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ENHANCING SAFETY AND WORKLOAD MANAGEMENT IN eVTOL COCKPITS THROUGH THE ASSESSMENT OF PILOT'S PERCEPTION OF HMI MODELS

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Abstract. The rapid emergence of electric vertical take-off and landing (eVTOL) aircraft is expected to revolutionize Urban Air Mobility (UAM) as eVTOL enabling low-emission, point-to-point aerial transportation. The viability of these aircraft is deeply tied to the concept of Single-Pilot Operations, which places intense cognitive, operational, and decision-making loads on the pilot, particularly in dense urban environments. In this context, the Human–Machine Interface (HMI) plays a critical role as it acts as pilot's "crew member", effectively functioning and supporting the pilot and increasing situational awareness, workload management, and safe decision-making. This study is a combined method of research design that was implemented, combining a structured online survey and interviews among aviation professionals, including pilots, engineers and human factors specialists to understand and detect their perceptions of HMI requirements for single-pilot eVTOL operations, focusing on workload management, situational awareness, automation interaction, and trust in advanced cockpit technologies. Moreover, open-source flight simulator *FlightGear* was used to partially depict the results. The findings revealed that maintaining situational awareness without a co-pilot is the dominant challenge, with strong preferences for "eyes-out" displays like physical controls and Head-Up Displays in high-workload scenarios. A significant connection was found between professional expertise and trust in AI co-pilots. Quantitative data from the survey were analyzed using descriptive and inferential statistics (e.g., t-tests, ANOVA, correlation, regression), supported by graphical representations. The findings show the crucial importance of pilot-focused HMIs for the most important determining factors namely, the problem of maintaining Situation Awareness, multi-tasking and managing cognitive load, the pilot's central problem without the assistance or presence of the co-pilot in the aircraft. This paper presents the Adaptive, Multimodal, Context-Aware (AMCA) HMI design framework that will benefit the future design of single-pilot eVTOL aircraft cockpits. The study provides concrete design inputs for manufacturers and regulatory and training bodies regarding the challenge of certification and operation of the newly developing Urban Air Mobility solutions.

Keywords: eVTOL, Urban Air Mobility, Human–Machine Interface, situational awareness, cognitive workload, single-pilot operations.

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1. Introduction

UAM represent a major paradigm shift in the aeronautical industry that has eased ground congestion as well as environmental concerns by the use of electric vertical take-off and landing (eVTOL) aircraft (Ahmed et al., 2020; Thipphavong et al., 2018). The reduction in noise emissions in relation to helicopters or any forms of rotorcraft has also fueled the prospects of such machines (Garrow et al., 2021). Indeed, several manufacturers have plans to introduce these aircraft within the near-term period of entry into service. It is projected that between seven and nine thousand eVTOL drones will be in operation in the coming decades up to 2050 (Frost & Sullivan, 2023). Although such technological developments exist, their operational feasibility is not solely dependent on propulsion and autonomy capabilities in eVTOL aircraft. Pilot considerations concerning his/her workload, awareness, and decision-making capabilities remain fundamental in ensuring efficiency and safety in their operation. In contrast to passenger aviation, many eVTOL designs include a Single-Pilot operation that abrogates any division of labour between Pilot Flying and Pilot Monitoring roles, as indicated by European Union Aviation Safety Agency (2023). This functional approach will radically change the role of the human operator in interacting with aviation automation (Vu et al., 2018), where the focus will shift to cockpit interaction. This, in turn, will make HMI an essential aspect of ensuring aviation safety in a single-pilot eVTOL. Highly automated aviation requires design complexities in regards to propulsion, energy, and routes in a highly populated urban sky, which when involved in accidents, contribute to aviation accidents (Endsley, 1995; Parasuraman & Riley, 1997). While there is a concern of high automation increasing aviation accident probabilities, which is supported by Green (2017). Johnson and Silva (2022) emphasize the importance of the development of the guidelines required specifically within the single-pilot flying of eVTOL aircraft on the basis that current standards are inadequate within the multi-crew aircraft cockpit. However, the beginning of the development cycle of flying the eVTOL introduces entirely new characteristics that are difficult to overcome, including vertical flight, battery systems, the urban environment, and the additional risk of battery 'thermal runaway (Hu et al., 2024; Namukasa et al., 2024).

A comparison of NASA-TLX workload across different cockpit configurations, revealing higher mental and temporal demands in current single-pilot operations and predictable improvements with advanced HMI systems, is shown in Figure 1. Data were adapted from aviation human factors studies (Cummings et al., 2020; Li et al., 2023).

Recent research by Carmody et al. (2024) indicates that unexpected safety issues provided by such battery-powered aircraft will definitely occur. For pilots, they deal with unique types of system failures. One of the psychological challenges for a pilot will be flying solo, without a co-pilot to double-check decisions or back him up in case something goes wrong (Janetzko & Kacem, 2024). This research addresses this crucial gap in knowledge by providing an empirical foundation for the future design of cockpits through systematic inquiry regarding pilot perceptions, issues with interface modalities, information priority, and automation interaction. A comparison of classic and advanced HMI system performance analytics, shows enhancements in Situational Awareness (SA), response time, and workload reduction. Replicated data from the reported studies on aviation interface evaluations are illustrated Figure 2.

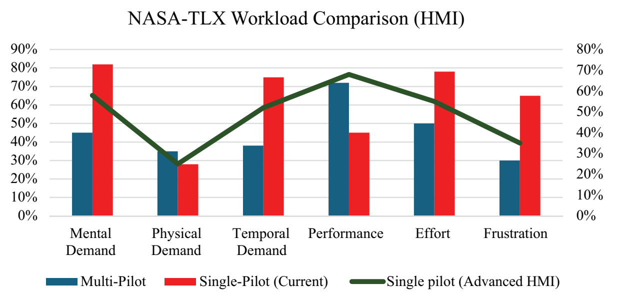

Figure 1. NASA-TLX workload comparison across pilot configurations and HMI types (source: Cummings et al., 2020)

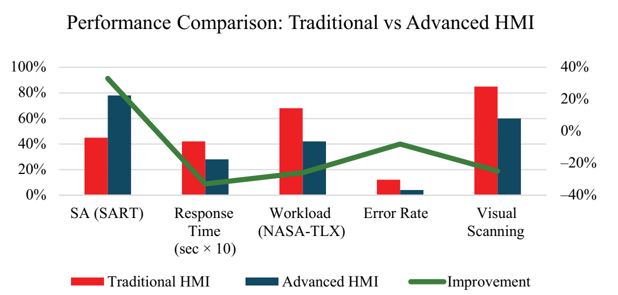

Figure 2. Workload scores across configurations and HMIs (source: Arthur et al., 2017; Namukasa et al., 2024)

This study contributes to eVTOL HMI research by (1) empirically validating pilot preference trends through mixed-methods analysis, and (2) proposing the Adaptive, Multimodal, Context-Aware (AMCA) framework as an integrated design approach for single-pilot operations. Practically, it provides manufacturers with specific interface priorities (hybrid controls, AR HUDs), informs regulators on certification pathways for adaptive interfaces, and guides training programs to address automation familiarity gaps.

2. Literature review

2.1. Theoretical foundations for HMI evaluation

The assessment of HMIs for eVTOLs requires a well-founded theoretical basis, supported by cognitive engineering. The research draws on three influential frameworks, combining a rich perspective on the subject (eVTOL HMI).

Endsley's Situation Awareness Model: SA described 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" (Endsley, 1995, p. 36), is arguably the most important predictor of performance in a complex, dynamic environment such as air operations. In the context of eVTOLs, it is essential that the HMI addresses all levels: making important information such as battery status and proximity to the obstacles prominent (Level 1), revealing relationships between different parameters such as power consumption vs. lift generated (Level 2), as well as supporting future predictions concerning both energy consumption and conflict resolution calculations (Level 3). The failure of any level can result in a total loss of SA, which has been identified as a contributor to a large percentage of air operations occurrences (Endsley & Garland, 2000).

Rasmussen's Decision Ladder (*Skill-Rule-Knowledge Framework*): Endsley's model explains the status of knowledge, while the Decision Ladder explains the process of deciding, as proposed in Rasmussen's model (Rasmussen, 1983). This model explains the human performance level from a three-tier perspective, namely skill, rule, and knowledge levels based on sensory motor activities, following procedures, and knowledge-dependent problem-solving, respectively. An effective HMI has to facilitate easy transitioning from one level to another. The interface has to enable skill-level activities effortlessly via convenient control systems, facilitate the rule-level functionality easily via accessible procedures, as well as guide knowledge level reasoning within novel situations, like a DEP system's possible powertrain fault, via convenient system model accessibility (Sanderson & Burns, 2017).

NASA-Task Load Index (*TLX*): The relationship between situation awareness and performance is filled by workload. The NASA-TLX, proposed by Hart and Staveland (1988), is a comprehensive, multidimensional measure for evaluating subjective workload on six dimensions: mental demand, physical demand, temporal demand, performance, effort,

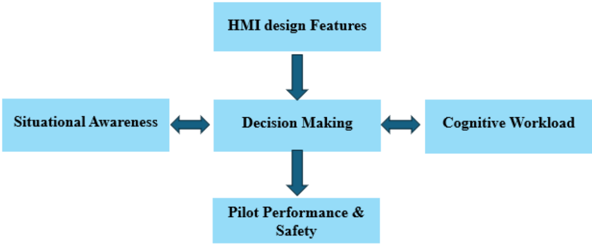

Figure 3. Conceptual model of the dynamic relationship between HMI design, Situation Awareness (SA), cognitive workload, and decision-making (source: developed by the authors)

& frustration. The advantage in eVTOL research resides in the level of specificity. For example, it can be observed that while automation has a reducing effect on both physical and temporal demands, it may increased the mental demand (monitoring) and frustration (due to automation opacity), as observed in highly automated flight decks (Hart & Wickens, 1990). It plays a critical role in determining the cognitive cost associated with human-machine interface interactions. An integrated conceptual design, illustrated in Figure 3, explains that HMI design features directly influence and are influenced by the dynamic interplay between SA, cognitive workload, and decision-making efficiency, ultimately determining pilot performance and safety.

2.2. Evolution of eVTOL HMIs and emerging challenges

In evolving from traditional rotorcraft aircraft and fixed-wing aircraft to new eVTOL platforms, a new aircraft environment has emerged. In distributed electric propulsion, there has to be monitoring of power sources, thermal dynamics, and flight control dynamics. On the other hand, autonomous flight control dynamics entail monitoring of vertical and horizontal flight. Current research on HMI systems supporting eVTOL aircraft is also driven by adaptive and multimodal interaction concepts. In adaptive interaction systems, information display is automatically varied according to flight phase or system status, eliminating visual distractions during critical phases (Airbus, 2024; Joby Aviation, 2023). In multimodal HMIs, visual, auditory, and haptic modalities are combined to share cognitive burdens among two or more modalities (Li & Zhang, 2025). The use of head-up or head-worn displays is particularly compelling means of enabling "eyes-out" cockpits, even at low altitude (Mobility Engineering, 2024; Vo et al., 2023). Simultaneously, new cockpit concepts bring forth challenges with regard to trust in automation and its transparency. Although AI-driven decision support systems hold great potential for workload reduction, insufficiently explainable automation may undermine pilot confidence or encourage complacency (Parasuraman et al., 2000). The central issue of certification and operational acceptance, therefore, remains the delicate balance between automating assistance and human authority.

Arthur et al. (2017) and Fadden et al. (1998) reviewed the advancement in aviation display systems and pilot interfaces to enhance SA and decrease cognitive workload. Head-Up and Head-Worn Displays (HUDs/HWDs (HUD and HWD) are highlighted as two main displays that project the most critical flight data directly into the pilot line of sight, with HWD providing an extensive, near 200° arc of view like natural vision. In particular, these displays help prevent excessive cognitive switching and thus ensure safety during a complex operation like landing in obstructed zones. Although, Parasuraman (2011), Klaproth et al. (2020) introduce the Neuroergonomic Paradigm, a new research area aiming at the design of predictive interfaces that can anticipate the state of the pilot's cognition by using physiological sensors such as EEG and eye-tracking. This neuroergonomic approach is considered one potential demand to manage cognitive bottlenecks, especially in single-pilot operations. Recent eVTOL-specific studies have begun applying these principles. For instance, simulation-based research is examining pilot visual behavior and trust during automated failure management (Li et al., 2024), while safety analyses (e.g., using STPA) are being adapted to address the unique human-automation interactions in single-pilot eVTOL operations (refer to broader safety engineering literature). A comprehensive solutions

Table 1. NASA-TLX workload comparison for multi-pilot versus single-pilot (current and advanced HMI) (source: compiled by the authors based on aviation human-factors literature)

HMI Technology	Human Factors Addressed	Theoretical Basis	Implementation Priority	Expected Impact
Adaptive Interfaces	Info Overload / Mode-confusion	Endsley's SA Model (Level 2)	High	35% reduction in visual scanning
Eye-Tracking Integration	SA / Attention management	Rasmussen's Skill-Rule-Knowledge	Medium-High	40% faster threat detection
Haptic Feedback Controls	CW distribution, Spatial awareness	Wickens' Multiple Resource Theory	Medium	25% reduction in heads-down time
Head-Worn Displays (HWD)	Visual clutter / Obstacles awareness	Fadden et al. (1998) attention models	High	50% improvement in urban navigation
Neuroergonomic Monitoring	Mental fatigue	Parasuraman's Neuroergonomics	Medium-Low	Early warning

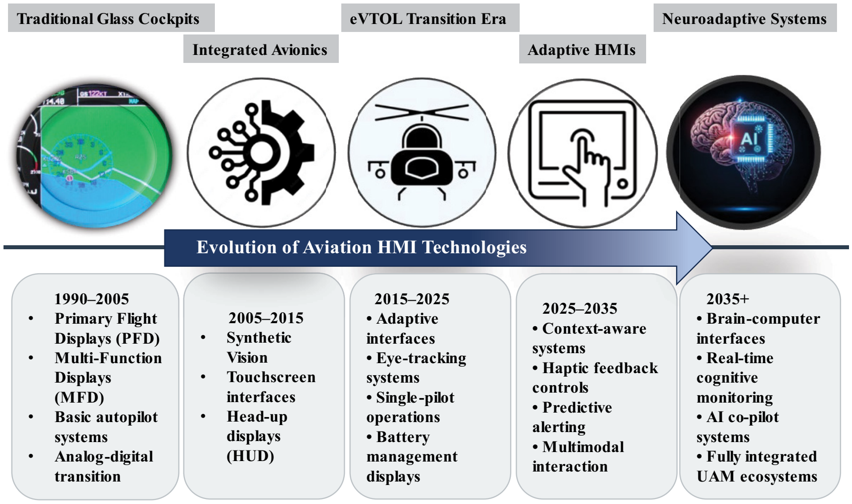

Figure 4. Timeline of HMI evolution toward adaptive, multimodal, and predictive interfaces for advanced eVTOL

matrix is presented in Table 1, below, which provides a structured approach addressing key human factors challenges through HMI technologies, with adaptive interfaces and head-worn displays identified as high-priority implementations.

The authors developed the progression of HMI technologies, as shown in Figure 4, which demonstrates a clear improvement toward adaptive and intelligent interfaces which are capable of supporting the unique demands of single-pilot eVTOL operations in urban dense environments.

3. Research methodology

3.1. Survey structure and dissemination

This particular study chose a mixed-methods design (Creswell & Plano Clark, 2017) to better understand professionals' perspectives regarding requirements in Human-Machine Interface (HMI) configuration for single-pilot eVTOL operations. A pragmatic approach in a mixed-methods study was chosen in this particular research to determine both trends at a broader professional group level as well as experiential details necessary in human factors investigation. The quantitative study used a structured web survey, while qualitative findings were gained through expert interviews. The combination of different methods helped develop methodological triangulation, where research findings could be explained and framed in accordance with expert opinions and feedback. The method is most relevant when it comes to exploratory research, specifically involving new ideas such as aviation concepts, where comprehensive operation-oriented information has not yet been obtained. The survey form was designed after a comprehensive review of the human factors of aviation literature, with a special focus on the aspects of situation awareness, workload, automation trust, and multimodal interfaces. The survey questionnaire had six parts, which were designed to gather professional details, operational challenges, preference for multimodal interfaces, information prioritization, workload, and open-ended design suggestions. In this study, the research tool used a combination of multiple-choice, ranking tasks, and five-point Likert-type items and open questions to determine the familiarity with eVTOL concepts and the importance of augmented reality head-up display and AI-assisted cockpit systems among others, using a Likert-type scale. To seek further information about the key aspects of cockpit interfaces and emergency response, the research utilized open questions. The pre-deployment testing and evaluation for relevance and consistency with aviation terminology were done informally by experts before the survey was distributed.

Participants and Data Collection: A total of 50 valid responses were collected for analysis, representing a purposive sample of aviation professionals with direct or indirect exposure to advanced cockpit systems and emerging eVTOL concepts. Given the exploration and niche focus on single-pilot eVTOL operations, this sample size is deemed suitable for identifying preliminary trends and design considerations within human factors research in novel aviation domains. The survey was disseminated via professional networking the LinkedIn platform and direct contacts within aviation communities, achieving a response rate consistent with expert-targeted surveys in this field. To complement and deepen the quantitative findings, four semi-structured expert interviews were conducted, ensuring thematic saturation on core topics such as situational awareness challenges, workload management, trust in automation, and interface modality preferences. The experts provided operational, regulatory, human factors, and industry strategy perspectives (Table 2).

Table 2. Sample demographic characteristics (N = 50)

Professional Expertise	n	%
General Aviation Pilot	18	36
Aerospace Engineer	13	26
Aviation Researcher	5	10
Human Factors Specialist	4	8
Commercial Airline Pilot	2	4
Other*	8	16

Note: *The Other category included aviation consultants, flight operations specialists, and aerospace engineering students with research focus on Urban Air Mobility (UAM).

3.2. Data analysis strategy

Considering the nature of the study as being exploratory and taking into consideration the characteristics of the data collected, a multi-stage approach to data analysis was adopted, using descriptive and exploratory inferential techniques. Descriptive statistics were performed to describe the sample and summarize response patterns across the survey items: frequencies and percentages for categorical variables; means, medians, and standard deviations were computed for Likert-scale items. These analyses provided an initial overview of professional backgrounds, perceived challenges, and HMI preferences. Although Likert-scale data are ordinal in nature, previous research has shown that parametric methods can be applied to five-point Likert scales with acceptable robustness when distributions are not highly skewed (Ovezmyradov et al., 2025; Sullivan & Artino, 2013). Consistent with common practice in aviation human factors research, exploratory inferential analyses were conducted with due caution. Given the sample size (N = 50), statistical analyses (regression, factor analysis, clustering) are presented as indicative trends rather than confirmatory conclusions, identifying design considerations rather than supporting broad generalizations.

Prior to conducting inferential analyses, the data distributions were reviewed for extreme skewness and potential outliers. In line with established practice in human factors and applied psychology research, Likert-scale responses were treated as interval data for parametric statistical tests an approach that is considered methodologically sound and robust for identifying preliminary patterns in exploratory studies. Although formal normality testing was precluded by the sample size, analytical emphasis was placed on interpreting the magnitude of effect sizes (e.g., correlation coefficients, standardized beta weights) in conjunction with p-values to assess practical relevance. Accordingly, all inferential results, including those from regression and factor analyses, are interpreted as indicators of meaningful trends to guide future design considerations, not as definitive, generalizable conclusions.

The following techniques were utilized:

- Independent-samples t-tests were used to explore differences in mean responses between pilots and non-pilot professionals in regard to automation comfort.
- One-way ANOVA was used to test differences among more than two professional groups, and the post hoc test was performed when necessary.
- Chi-square tests of independence were performed, focusing on the associations of categorical variables such as professional background and perceived operational challenges.
- The Pearson correlation analysis explored the relationships between eVTOL familiarity and attitudes towards the advanced HMI technologies.

All inferential analyses were interpreted as exploratory, and statistical significance was assessed using a threshold of $p < 0.05$.

Exploratory Multivariate Analysis: To explore the interaction of various factors with regard to the acceptance of automation, an exploratory analysis of multiple regression was conducted with comfort with AI-cockpit systems as the dependent variable. The independent variables consisted of familiarity with eVTOL systems, professional experience, and the perception of operation complexity. It was necessary to carry out diagnostic tests on the analysis to determine the presence of multicollinearity. Furthermore, exploratory factor analysis was also carried out on the factors related to the preferred HMI interaction modalities during high workload conditions. This analysis attempted to discover the underlying structures in the preferred interaction modalities. Rather, factors related to the preferred interaction modalities were grouped into factors that might help develop adaptive interfaces. Because sample size is a concern, the results from the factors related to the preferred interaction modalities were considered indicative rather than confirmatory.

Qualitative Interview Analysis: The expert interviews were conducted through a semi-structured style that allowed flexibility and consistency to uncover emerging themes. The areas explored during the interviews include perceptions regarding operational challenges, trust in automation, and implications for the implementation of HMI. The interviews were analyzed through thematic analysis, working with an inductive method of seeking recurring patterns. The themes established from interviews were then employed for placing specific findings from surveys within a certain context that enabled informing a proposed framework for an HMI.

Methodological Limitations: There are some limitations within methodological considerations. Firstly, self-selection and a fairly small subject population restrict generalizability. Secondly, because both variables are self-reported, there could be some issues with response bias. Thirdly, because some questions were posed within a series of scenarios, they measure expected rather than actual behavior.

4. Research findings

4.1. Survey results analysis

Perceived Operational Challenges in Single-Pilot eVTOL Operations: The participants were asked which of the most

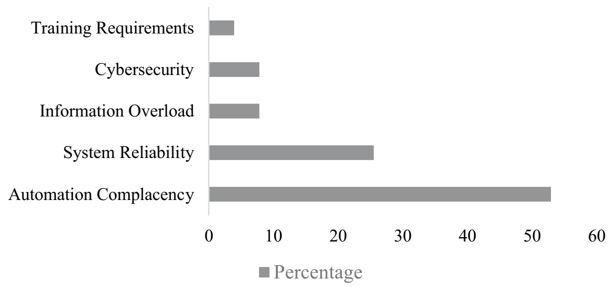

Figure 5. Distribution of primary concerns regarding advanced HMI systems

challenging aspects, related to single-pilot operations of eVTOL aircraft, they were required as pilots/ratings to deal with most frequently. The most important aspects were maintaining SA, abnormal/emergency workload, and advanced automation system interaction. Issues of energy control and path planning in urban areas also emerged quite often, especially with reference to decisive actions in time-critical situations. Problems of complexity and the absence of a copilot also got considerable attention. The result of the descriptive analysis disclosed that the level of perceived SA challenges is high for all respondents irrespective of their categories, with no statistically significant difference between the respondents who are pilots and those who are non-pilots ($p > 0.05$). Figure 5 depicts the distribution of primary HMI concerns among aviation professionals.

Human Machine Interface Modality Preferences: The participants were asked to assess the effectiveness of different HMI formats under normal as well as heavy workload conditions. The hybrid control formats, with the use of touch-based and physical controls, scored the highest on effectiveness. The fully touch-based interface scored well under normal conditions but dropped significantly under heavy workload conditions or abnormal scenarios. Figure 6, displays the distribution of control balance preferences.

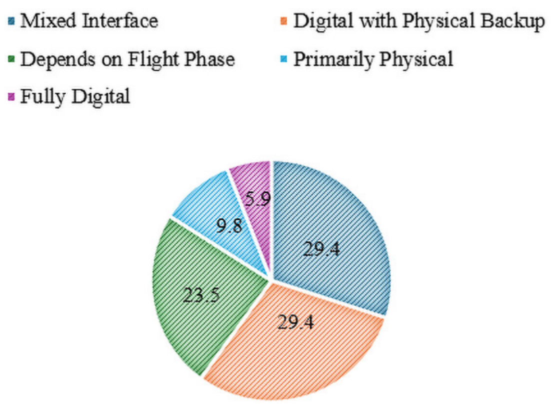

Figure 6. Preferred balance between physical and digital controls

Physical controls are valued for being considered reliable and providing touch feedback, especially during time sensitive phases of flight. On the other hand, voice interaction got mixed reviews, with questions being raised about reliability in a noisy setting and distraction to cognition. The trends were common across the professional backgrounds, albeit the slight preference for the physical backup demonstrated by the pilot group over the other group.

Augmented Reality & Head-Up Display Technology: Augmented reality head-up displays were considered valuable for improving "eyes-out" situational awareness, especially at low altitude in urban operations. Participants assessed that augmented reality overlays for obstacle awareness, traffic awareness, and flight path direction could help in reducing heads-down times. The average ratings on the Likert scale for AR HUD usefulness were found to be significantly higher compared to the traditional head down display for all professionals. No significant difference exists between pilots and non-pilots on the perception of AR values ($p > 0.05$). Respondents were asked to identify the most critical challenges associated with single-pilot eVTOL operations. Maintaining SA was consistently rated as the most significant challenge, followed by workload management during abnormal or emergency situations and interaction with advanced automation systems.

Descriptive analysis revealed that perceived SA challenges were consistently high across all respondent categories, with no statistically significant differences observed between pilots and non-pilots ($p > 0.05$).

Workload Distribution and Information Prioritization: The subjects were required to give priority to various elements of information in a scenario with a high workload. Information on traffic proximity, clearing obstacles, energy condition, and system status were considered of utmost priority.

The results from the survey have shown a preference for context-dependent information filtering, which involves the non-essential data being hidden when the operator is under higher workload conditions. This was shown both in the ranking and the comments obtained.

Automation: *Trust and AI-Based Assistance*: Attitudes on AI-related cockpit assistance revealed some divergence among the sample but indicated distinct tendencies. Indeed, there was both overall approval of AI-assisted decision-making in aviation and a tendency conditioned in its acceptance.

Exploratory correlation analysis showed a positive link between reported familiarity with eVTOL systems and comfort with AI assistance on the task ($r \approx 0.45$, $p < 0.01$). Role, whether the participant was a pilot or not, did not significantly link to the degree of automation comfort.

An exploratory multiple regression analysis also showed that familiarity with eVTOL aircraft was identified as the most significant predictor for comfort with AI-related cockpit functions, explaining a significant amount of variance within the analysis. Given the sample size, these outcomes may be considered inferential rather than confirmatory.

Exploratory Factor Structure of HMI Interaction Preferences: Exploratory factor analysis was used in investigating the underlying factors that are inherent in the preferred forms of HMI interaction during high workload. Two main factors were obtained:

- Direct Manual Interaction, including physical controls and tactile feedback.
- Assisted Digital Interaction, such as AR HUDs, adaptive displays, and AI-based decision aids.

These findings point toward a conceptual difference between the types of interactions that can enable immediate control of power and those that can enable stronger cognitive support. Given the limited sample, this model is an initial look at a proposed finding.

Technology Acceptance and Correlational Analysis: Quantitative analysis of technology acceptance revealed surprising patterns regarding AI co-pilot comfort. Descriptive statistics for key research variables are presented in Table 3.

Table 3. Descriptive statistics for key research variables (N = 50)

Variable	Mean	Standard Deviation	Minimum	Maximum
eVTOL Familiarity	3.28	1.20	1	5
AI Co-pilot Comfort	3.98	0.55	3	5
AR HUD Value	4.10	0.86	2	5

Overall, there is strong consensus over all professional groups that AR HUD (4.10/5.00) has a high mean with moderate standard deviation (0.86) as one of its highest scores. This comparatively high level of AI comfort (about 3.98/5.00) with low standard deviation (0.55) suggests general acceptance for automation support.

Predictive Modeling of AI Comfort: Results involving working experience and automation acceptance were surprising. As shown in Table 4, it seems that both pilots and non-pilots were very comfortable with working with AI co-pilots, as there was no significant difference between these two groups. As shown, an average difference of 0.13 was insignificant. Actually, a t-test value of –0.833 with a p-value of 0.409 shows no significance. Also, the standard deviation for these two groups seems very low, reflecting

Table 4. Multiple regression analysis predicting AI co-pilot comfort

Predictor	B	SE	β	t	p
eVTOL Familiarity	0.371	0.039	0.802	9.413	< .001
HMI Concern	0.097	0.054	0.154	1.780	.082
Pilot Group	0.054	0.094	0.048	0.570	.571
Operational Challenge	–0.010	0.040	–0.022	–0.254	.801

Note: R^2 = .686, F(4.45) = 24.55, p < .001. B = unstandardized coefficients, β = standardized coefficients.

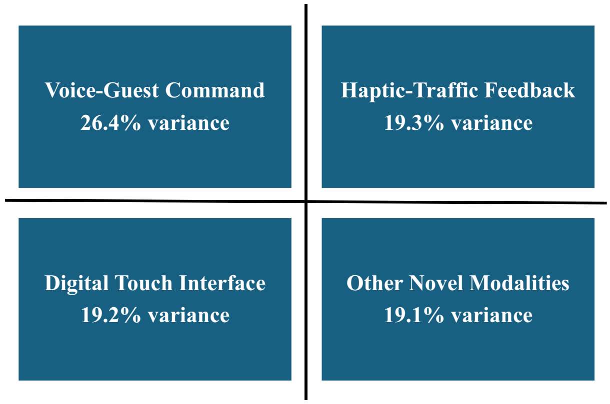

Figure 7. HMI modality factor structure

consistency among these people in terms of their perceptions about working with AI.

The explanation for the automation acceptance gap, however, the first required the regression analysis of automation acceptance predictors. The automation acceptance regression analysis of cofactors results were, however, unambiguous and startling. The Table 3 reveals that eVTOL knowledge was the only dependable predictor (β = 0.802, p < 0.001). Other predictors that were dwarfed included eVTOL knowledge and professional background (β = 0.048, p = 0.571). Other predictors were prior eVTOL knowledge and operational background (β = –0.022, p = 0.801). The overall model was also highly predictive. The variance in the comfort scores was 68.6% of the variance (F(4.45) = 24.55, p < 0.001). This was a significant shift from solely the profession to the level of professional eVTOL knowledge. The greater eVTOL knowledge one possessed, the more the individual was likely to trust the AI.

HMI Modality Factor Structure: Factor Analysis on preferred modes of interaction demonstrated a strong-four factor solution grouping various HMI modes into conceptually coherent sets. As shown in Figure 7, factors included Voice-Gesture Commands (26.4% variance), dominated by voice commands and gestures (loading = 0.640 and 0.738 respectively); Haptic/Tactile Feedback Systems (19.3% variance), dominated by haptic feedback systems (loading = 0.939); Digital Touch Interfaces (19.2% variance), dominated by touch interfaces (loading = 0.967); and Other Novel Interfaces (19.1% variance), dominated by emerging modes of interactions (loading = 0.947). The resultant comprehensive framework enables conceptual basis for adaptive and flexible HMI system designs that would support various modes of interactions within specific operation environments.

Professional Segmentation Analysis: From the data represented in Figure 8, the K-means clustering analysis identified three professional groups, based on their attitudes towards technology. In the first cluster, the Moderate Adopters, consisting of 21 individuals, had an M = 2.0 low eVTOL awareness, yet they expressed positive attitudes towards automation. The second cluster is the Balanced Experts, consisting of 18 individuals who knew a great deal

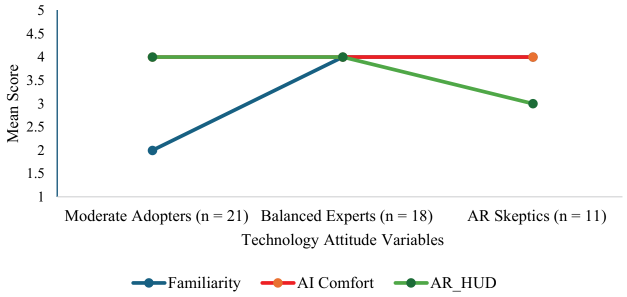

Figure 8. Professional segmentation through clustering

on the subject, and had a balanced preference on automation. The final cluster is, AR skeptics with 11 individuals who had a great deal of subject awareness, but their value towards the AR HUD was significantly low. In two iterations of data pointing, the cluster centers converged, suggesting that the data points were stable and efficiently separated. With the different attitudes and needs being expressed in this professional field, different target segments were created. The professional field that possesses a great deal of AR related technology knowledge, but does not engage with AR technology, suggests a low tech comfort, and has unanswered AR technology concerns.

Human Machine Interface Modality Preferences: Participants evaluated the perceived effectiveness of various HMI modalities under both normal and high-workload conditions. Hybrid control architecture, combining digital touch-based interfaces with physical controls, received the highest overall ratings. Fully touch-based interfaces were rated favorably under normal conditions but showed a marked decline in perceived suitability during high workload or abnormal situations. Physical controls were consistently valued for their perceived reliability and tactile feedback, particularly during time-critical phases of flight. Conversely, voice interaction received mixed responses, with concerns raised regarding reliability in noisy environments and potential cognitive distraction. These trends were consistent across professional backgrounds, although pilots demonstrated a slightly stronger preference for physical backups compared to non-pilot respondents.

Chi-square test showed no statistically significant association between workload type and control balance preferences ($\chi^2 = 11.890$, df = 12, $p = 0.455$). Figure 9 depicts the workload Types' Interface Preference Distribution.

Table 5 below shows the distribution of control interface preferences; there was no association for a statistical significance in the four types of the workload. However, there is a clear understanding of the mosaic of the distribution of the interfaces suggesting the specific requirements for the human-machine interface design.

Augmented Reality and Head-Up Display Technologies: AR HUD systems were found to be valuable in improving "eyes-out" situational awareness, especially during low-altitude operations in urban environments. The AR overlays for obstacle awareness, traffic awareness, and flight path direction were found to be useful in decreasing heads-down time.

The mean scores of usefulness of AR HUD systems on a Likert scale were significantly higher compared to conventional head-down displays overall. Non-significant differences in perceived AR value were noticed in this study concerning pilots and non-pilots ($p > 0.05$), which indicated a collective perception of professionals about usefulness in this area.

Workload Distribution and Information Prioritization: Respondents were asked to rank information elements in order of importance under high workload conditions. Proximity of traffic, obstacle clearance, energy state, and system health indicators were consistently ranked as the most critical information categories. Responses to the survey questionnaire highlighted a strong context-sensitive information filtering preference, suppressing non-essential

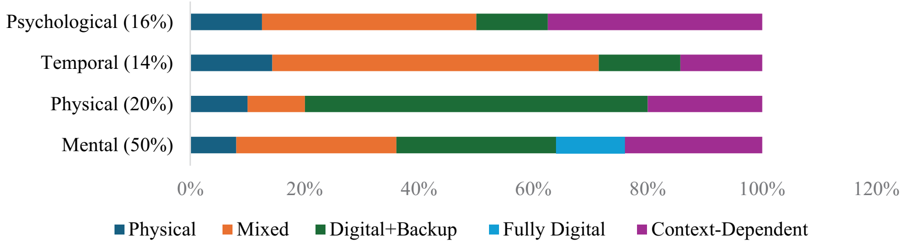

Figure 9. Workload types' interface preference distribution

Table 5. The distribution of control interface preferences

Workload Type	Physical Controls	Mixed Interface	Digital + Backup	Fully Digital	Context-Dependent
Mental (50%)	8%	28%	28%	12%	24%
Physical (20%)	10%	10%	60%	0%	20%
Temporal (14%)	14.3%	57.1%	14.3%	0%	14.3%
Psychological (16%)	12.5%	37.5%	12.5%	0%	37.5%

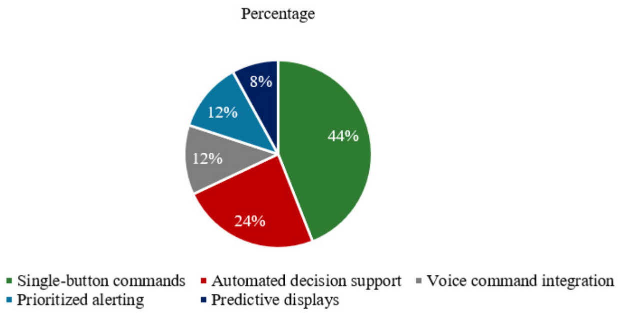

Figure 10. Single-button commands dominate system usage

data during peak workload periods. This preference was evident in quantitative rankings and supporting qualitative comments that reinforced the principle of information overload avoidance during critical phases of flight.

Exploratory Factor Structure of HMI Interaction Preferences: Exploratory factor analysis was used to investigate the underlying structure in preferred HMI interaction modalities in high-workload conditions. The analysis revealed two prominent factors:

1. Direct Manual Interaction, including physical controls and manual feedback systems.
2. Assisted Digital Interaction, such as AR HUDs, Adaptive Displays, and AI-driven decision support systems

These seem to point towards a conceptual difference between the interaction types that warrant immediate control authority, as opposed to those which also warrant stronger cognitive support. For reasons of sample size, this structure will be offered instead as an initial insight rather than a proven model. Figure 10, the distribution of the identified critical features of HMI is presented. The single-button command systems emerged as the most dominant preference with 44% of the votes, while decision support system automation followed behind with 24%. This distribution clearly indicates the most pressure HMI features professionals.

4.2. Qualitative insights from expert interviews

Four semi-structured expert interviews were very helpful. They served to add some qualitative depth to the quantitative findings. The experts were from regulatory & operational, ex-fighter pilot, commercial airline pilot, human factors specialist and eVTOL BD lead.

The opinions gathered in the expert interviews were supportive of some of the survey results. There was universal endorsement in the interviews concerning the relevance of SA preservation in single-pilot operation environments.

Often, regulatory aspects, especially for adaptive and AI-driven interface certification, cropped up in conversations. The role of gradual implementation and human control over automated aspects was emphasized by experts. Based on the interview results, the following findings were identified:

- The criticality of decluttering and tactile feedback: In emergency situations, the most needed HMI feature, is the declutter function," two experts noted the importance of decluttering as pilots suffer TMI (Too Much Information) at high workload. One expert explained regarding tactile feedback, "vibrations in the seats would be most helpful as they feedback directly into the sensorimotor channel." One proposed a hierarchy wherein feedback in the seat would be more preferable than hand or leg vibrations.
- The automation trust-regulation paradox: Three experts explained the regulatory challenges for AI within regulations are the biggest challenges apart from AI implementation. ICAO still does not have black and white regulatory guidance. One expert stated that AI is designed by people, for people but cannot replace people. The reliability of AI is not superior to the duo of people.
- Augmented Reality as Situational Awareness Multiplier: Two experts strongly advocated for AR displays. They confirmed that "Augmented Reality would be very helpful for eVTOL operations" because there are low-altitude operations in urban areas and one would have to react in a very short time. Although they stated that "Head-Up Displays are crucial for eVTOLs" because pilots are at a low altitude and don't have time to look at the instruments for a long time.
- Controlled Autonomy in Emergency Management: Regarding AI autonomy levels, warned that giving AI a free hand, you have the black box problem. He suggested that "executives should remain with the pilot, and the AI should be an assistant, not an executor." One suggested a stepwise approach: What if? Prompts where one of executives suggest the automation would periodically check in with the pilots to see whether the automation's planned action is acceptable.
- Hybrid Control Philosophy: two experts expressed doubt on completely digital interfaces: Touch systems are not yet reliable for eVTOLs. There should be part-conventional instruments and buttons.

5. Discussion

The results of this study provide empirical evidence for the pivotal role of HMI design in enabling single pilot eVTOL operations to be both safe and effective. Operational challenges associated with maintaining SA were ranked as most critical across the various professional groups, which further supports the concerns raised in earlier research on cognitive workload in highly automated, low altitude flying regimes. In contrast with conventional multi-crew operations, single-pilot eVTOL missions are heavily reliant on interface-mediated support to compensate for the lack of a dedicated monitoring role.

The strong preference for hybrid control architecture indicates there is an important balance between innovation and operational robustness. While digital interfaces and adaptive displays can provide flexibility and information richness, physical controls simply remain appealing due to their tactile reliability-especially under high workload or abnormal conditions. This result is in accordance with basic principles of human factors, which indicate the role of haptic feedback and muscle memory during time-critical tasks. The high valuation of AR head-up displays across different professional backgrounds testifies to the expected added value in enhancing "eyes-out" situational awareness. Over urban environments, where pilots must be constantly aware of obstacles, traffic flow, and landing zones, AR-based overlay information could help to avoid attentional tunnelling and minimize the need for head down displaying). These advantages depend on careful filtering of the information in order not to create visual clutter, especially during phases of maximum workload.

Attitudes toward AI-based cockpit assistance thus reflect a complex interplay between trust and familiarity. In the context of such findings, that technical familiarity with eVTOL systems and not professional role was the best predictor of automation acceptance suggests that exposure and training might prove to be determining factors in shaping the trust of operators. This has strong implications for certification, training curricula, and progressive introduction of advanced automation. Instead of assuming innate pilot resistance toward AI, all stakeholders should put more emphasis on making transparency and explainability of AI central (Kim & Ji, 2024) and introducing an advanced system incrementally.

6. Adaptive, multimodal, context-aware HMI framework

Based on the knowledge gathered from integrating survey results, expert interview results, and established human factors theories, the proposed study suggests the AMCA HMI framework for design concepts for the cockpit of an eVTOL aircraft.

6.1. Conceptual framework

The AMCA framework as illustrated in Figure 11 below is based on three core principles that were distilled from empirical evidence. The proposed AMCA framework aligns with and extends principles of adaptive automation and context-aware computing explored in other complex human-machine systems, tailoring them to the high-tempo, high-risk environment of urban single-pilot operations.

1. *Adaptive Information Management*: HMI systems should dynamically adjust information presentation based on flight phase, system state, and workload level. During high-demand situations, non-essential information should be suppressed to preserve cognitive resources.
2. *Multimodal Interaction*: Good HMIs should balance information across visual, auditory, and haptic modalities to avoid overwhelming the senses of one modality. AR HUD systems are available for visual notification, and auditory and haptic systems can be used for confirmatory notification of critical alerts.
3. *Context-Aware Automation Support*: Automation has to be cognizant of the context in which operations happen and have human authority as a distinct factor. Assistance by AI has to provide support in decision-making without clouding the logic of the system or the engagement of the pilots.

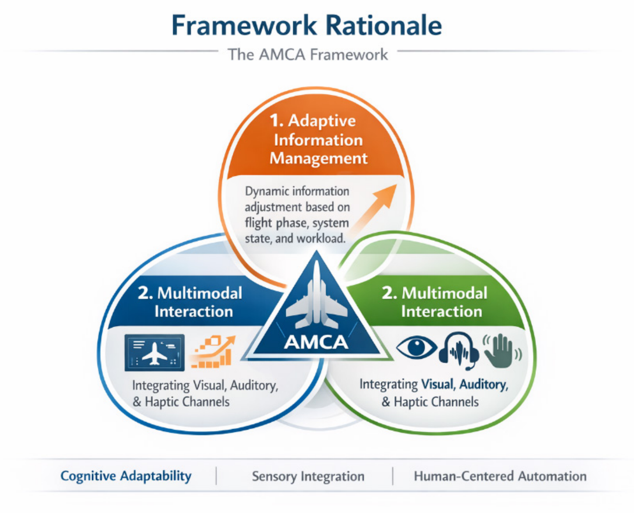

Figure 11. AMCA conceptual framework (source: conceptualized by authors, generated using AI (OpenAI, 2026))

6.2. Application to single-pilot eVTOL operations

In the framework of the AMCA, the HMI is a virtual crew member and helps the pilot in the following ways:

- Progressive disclosure of information, aligned with workload levels.
- Predictive cues, such as energy trend projections and conflict alerts.
- Redundant interaction pathways, ensuring continued control under degraded conditions.

Notably, the framework promotes controlled autonomy, whereby the automation system helps, rather than replaces, the pilot in making decisions. Controlled autonomy has been advocated by expert systems to achieve explainability in expert systems.

6.3. Conceptual nature and certification considerations

The AMCA framework is purposefully framed more as a conceptual or design- oriented model than one which has been validated or is certifiable in its own right. Although certain aspects, such as AR HUDs or adaptive displays, are already in development, other aspects, especially those dealing with highly advanced adaptation through AI, need additional empirical support and engagement with regulators. A step by step implementation process, testing incorporating the human in the loop, and an explicit logic of automation is a prerequisite to operational integration.

6.4. Limitations

There are points that need to be noted in respect to the result generation. Since the study has a small sample pool, it hampers statistical generalizability. Also, it has a self-selection bias. The results generated would include expected behaviors, not actual behaviors observed during operation. Furthermore, this study aims at getting the perspective of professionals, not at actual pilot behaviors in simulated or actual flights. These points highlight the early nature of this study in a developing aviation sector. While the current analyses with small samples applied parametric analyses cautiously, The authors aim to proceed with future studies in the frame of PhD study to formally test distributional assumptions and validate the observed factor structures using confirmatory techniques on larger samples.

6.5. Visualization methodology

The visuals were made with the help of pictures of various aircraft from the open-source flight simulator FlightGear. It is important to note that FlightGear was used solely for visualization purposes to create static representations of the proposed HMI states, and was not employed for active pilot-in-the-loop data collection or dynamic simulation trials. The cockpit of an A320-family aircraft was selected as the representative model, as it has a modern glass cockpit architecture that is, in a way, similar to the proposed eVTOL interfaces. To make it clear how the instrument clusters play a key role in the AMCA framework, this picture was annotated. Also, a photo of a Head-Up Display (HUD) was changed to show the idea of adaptive decluttering in an emergency scenario.

Conceptual Interface States

Two distinct interface configurations were visualized to demonstrate AMCA principles:

1. Normal Operational Configuration (Figure 12): Regular Operational Setup: This image illustrates the fully equipped glass cockpit in a fully operational state. The labelled the displays for the Attitude Air-

Figure 12. Conceptual visualization of the proposed AMCA HMI in normal operational configuration, showing comprehensive glass cockpit instrumentation

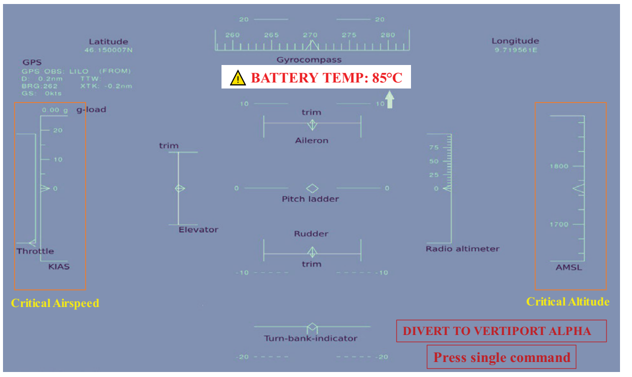

Figure 13. Emergency decluttered configuration, visualization using FlightGear

speed Altitude Primary Flight Display, the Navigation Display that includes "The Route and Terrain", the "Engine Indication", "Crew Alerting System" and the flight control panels to the pilot. This is the baseline information environment that is the most data-rich from which the adaptive alterations would be made.

2. Emergency Decluttered Configuration (Figure 13): This modified HUD visualization shows how the AMCA concept of context-aware information display can be used. The display has been simplified by an algorithm to illustrate the situation of a battery thermal anomaly during descent. Only three critical parameters – current altitude, airspeed and battery temperature with a warning indication – are still clearly visible, while the less important data is unhighlighted. The graphic also features the emergency action prompt, which stands for the single-command interface that 44% of survey participants indicated as their preference in high-workload scenarios.

7. Conclusions and future research

This research provides evidence based on the requirements of HMI in the context of single-pilot operation of eVTOL aircraft on the themes of situational awareness preservation, control architecture type, and context-related information management. The results have implications on assumptions about resistance to automation and demonstrate the important factors are those of familiarity and transparency.

Moreover, the study reveals that the eVTOL HMI design that leads to success should go beyond the conventional cockpit models and instead adopt a holistic approach that:

1. Supports pilot cognition instead of substituting it by AR-focused information delivery;
2. Maintains the balance between digital and physical worlds by hybrid control architectures;
3. Develops trust in usage through open, controllable AI systems;
4. Changes according to situation and workload through smart interface management.

The AMCA HMI framework provides a conceptual groundwork that would continue to shape the design of cockpits, training programs, and certification discourse in the future. In the future, areas of study would include simulations and training for extended periods, as well as collaborative studies to evaluate the adaptation and AI-related interfaces. Human-centric HMI design will continue to play a crucial role in realizing safe and viable flight systems through technological innovation in urban air mobility in the years to come.

Disclosure statement

The authors declare that they have no competing financial, professional, or personal interests from other parties.

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AI (*GPT-5.3*) was used to generate one image and refine 21% of the entire article in reference to English language.

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