilots' perception, comprehension, and projection of dynamic information on the flight deck reflect the requirement of three-level SA in the current operational environment and tasks (Endsley, 1995). Measures of SA provide an index of how well operators can integrate information in a complex environment where data may strive for their attention. Several techniques for SA measurement have been developed, one of which most used and tested widely is Situational Awareness Rating Technique (Taylor, 1990). SART is a simplistic post-trial subjective assessment that was originally developed for assessing pilot's SA based on their performance of the current task. The ratings are then combined into the three dimensions: Demands on attentional resources, supply of attentional resources, and understanding of the situation. SART ratings have been found to be correlated with operator performance in evaluations of cockpit designs and subjective measures of workload (Selcon and Taylor, 1990).

2.4. Implication and hypotheses

The implementation of AR on the flight deck introduced new HCI paradigms by blending augmented visual stimulus and objectives with the operating environment. The design principles of AR must be consistent with human cognitive information processing, which is the key element in ensuring innovative technology can be used by human operators. The AR checklist developed in this research has holographic interactive menus, voice-controls vs gesture-control, and spatial overlay. The use of AR gesture-commands has been compared with voice-commands since both interactive modes are available with the first-generation HoloLens. The direction indicators of guiding arrows and spatial highlights have been added to facilitate the pilots' SA. This study has been motivated by previous research on AR applications for flight deck design and single pilot operations (Tran et al., 2018; Comerford and Johnson, 2007; Hilton, 2012). The rationale is that well-designed AR interaction modes can improve pilots' SA and reduce perceived workload. Pilot's cognitive aspects when correlated to the properties of an AR device has been shown to influence on the pilot decision to offload information processing by means of supplemented visual cues (Fiore and Wiltshire, 2016). The objectives of this research were to evaluate the cognitive demands and SA while using different AR interactive modes during an Instrument Landing. The participants experience with traditional checklists was used as the baseline for comparison with AR gesture-commands and voice-commands. To ensure participants had same level of familiarity with the interface and interactive modes on an AR device, participants were inviting to conduct a tutorial briefing on the HoloLens and practice the ILS landing whilst wearing a HoloLens device until they felt comfortable to start the trials. Therefore, the research has identified the following two hypotheses regarding the pilots' perceived workload and SA while interacting with AR control modes:

H1. There is a significance on pilots' perceived workload using different AR interactive modes on ILS landing

H2. There is a significance on pilots' situation awareness while using different AR interactive modes on ILS landing

3. Method

3.1. Participants

There were 34 participants including 6 females (17.65%) and 28 males (82.35%), aged between 21 and 55 years old (M = 29.79, SD = 9.85) attending this trial. All participants were from the aviation industry including 15 pilots (44.12%) and 19 avionics engineers (55.88%) with flight experience (M = 436.00, SD = 915.45). The pilots consist of six commercial pilots (40.00%), three military pilots (20.00%), and six private pilots (40.00%), and their flight experience is from 50 h to 3000 h (M = 987.20, SD = 1179.78). A research proposal was approved by the research institute ethics committee before conducting the experiment, since this research involved collecting data from human subjects. Each participant was required to sign a consent form which provided detailed information related to the experiment and content of the data collection. Participants were also informed that they had the right to terminate and withdraw from the experiment at any stage even after the data collection phase. This research has followed the data protection act which is the UK's implementation of the general data protection regulation (GDPR).

3.2. Apparatus

3.2.1. Flight simulator

The experiment was run on the Large Aircraft Flight Simulator with a representative model of the Boeing 747 flight deck. It comprises of a realistic mock-up of the cockpit of a Boeing commercial aircraft with functioning flight controls, stick-shaker stall warning, over-speed alerts, primary flight and navigation displays, and landing gear lever to name a few. The simplified overhead panel is composed of light switches, engine fire emergency levers and engine ignition switches (Fig. 1a). The ICAO (2013) international working group established a new methodology for the development of a recurrent training and assessment programme known as Evidence-based Training (EBT). The aim of this programme is to identify, develop and evaluate the competencies required to operate safely and efficiently in a commercial flight operation whilst addressing the most relevant threats according to evidence collected during accidents/incidents and training. The scenario investigated by this research is an Instrumented Landing System (ILS) during final approach. The rational for selecting an ILS scenario for testing AR interactive modes is that the ILS provides pilots with both vertical and horizontal guidance during an approach to land and is used for the majority of landings in flight operations that relate to HCI and aviation safety. ILS is most beneficial when the visibility is poor, since it allows the pilots to fly the aircraft all the way down to the runway precisely. For the investigated scenario, the aircraft is set at 2000 ft and eight nautical miles (NM) from the airfield. As soon as the simulation starts, participants must execute a pre-landing checklist by interacting with the AR device and flying the aircraft to a successful landing.

3.2.2. Augmented reality device

The Augmented Reality device used in the experiment is the first-generation HoloLens headset (Fig. 1b). These glasses comprise see-through holographic waveguides, two HD 16:9 light engines and built-in processors that can display holograms with a resolution of 1280 × 720 pixels per eye, a FOV of 30° × 17.5° and a refresh rate of 60 Hz. Brightness and audio volume can be adjusted by 4 buttons located on the headset. The HoloLens comes with built-in sensors: an Inertial Measurement Unit (IMU), four environment understanding cameras, one depth camera, one 2 MP photo/HD video camera, four microphones and one ambient light sensor. Its audio output consists of two speakers located near the user's ears that can emit spatial sound. The colour contrast of an AR application depends on the light and colour conditions of the user interface design, which can be variable, as there is flexibility to established rules for AR UI design (Microsoft, 2015).


a b

Fig. 1. The cockpit display systems on flight simulator on the scenario of instrument landing (1a); participant wears the head-mounted display Augmented Reality device (HoloLens) during the experiment (1b).

3.3. Application on AR device

The application to create virtual checklist SOPs on the HoloLens has been developed using the Unity 3D game engine and Microsoft Mixed Reality Toolkit (MRTK) and prepared specifically to be used with the B747 simulator. Participants must follow the procedures to control flap, airspeed, altitude, descent rate, flare, and touchdown for safe operation. Interacting with the virtual checklist can be triggered either by voice control or gesture control (air-tap). With gesture control, the participant moves the central cursor with his head and selects a checklist item by placing the cursor over it and by performing the “air tap” gesture within the depth camera FOV (Fig. 2a). With voice control, all the visual cues and physical setting in the flight simulator are exactly the same with gesture-control; the only difference is that participant must read aloud the checklist title in order to activate it and validate each checklist item by stating “Check”. The virtual SOPs on the HoloLens that are integrated with the flight simulator include: Flap 30-Degree, Landing Gear-DOWN, Speedbrakes-ARM, Landing Lights-ON (Fig. 2b). The symbolic objects on the HoloLens that are linked to the visual appearance provide the user with valuable indications of the functions and actions, such as arrow, circle, QR-code, and rectangle with text (Fig. 3a, b & 3c). The yellow arrow indicators and attentional cycles on the AR checklist are to increase participants’ SA during flight operations. The corresponding animation within the AR can facilitate participants’ attention to the clue to reduce cognitive demand.

3.4. Research design

Participants were briefed that the experiment would involve them wearing a HoloLens AR device and that they would be required to perform an instrument landing procedure in a flight simulator using different types of interaction modes for checklists. Due to the limitations on collecting flight data and pilot’s performance, this study has only analysed pilots’ situation awareness and perceived workload based on the subjective questionnaires of NASA-TLX and SART-10D. Participants are required to fill in the questionnaires immediately after each trial. All participants had no previous experience using the HoloLens AR device. Therefore, familiarity with the HoloLens interactive modes is a critical factor to this research. Participants received the same instruction and demonstration on how to interact with HoloLens for instrument landing using gesture-command and voice-command interactive modes. Each participant had been offered sufficient time for practicing HoloLens until they were comfortable with the different interactive modes. All participants had accurately interacted with the HoloLens using both air-tap and voice-command in a range between five to 10 min. The procedures for all participants were as follows: (1) complete the demographic variables including age, gender, qualifications, and total flight hours (5 min); (2) complete a briefing regarding the purpose of the study and how to interact with HoloLens on the instrument landing scenario (10 min); (3) participant sat in flight simulator (Fig. 3a) to calibrate the AR device (Fig. 3b) (5 min); (4) familiarization with the instrument landing checklist on the simulator (10 min); (5) briefing on the AR checklist application as shown in Fig. 3c, with a detailed explanation of the visual highlights by gesture control and voice control (10 min); (6) perform a landing using three different checklists randomly: traditional checklist, HoloLens AR gesture command checklist and AR voice command checklist (each scenario lasting between three and 5 min depending on the participant’s experience and operational performance). A random table for these three different types of checklists was generated to counterbalance practice effects; (7) complete evaluation forms using both NASA-TLX and SART-10D and provide feedback regarding the cognitive demands of using an AR device during flight operations (15 min). The duration of the experiment lasted around 70 min for each participant.

3.5. Statistical analysis

To investigate the effects of the three interactive modes of checklist on both pilot’s perceived workload and SA when performing ILS pre-landing checklists, one-way repeated measures ANOVA is applied on data analysis. The application of one-way repeated measure ANOVA can eliminate the influence of participants’ individual differences (such as flight experience), so that an unbiased analysis on the three interactive modes can be obtained. The outliers were tested based on the lower quartile (Q_1, 25th percentile) and upper quartile (Q_3, 75th percentile) in the boxplot. The upper and lower fences are set at 1.5 times the inter-quartile range (Q_3-Q_1), and any observation outside these fences is considered a potential outlier. The assumption of normality was checked visually by Q-Q plots. The observed values lie close to and approximately distribute evenly on both sides of the reference line of standardized normal distribution, which indicates that these data sets are in the normal distribution. Mauchly’s test was used to verify the homogeneity of covariance assumption. The Huynd-Feldt correction would be applied if the Mauchly’s test were violated. The post-hoc pairwise comparisons were performed by Bonferroni, and effect sizes of samples were quantified by partial eta square (η_p^2).

4. Results

4.1. Sample characteristics

Sample size is a crucial characteristic of experimental analysis, especially when the population parameters are unknown. Based on Central Limit Theorem (CLT), a sample size of 30 can increase the confidence interval of the population data set enough to warrant assertions against the findings of statistical analysis (Chang et al., 2006). In the current study, the 34 samples for one-way repeated measures ANOVA are acceptable sample size for applied research in the aviation domain. Based on the visual examination of the Q-Q plots, the NASA-TLX and SART-10D data on three interactive modes distributed normality. The analysis of the six dimensions of NASA-TLX boxplots demonstrated that potential outliers were found in physical demand on AR gesture-command (5.88%); temporal demand on AR voice-command (2.94%); performance on both AR gesture-command (2.94%) and

a b

Fig. 2. Participant wears a HoloLens device using gesture-command in the flight simulator (2a); participant’s point of view in the flight deck while interacting with virtual SOPs on pre-landing checklist by gesture command, the virtual checklist (red) is the currently SOP item, the crosshair (white) centred shows participant’s visual attention, the guiding arrows (yellow) indicate the next SOP action to operate Landing-Gear down (2b). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

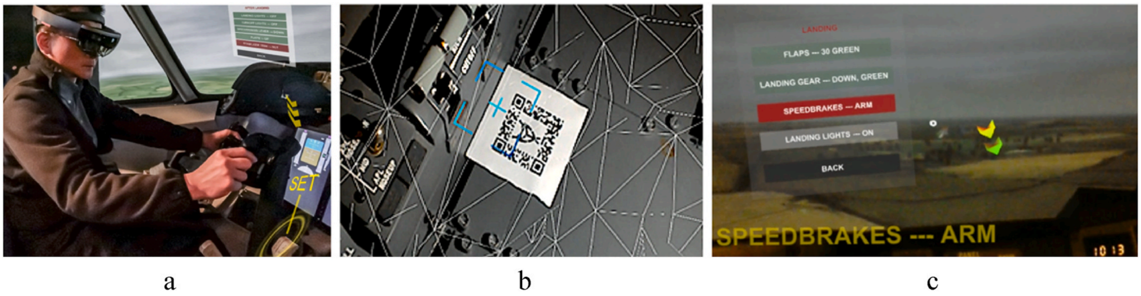

Fig. 3. The visual cue design of application on HoloLens for instrument landing, the yellow guiding arrows directing to the position for next action, the yellow text indicating the current SOP (3a); HoloLens view of QR code and alignment with a square with a cross in blue colour indicate registration calibration completed in the flight deck (3b); visual cues of guiding position for confirmation the execution of checklist in red colour (3c). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

voice-command (8.82%); and effort on AR gesture-command (5.88%). According to the sensitivity analysis by run one-way repeated measures ANOVA on both entire and without-outlier data, the outliers show no influence on statistical analysis results. So that these outliers were included in further data analysis and results report. The dimension of temporal demand violated homogeneity of covariance assumption on Mauchly's test ($\chi2 = 10.36$, $p < .01$, $\varepsilon = 0.82$), therefore Huynd-Feldt ($\varepsilon > 0.75$) was applied to correct the degree of freedom. There is no outlier, and all assumptions are met on SART-10D. Participants' perceived workload and SA on three interactive modes (Mode 1: traditional, Mode 2: AR gesture-command, and Mode 3: AR voice-command) by NASA-TLX and SART-10D are analysed and compared. The descriptive statistics of NASA-TLX and SART-10D scores on three interactive modes whilst performing ILS pre-landing checklists are shown in Figs. 4 and 5.

4.2. Interactive modes impacted on perceived workload

There is a significant difference on perceived workload by NASA-TLX total score while pilots interacted with three modes on pre-landing checklist, F (2, 66) = 41.36, $p < .001$, $\eta2 = 0.56$. Therefore, 'H1: There is a significance on pilots' perceived workload using different AR interactive modes on ILS landing' is supported. Post-hoc comparison indicates that the AR gesture-command induced significantly higher workload than traditional mode ($63.63 > 46.27$, $p < .001$) and AR voice-command ($63.63 > 42.94$, $p < .001$). Furthermore, there is a significant difference on pilots' Mental demand among three interactive modes, F (2, 66) = 12.40, $p < .001$, $\eta2 = 0.27$. Post-hoc comparison shows that the mental demand on the AR gesture-command is significantly higher than traditional mode ($61.67 > 43.24$, $p = .002$) and AR voice-command ($61.67 > 43.09$, $p < .001$). There is a significant difference on Physical demand among three modes, F (2, 66) = 44.89, $p < .001$, $\eta2 = 0.58$. Post-hoc comparison shows that the physical demand on the AR gesture-command is significantly higher than the traditional checklist ($74.71 > 43.82$, $p < .001$) and AR voice-command ($74.71 > 37.35$, $p < .001$). There is a significant difference on Temporal demand among three interactive modes, F (1.63, 53.83) = 14.32, $p < .001$, $\eta2 = 0.30$. Post-hoc comparison shows that the temporal demand on AR gesture-command is significantly higher than the traditional ($65.88 > 47.65$, $p = .008$) mode and AR voice-command ($65.88 > 40.29$, $p < .001$). There is a significant difference on Performance among three interactive modes, F (2, 66) = 18.71, $p < .001$, $\eta2 = 0.36$. Post-hoc comparison shows that participants' performance on the AR gesture-command is significantly lower than traditional mode ($39.12 < 67.06$, $p < .001$) and AR voice-command ($39.12 < 67.50$, $p < .001$). There is a significant difference on Effort among three modes, F (2, 66) = 38.56, $p < .001$, $\eta2 = 0.54$. Post-hoc comparison shows that participants' effort on the AR gesture-command is significantly higher than the traditional mode ($71.18 > 38.68$, $p < .001$) and AR voice-command mode ($71.18 > 37.50$, $p < .001$). There is a significant difference on Frustration among three different interactive modes, F (2, 66) = 31.64, $p < .001$, $\eta2 = 0.49$. Post-hoc comparison shows that participants' frustration using the AR gesture-command mode (M = 69.12, SD = 19.44) is significantly higher ($p < .001$) than the traditional mode ($69.12 > 37.21$, $p < .001$) and the AR voice-command mode ($69.12 > 31.91$, $p < .001$). The differences of perceived workload by NASA-TLX among three interactive modes on performing ILS pre-landing checklists are shown as Fig. 4.

4.3. Interactive modes impacted on SA

There is a significant difference on pilots' SA among three interactive modes, F (2, 66) = 19.87, $p < .001$, $\eta2 = 0.38$. Therefore, 'H2: There is a significance on pilots' situation awareness while using different AR interactive modes on ILS landing' is supported. Post-hoc comparisons show that the SART-10D total score on AR gesture-command is

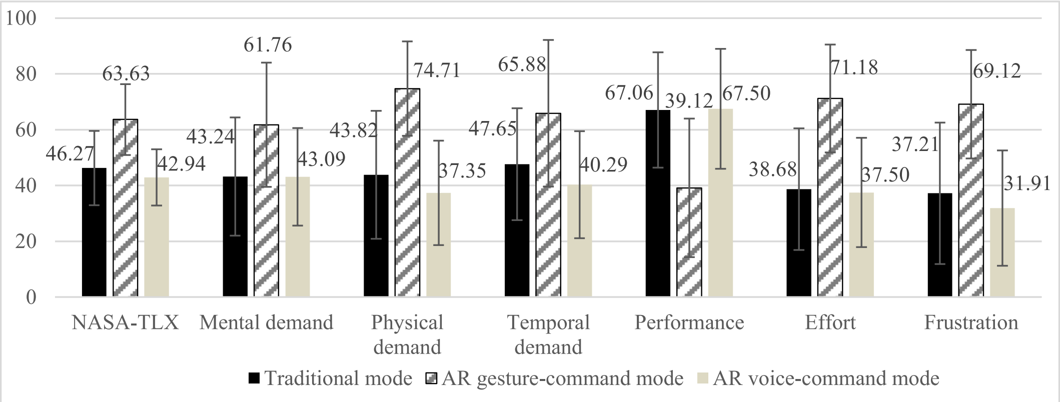

Fig. 4. The differences of perceived workload by NASA-TLX total scores and six dimensions among three interactive modes on performing ILS pre-landing checklists.

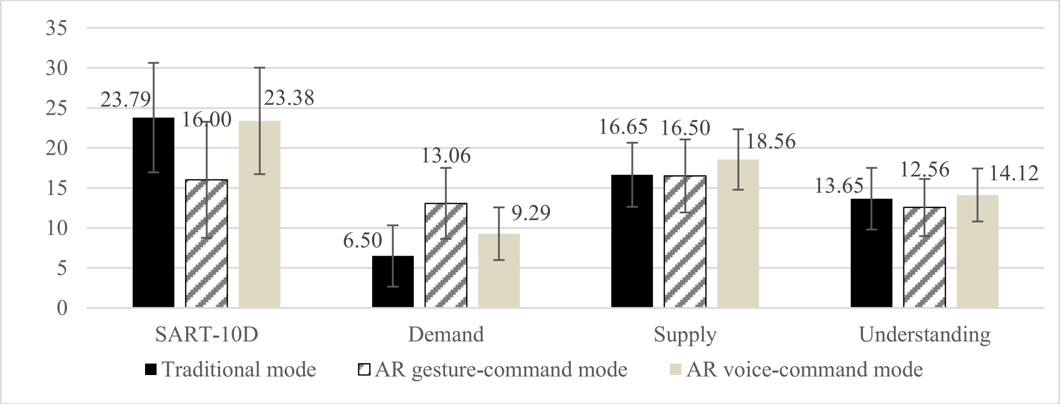

Fig. 5. The differences of participants' SA on SART-10D to three interactive modes on performing ILS pre-landing checklists.

significantly lower than traditional mode ($15.15 < 24.12$, $p < .001$) and AR voice-command ($15.15 < 23.41$, $p < .001$). Furthermore, there is a significant difference on the dimension of Demand among the three interacted modes, $F(2, 66) = 36.56$, $p < .001$, $\eta 2 = 0.53$. Post-hoc comparisons indicate that the traditional mode shown the lowest demand, followed by voice-command, and gesture-command ($6.35 < 9.47 < 13.59$, $p < .01$). There is a significant difference on the dimension of Supply among three interacted modes, $F(2, 66) = 3.35$, $p < .05$, $\eta 2 = 0.09$. Post-hoc comparisons show no significant difference of Supply among these three interactive modes, though voice-command is relatively high. There is no significant difference on the dimension of Understanding among three interacted modes, $F(2, 66) = 2.82$, $p = .067$, $\eta 2 = 0.08$. Participants' SART-10D scores among three interactive modes while performing ILS pre-landing checklists are shown as Fig. 5.

5. Discussion

5.1. AR voice-command reduces pilot's perceived workloads

Suitable human-centred design can have positive effects on boosting users' performance and reducing cognitive workload (Tobaruela et al., 2014), increasing cognitive capacity to achieve multitasks simultaneously during flight operations (Wickens, 2008). The results of this research support the first hypothesis that 'there is a significance on pilots' perceived workload using different AR interactive modes on ILS landing'. Participants rated the AR voice-command mode with the lowest perceived workload with large effect size ($\eta^2 = 0.56$) and the highest score for performance with large effect size ($\eta^2 = 0.36$) when compared with gesture-commands and a traditional checklist (Fig. 4). This finding may only be applicable with this research using an ILS scenario, since it is not suitable for over-interpretation to other scenarios without further investigation. The use of voice-command leads to better perception of the current operational status in the flight deck. In essence, the positive effects of voice-command were observed while participants performed an ILS pre-landing checklists whilst interacting with augmented artifacts which integrate the visualization on physical objects (such as directing to the position of landing gear) and the subsequent required actions (Fig. 3c). The AR voice-command conveys both semantic guidance and visual cues to guide participant's attention for the next required action without additional effort when compared the effort required to use a gesture-command based on NASA-TLX (Table 1). Participants had experienced various degrees of frustration due to a lack of response to voice commands - especially if participants cannot pronounce in a standard English accent. Furthermore, some participants felt frustration whilst trying to make gesture-commands using the "air tap". Participants must perform multiple tasks using their hands to operate the landing gear, landing lights and speed-brakes, the results demonstrated that participants' frustration levels on voice-command were lower than gesture-command in general (Table 1).

Currently pilots only have one input channel by an available hand to execute required actions, as the other hand must handle the control column/stick to fly aircraft. Pilots must interact and monitor several dynamic visual artifacts including flight information displays, switches, knobs, and levers related to ILS procedures. The challenge of flight operations is that there are various tasks that must be executed precisely in a limited time frame using one hand. If the pilots' voice can be used as an additional input channel to execute required actions, it will enhance pilots' performance and reduce cognitive task loads. This may be the reason that participants in this research prefer AR voice-command and dislike the gesture command which increases their workload by requiring the only one available hand to be occupied using the "air-tap" for ILS procedure (Fig. 6a). This hand must perform multitasks including manoeuvring the flaps lever (Fig. 6b), landing gear (Fig. 6c), speed-brakes lever (Fig. 6d), and landing light switches (Fig. 6e). Furthermore, due to the small field of view on HoloLens not always being able to recognize a user's gesture accurately, participants feel frustrated on the failures of gesture-command. On the other hand, the voice-command combines both virtual SOPs with the physical operational environment with guiding cues (Fig. 6b–e) which match the principle of human-centred design and being able to reduce participants' mental and physical demands.

Table 1
The ranking of three interactive modes on perceived workload and SA by NASA-TLX and SART-10D (grey highlighting the most rewarding one).

	NASA-TLX	Mental demand	Physical demand	Temporal demand	Performance	Effort	Frustration	SART-10D	Demand	Supply	Understanding
Mode 1	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	Low	Medium	Medium
Mode 2	High	High	High	High	Low	High	High	Low	High	Low	Low
Mode 3	Low	Low	Low	Low	High	Low	Low	Medium	Medium	High	High

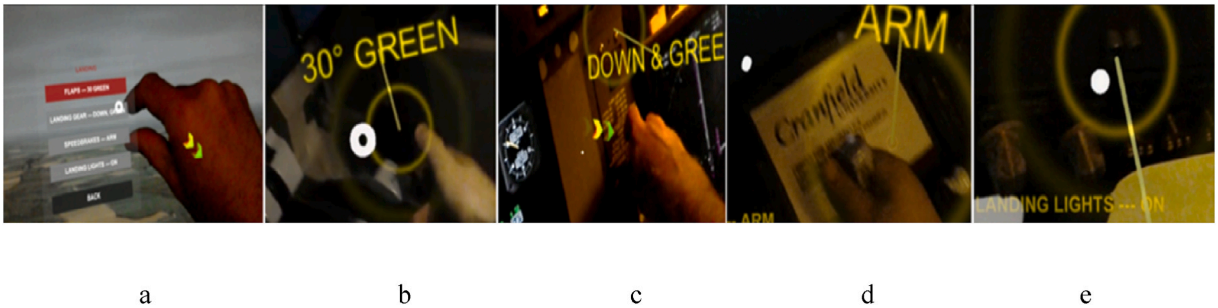

Fig. 6. Participant's point-of-view on wearing HoloLens conducting ILS checklists by gesture-command (6a); both gesture-command and voice-command checklists including moving flaps lever to 30-degree (6b); moving landing gear DOWN and check green light (6c); moving speed-brakes to ARM position (6d); and switching landing light ON (6e). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5.2. AR interactive modes influencing aspects of SA

The wearable AR display can provide real-time visual feedback to increase user's task performance and support decision-making (Rowen et al., 2019; Stanton, 2016). To examine if there are any differences with SA among different interactive modes, participants were requested to rate their SA using SART-10D after performing ILS pre-landing checklists. The results supported the second hypothesis that 'there is a significance on pilots' situation awareness while using different AR interactive modes on ILS landing'. Participants obtained the highest Supply (moderate effect size, $\eta^2 = 0.09$) and Understanding (moderate effect size, $\eta^2 = 0.08$) when performing an ILS landing with AR voice-command compared to gesture-command and the traditional checklist (Fig. 5 & Table 1). Again, this finding on pilots' SA relating to AR interactive modes may only be applicable to the current research using an ILS scenario, since it is not suitable for over-interpretation to other scenarios. The AR voice-command checklist presents timely information and feedback via an intuitive approach of semantic control, providing participants an awareness of the current state and next-step for required action. The AR voice-command can improve user perception (SA level-1) and comprehension (SA level-2), both often associated with aspects of Supply and Understanding on SART-10D assessment (Klueber et al., 2019). However, the graphic salience and visual clutter of AR head-up displays might lead to operator cognitive distraction (Sharfi and Shinar, 2014) and thus induce higher attentional demand (Burnett and Donkor, 2012). Some participants were unfamiliar with AR application in flight operations which might have influences on their responses on SART. This could also be the reason why participants evaluated the traditional checklist as the highest for SA (large effect size, $\eta^2 = 0.38$) and lowest for Demand (large effect size, $\eta^2 = 0.53$) (Fig. 5 & Table 1). Furthermore, participants' experience of AR devices might be an important factor in human cognition and preference - people might prefer familiar things because of their previous experience compared to the novel ones (Liao et al., 2011).

The aspect of Demand on SART-10D might have association with participants' perceived workload on NASA-TLX. Participants' SA was lowest (large effect size, $\eta2 = 0.38$) when performing an ILS pre-landing checklists with AR gesture-command compared with voice-command and the traditional checklist. Furthermore, the AR gesture-command could induce the highest cognitive Demand (large effect size, $\eta2 = 0.53$) and provide the lowest Supply (moderate effect size, $\eta2 = 0.09$) and Understanding (moderate effect size, $\eta2 = 0.08$) (Fig. 5 & Table 1). The reasoning for this might be that the complicated interactive procedures required physical movements during the "air-tap" gesture (Fig. 6a) which most participants might have to learn how to use it as first-time user. Therefore, the learnability may have to be investigated in the future research. Due to the novel features of an AR display and the unfamiliar interaction mode of the air-tap, participants committed more attention and cognitive resources on the gesture-command itself rather than on the flight operations. Furthermore, participants must use one hand to perform "air-tap" to command the AR checklist while another hand is busy with engaging ILS pre-landing checklists on final approach. Performing multiple tasks (flying the aircraft and using the AR device) by using both hands simultaneous required bi-manual coordination and psychomotor skills, which would be associated with large cognitive loads (Fernandes et al., 2016) and depleting attention resources, thus, decreasing their SA performance. This research demonstrated that augmented visualization and spatial mapping capabilities of AR can allow it to be integrated into a user's decision support system which is consistent with previous studies (Rohacs et al., 2019). AR applications may be able to facilitate single pilot operations (SPO) in the future flight deck design.

5.3. Considerations of applied AR for future flight deck design

The design of the AR application has integrated audio cues for guiding the current checklist item by combining with a visual highlight and text in current research. The audio sources of voice are located at the centre of each yellow highlight circle; therefore, users can hear semantic instructions as if they were emitting from the operational environment. The AR also verifies that the user has completed the checked item before allowing user to move to the next SOP. The user is required to fixate their view on the highlighted instrument (e.g. flap, landing gear or speed-brakes lever) by bring the central cursor (white dot) over the yellow target circle highlight for at least a duration of 500 ms to validate the checklist (Fig. 6b). A notification sound will be activated when this required action has been done. When a checklist is completed, a notification sound is played and followed by announcement of 'checklist complete'. These audio and visual feedbacks were designed to confirm the task completion, induce satisfaction and reduced workload in flight operations. It is very interesting to find that participants' perceived workload and performance between voice-command and traditional checklist show almost no differences on NASA-TLX total score (Fig. 4). A large number of participants (75%) admitted that they preferred voice control to gesture control. Some mentioned that the gesture-command was very "frustrating", "cumbersome to use" and "distracting". Furthermore. (55%) participants also highlighted the effect of practising with an AR device would facilitate their performances especially when using voice-command. Professional pilots (33%) mentioned that some of the instrument checks could only be performed without looking at the corresponding switch or lever, but by touching the item only, such as the switching landing lights, in this case voice-command was particularly useful (Fig. 6e). Both pilots and avionics engineers agreed (85%) that the AR application could be a great tool for training, as they believe junior pilots could easily learn flow-checks and scanning patterns of checklists.

The key utilization of Augmented Reality in aviation is its capacity to overlay and integrate information at the point of need. It promotes visualization of navigation systems, automation systems, weather, terrain, and airspace information in a 3D intersection – where it is easy to perceive changes, understand a developing situation and predict future actions. The dynamic arrow indicators (Fig. 6a–e) and attention guidance circles on the AR checklist are effectively promoting participants' performance and preventing omissions from the checklist. The yellow arrows and corresponding animation within the AR visualization represent an efficient multimodal cue that can facilitate operators' attention to the cue and reduce mental demand on 'thinking' and physical demand on 'searching'. The dynamic indication of these arrows helps to prevent mode confusion and minimises human error which may lead to pilots failing to execute a required procedure in the checklists. The dynamic indication assists in preventing distraction on the flight deck and allows pilots to use selective attention to process available information to increase SA (Wickens and Alexander, 2009). The dynamic indication producing a ripple effect is similar to the attention directing system in a study of 3D crosshairs and a dynamic path to draw operator attention towards the location (Merenda et al., 2018). The attention guidance system also feeds auditory and visual feedbacks to the participants in the form of checklist item confirmation on execution. The AR device provides semantic feedback after checklist items have been fully executed. This allows participants to mentally move on to the next task and reducing mental workload.

5.4. *Current limitations and future perspectives*

There is an increasing prevalence of AR applications used in various domains such as manufacturing, medical care, military applications, and aviation (Bowman et al., 2012; Carey, 2018; Krichenbauer et al., 2018; Aromaa et al., 2020; Borgen et al., 2021). For many participants, wearing an AR headset to perform the checklist is a brand-new experience. Furthermore, there are some barriers to AR applications in flight operations identified by this research. The confirmation action that requires participants to guide the cursor of the headset to the highlighted area creates extra head movement. This limitation leads to the consequence that participants were forced to move their head to place the cursor on the checklist when they could more easily select by only moving the eyeball. This issue may be resolved with new AR devices that are equipped with eye-tracking capabilities that allow participants to control the cursor by their eye movement. Another limitation is the readability of virtual object (text) on the HoloLens display when targets are located outside the field of view. The AR see-through function may potentially create blind spots. This finding is in line with previous research that one of the key challenges with AR is the difficulty of accurately superimposing virtual objects into the real operational environment (Moussa et al., 2012). The solution to current AR limitations may be to develop more accurate gaze-control function to serve as additional input within a wider FOV. Moreover, there is a limitation on flight data collection in the current flight simulator. Current research was mainly based on participants' subjective rating on their perceived workload and SA while interacting with an AR device. For applying AR technology on the flight deck, it is necessary to utilize an advanced simulator with full access to flight data and parameters related to the pilots' performance in the future research. Therefore, the pilot's cognitive workload from interacting with an AR device could provide more detailed overview of how to address these limitations to improve the applicability of AR in future flight operations.

6. Conclusion

AR applications have a potential on facilitating pilot's SA performance and reducing perceived workload in differing ways. Therefore, the implementation of innovative AR technology in the flight deck requires further investigation for validation and certification purposes. This study aimed at investigating participants' cognitive demands while interacting with different interactive modes on an AR device. The results show that the gesture-command gives increasing unnecessary workload plus decreasing SA and tends to be cumbersome to use. On the other hand, voice-command checklists could constitute a real improvement in terms of reduced participants' perceived workload and maximum SA performance. The findings provide evidence that interactive modes of AR interface design can influence participant's cognitive information processing and perceived workload associated with task performance in the flight deck. Furthermore, the AR device can be a great tool for aviation training and the implementation of AR design may provide potential solution for single pilot operations in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is available from the Cranfield Online Research Data Repository (CORD): https://doi.org/10.17862/cranfield.rd.21399729.v1.

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References

Aromaa, S., Väätänen, A., Aaltonen, I., Goriachev, V., Helin, K., Karjalainen, J., 2020. Awareness of the real-world environment when using augmented reality head-mounted display. Appl. Ergon. 88, 1–7. https://doi.org/10.1016/j.apergo.2020.103145.

Beitzel, S., Dykstra, J., Huver, S., Kaplan, M., Loushine, M., Youzwak, J., 2016. Cognitive performance impact of augmented reality for network operations tasks. In: Nicholson, D. (Ed.), Advances in Human Factors in Cybersecurity. Springer, Cham, pp. 139–151. https://doi.org/10.1007/978-3-319-41932-9_12.

Boeing, 2018. Boeing tests augmented reality in the factory. Boeing online: Innovation. Boeing (online), Boeing.com, Features & Multimedia. Retrieved March 4, 2019 from. https://www.boeing.com/features/2018/01/augmented-reality-01-18.

Borgen, K.B., Ropp, T.D., Weldon, W.T., 2021. Assessment of augmented reality technology's impact on speed of learning and task performance in aeronautical engineering technology education. Int. J. Aerospace Psychol. 31 (3), 219–229. https://doi.org/10.1080/24721840.2021.1881403.

Bowman, B., Elmqvist, N., Jankun-Kelly, T.J., 2012. Toward visualization for games: theory, design space, and patterns. IEEE Trans. Visual. Comput. Graph. 18 (11), 1956–1968. https://doi.org/10.1109/TVCG.2012.77.

Burnett, G.E., Donkor, R.A., 2012. Evaluating the impact of head-up display complexity on peripheral detection performance: a driving simulator study. Adv. Transport. Stud. 28, 5–16. https://doi.org/10.4399/97888548555261.

Carey, S., 2018. How Microsoft HoloLens Is Being Used in the Real World. May 16. Computerworld. https://www.computerworld.com/article/3412263/howmicrosoft-hololens-is-being-used-in-the-real-world.html.

Carmigniani, J., Furht, B., Anisetti, M., Ceravolo, P., Damiani, E., Ivkovic, M., 2011. Augmented reality technologies, systems and applications. Multimed. Tool. Appl. 51, 341–377. https://doi.org/10.1007/s11042-010-0660-6.

Cecilia, R.A., Marti, A.H., 2005. Improving aviation safety with information visualization: a flight simulation study. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. Association for Computing Machinery, New York, NY, pp. 441–450. https://doi.org/10.1145/1054972.1055033.

Chang, H.J., Huang, K., Wu, C., 2006. Determination of sample size in using central limit theorem for weibull distribution. Int. J. Inf. Manag. Sci. 17 (3), 31.

Chu, C., Ko, C., 2021. An experimental study on augmented reality assisted manual assembly with occluded components. J. Manuf. Syst. https://doi.org/10.1016/j.jmsy.2021.04.003 (in press).

Comerford, D., Johnson, W.W., 2007. Potential capabilities in a future, augmented cockpit. Ergon. Des 15 (1), 8–13, 10.1177%2F106480460701500105.

Dorneich, M.C., Dudley, R., Letsu-Dake, E., Rogers, W., Whitlow, S.D., Dillard, M.C., Nelson, E., 2017. Interaction of automation visibility and information quality in flight deck information automation. IEEE Trans. Human-Machine Syst. 47 (6), 915–926. https://doi.org/10.1109/THMS.2017.2717939.

Dorneich, M.C., Rogers, W., Whitlow, S.D., DeMers, R., 2016. Human performance risks and benefits of adaptive systems on the flight deck. Int. J. Aviat. Psychol. 26 (1–2), 15–35. https://doi.org/10.1080/10508414.2016.1226834.

Endsley, M.R., 1988. Design and evaluation for situation awareness enhancement. Proc. Hum. Factors Soc. Annu. Meet. 32 (2), 97–101. https://doi.org/10.1177/154193128803200221.

Endsley, M.R., 1995. In: Fuller, R., Johnston, N., McDonald, N. (Eds.), Human Factors in Aviation Operations. Avebury Aviation, Ashgate Publishing Ltd, Aldershot, England, pp. 287–292.

Endsley, M.R., Selcon, S.J., Hardiman, T.D., Croft, D.G., 1998. A comparative analysis of SAGAT and SART for evaluations of situation awareness. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 42. SAGE Publications, Sage CA: Los Angeles, CA, pp. 82–86. https://doi.org/10.1177/154193129804200119, 1.

Fernandes, A., Braarud, P.Ø., 2015. Exploring measures of workload, situation awareness, and task performance in the main control room. Procedia Manuf. 3, 1281–1288. https://doi.org/10.1016/j.promfg.2015.07.273.

Fernandes, V.R., Ribeiro, M.L.S., Melo, T., de Tarso Maciel-Pinheiro, P., Guimarães, T.T., Araújo, N.B., et al., 2016. Motor coordination correlates with academic achievement and cognitive function in children. Front. Psychol. 7, 1–8. https://doi.org/10.3389/fpsyg.2016.00318.

Fiore, S.M., Wiltshire, T.J., 2016. Technology as teammate: examining the role of external cognition in support of team cognitive processes. Front. Psychol. 7, 1–17. https://doi.org/10.3389/fpsyg.2016.01531.

Gardony, A.L., Martis, S.B., Taylor, H.A., Brunyé, T.T., 2018. Interaction strategies for effective augmented reality geo-visualization: insights from spatial cognition. Hum. Comput. Interact. 37 (2), 107–149. https://doi.org/10.1080/07370024.2018.1531001.

Grabowski, M., Rowen, A., Rancy, J.P., 2018. Evaluation of wearable immersive augmented reality technology in safety-critical systems. Saf. Sci. 103, 23–32. https://doi.org/10.1016/j.ssci.2017.11.013.

Hart, S.G., Staveland, L.E., 1988. Development of NASA-TLX (task load index): results of empirical and theoretical research. Adv. Psychol. 52, 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9.

Hidalgo-Muñoz, A.R., Mouratille, D., Matton, N., Causse, M., Rouillard, Y., El-Yagoubi, R., 2018. Cardiovascular correlates of emotional state, cognitive workload and time-on-task effect during a realistic flight simulation. Int. J. Psychophysiol. 128, 62–69. https://doi.org/10.1016/j.ijpsycho.2018.04.002.

Hilton, B., 2012. ScholarWorks at WMU Comparing the Effects of Simulated , Intelligent Audible , Checklists and Analog Checklists in Simulated Flight. PhD Dissertation, Western Michigan University, Kalamazoo, Michigan, USA. Retrieved from. https://scholarworks.wmich.edu/cgi/viewcontent.cgi?article=1114&context=dissertations.

ICAO, 2013. Manual of Evidence-Based Training. International Civil Aviation Organization. Montréal, Quebec, Canada. https://skybrary.aero/sites/default/files/bookshelf/3177.pdf.

Kim, S., Nussbaum, M.A., Gabbard, J.L., 2019. Influences of augmented reality head-worn display type and user interface design on performance and usability in simulated warehouse order picking. Appl. Ergon. 74, 186–193. https://doi.org/10.1016/j.apergo.2018.08.026.

Klueber, S., Wolf, E., Grundgeiger, T., Brecknell, B., Mohamed, I., Sanderson, P., 2019. Supporting multiple patient monitoring with head-worn displays and spearcons. Appl. Ergon. 78, 86–96. https://doi.org/10.1016/J.APERGO.2019.01.009.

Knibbe, J., Schjerlund, J., Petraeus, M., Hornbæk, K., 2018. The dream is collapsing. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, 48. ACM, New York, NY, pp. 1–13. https://doi.org/10.1145/3173574.3174057.

Kramer, L.J., Bailey, R.E., Prinzel III, L.J., 2009. Commercial flight crew decision making during low-visibility approach operations using fused synthetic and enhanced vision systems. Int. J. Aviat. Psychol. 19 (2), 131–157. https://doi.org/10.1080/10508410902766440.

Krichenbauer, M., Yamamoto, G., Taketom, T., Sandor, C., Kato, H., 2018. Augmented reality versus virtual reality for 3D object manipulation. IEEE Trans. Visual. Comput. Graph. 24 (2), 1038–1048. https://doi.org/10.1109/TVCG.2017.2658570.

Li, W.-C., Yan, Z., Zhang, J., Braithwaite, G., Court, S., Lone, M., Thapa, B., 2020. Evaluating pilot's perceived workload on interacting with augmented reality device in flight operations. In: Harris, D., Li, W.-C. (Eds.), Proceedings of Engineering Psychology and Cognitive Ergonomics. Cognition and Design. Springer, Cham, pp. 332–340. https://doi.org/10.1007/978-3-030-49183-3_26.

Liao, H.I., Yeh, S.L., Shimojo, S., 2011. Novelty vs. Familiarity principles in preference decisions: task-context of past experience matters. Front. Psychol. 2 (43), 1–8. https://doi.org/10.3389/fpsyg.2011.00043.

MacPhedran, S., 2018. Augmented Manufacturing: the Big Six HoloLens Use Cases for Manufacturers. April 6. Smith. https://blog.smith.co/2018/augmentedmanufacturing.

Merenda, C., Kim, H., Tanous, K., Gabbard, J.L., Feichtl, B., Misu, T., Suga, C., 2018. Augmented reality interface design approaches for goal-directed and stimulus-driven driving tasks. IEEE Trans. Visual. Comput. Graph. 24 (11), 2875–2885. https://doi.org/10.1109/TVCG.2018.2868531.

Microsoft, 2015. HoloLens: a New Way to See Your World. Retrieved. https://www.microsoft.com/microsoft-hololens/enus/hardware. (Accessed 7 July 2015).

Moussa, G., Radwan, E., Hussain, K., 2012. Augmented reality vehicle system: left-turn maneuver study. Transport. Res. C Emerg. Technol. 21 (1), 1–16. https://doi.org/10.1016/j.trc.2011.08.005.

Neumann, U., Majoros, A., 1998. Cognitive, performance, and systems issues for augmented reality applications in manufacturing and maintenance. March. In: Proceedings. IEEE 1998 Virtual Reality Annual International Symposium (Cat. IEEE, pp. 4–11. https://doi.org/10.1109/VRAIS.1998.658416. No. 98CB36180).

Obrist, M., Velasco, C., Vi, C., Ranasinghe, N., Israr, A., Cheok, A., Spence, C., Gopalakrishnakone, P., 2016. Sensing the future of HCI: touch, taste, and smell user interfaces. Interactions 23 (5), 40–44. https://doi.org/10.1145/2973568.

Rohacs, J., Jankovics, I., Rohacs, D., 2019. Less-skilled pilot decision support. Aircraft Eng. Aero. Technol. 91 (5), 790–802. https://doi.org/10.1108/AEAT-12-2017-0269.

Rowen, A., Grabowski, M., Rancy, J.P., Crane, A., 2019. Impacts of wearable augmented reality displays on operator performance, situation awareness, and communication in safety-critical systems. Appl. Ergon. 80, 17–27. https://doi.org/10.1016/j.apergo.2019.04.013.

Selcon, S.J., Taylor, R.M., 1990. Evaluation of the situational awareness rating technique (SART) as a tool for aircrew systems design. In: Situational Awareness in Aerospace Operations. AGARD-CP-478) (pp. 5/1–5/8).

Spicer, R.P., Russell, S.M., Rosenberg, E.S., 2017. The mixed reality of things: emerging challenges for human-information interaction. Next-Generation Analyst V 10207, 1–13. https://doi.org/10.1117/12.2268004.

Sharfi, T., Shinar, D., 2014. Enhancement of road delinea- tion can reduce safety. J. Saf. Res. 49, 61–68. https://doi.org/10.1016/j.jsr.2014.02.011.

Stanton, N.A., Plant, K.L., Roberts, A.P., Harvey, C., Thomas, T.G., 2016. Extending helicopter operations to meet future integrated transportation needs. Appl. Ergon. 53, 364–373. https://doi.org/10.1016/j.apergo.2015.07.001.

Taylor, R.M., 1990. Situational Awareness Rating Technique (SART): the development of a tool for aircrew systems design. In: Proceedings of Situational Awareness in Aerospace Operations Conference, 478. France: NATO - AGARD, Neuilly Sur Seine, pp. 1–17.

Tobaruela, G., Schuster, W., Majumdar, A., Ochieng, W.Y., Martinez, L., Hendrickx, P., 2014. A method to estimate air traffic controller mental workload based on traffic clearances. J. Air Transport. Manag. 39, 59–71. https://doi.org/10.1016/j.jairtraman.2014.04.002.

Tran, T.H., Behrend, F., Fünning, N., Arango, A., 2018. Single pilot operations with AR-glasses using Microsoft HoloLens. In: Proceedings of 2018 IEEE/AIAA 37th Digital Avionics Systems Conference. IEEE, London, UK, pp. 1–7. https://doi.org/10.1109/DASC.2018.8569261.

Virgin, 2018. Virgin Atlantic Brings in Augemented Reality Training for Carbin Crew. https://airwaysmag.com/industry/virgin-atlantic-brings-in-augmented-reality-training-for-cabin-crew/.

Wickens, C.D., 2008. Multiple resources and mental workload. Hum. Factors 50 (3), 449–455. https://doi.org/10.1518/001872008X288394.

Wickens, C.D., Alexander, A.L., 2009. Attentional tunneling and task management in synthetic vision displays. Int. J. Aviat. Psychol. 19 (2), 182–199. https://doi.org/10.1080/10508410902766549.

Wickens, C.D., Goh, J., Helleberg, J., Horrey, W., Talleur, D.A., 2003. Attentional models of multi-task pilot performance using advanced display technology. Hum. Factors 45, 360–380. https://doi.org/10.1518/hfes.45.3.360.27250.

Yang, Z., Shi, J., Jiang, W., Sui, Y., Wu, Y., Ma, S., Kang, C., Li, H., 2019. Influences of augmented reality assistance on performance and cognitive loads in different stages of assembly task. Front. Psychol. 10, 1–17. https://doi.org/10.3389/fpsyg.2019.01703.

Yeh, M., Merlo, J.L., Wickens, C.D., Brandenburg, D.L., 2003. Head up versus head down: the costs of imprecision, unreliability, and visual clutter on cue effectiveness for display signaling. Hum. Factors 45 (3), 390–407. https://doi.org/10.1518/hfes.45.3.390.27249.

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The influence of augmented reality interaction design on Pilot's perceived workload and situation awareness

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