Design and positioning of an HMI for cooperative working between human air traffic controller and digital controller

Julian Böhm[1], Jana Meier[1], Sebastian Schier-Morgenthal[1], Justus Renkhoff[1]

[1] German Aerospace Center, Institute of Flight Guidance, Lilienthalplatz 7, 38108 Braunschweig, Germany

Contact: Julian.Boehm@dlr.de

The scarcity of human air traffic control officers (ATCO) and the advancements in automation and artificial intelligence have prompted the investigation of novel concepts in air traffic management (ATM). A notable concept is that of single controller operation (SCO), which involves a symbiotic collaboration between human and digital ATCO. This paradigm shift in the nature of work demands a re-evaluation of the roles and responsibilities of human air traffic control officers. In addition to operating their dedicated aircraft, human ATCOs are charged with the oversight of aircraft guided by the digital controller within the same sector. The interaction with the digital controller necessitates the design and configuration of the human-machine interface (HMI), which facilitates these interactions to be self-explanatory and solvable in short time.

This study will methodically compare two different HMI designs, each integrated into the existing working position of the human ATCO. One design is based on a flight strip design, whereas the second design is on a separated display. The evaluation of the designs is conducted through a workshop involving ten experts in the field of ATM, followed by validation using a prototype of two designs indifferent scenarios. These consists out of a conflict, an emergency and a direct, which includes a redirection of an airplane. The validation of the designs is conducted by the ATCO and experts in ATM.

The conclusion of the workshop's outcomes and the validation of the prototypes culminates that the integration of a future HMI, designed for collaborative operation between human and digital ATCO, should be seamlessly incorporated into the prevailing working position. In the event that implementation of the HMI into the existing interface is not possible, it is imperative that its design align closely with existing HMI designs and be positioned in close proximity to existing displays, ensuring that the HMI remains within the field of view of the human ATCO. In the study the ATM experts prefer the separated display design.

1. Introduction

The air traffic system owns the advantage of a centralized control instance: Any participant in the system basically requires a connection to Air Traffic Control (abbr. ATC) for a safe, order and efficient flight. To fulfill this task, ATC must provide sufficient resources. This is currently not the case in Europe as ATC is being responsible for more than 50% of the current delays [1] and a staff gap of approximately 700 controllers is existing. The future developments indicate that this situation will worsen due to rising traffic volumes [2] if any countermeasures are taken.

Possible countermeasures to this challenge are available on different levels. One solution is to endorse the available controllers more flexibly, so that a shift of staff to sectors with higher demand can be performed more easily [3]. Other concepts aim on elimination of traditional sector boundaries again to allocate controllers more flexible to the existing traffic [4] or to delegate the separation task in specific cases to the cockpit crews and their support systems [5]. All of these solutions are able to increase flexibility or productivity of ATC. Nevertheless, all of these solutions require a change of existing regulations.

One solution which is already available today is the principle of Single Controller Operations. This procedure allows to have one controller taking over the roles of the so called executive and planner. Today, this principle is only applied in low traffic situations (e.g. at night). The German Aerospace Center showed that with appropriate assistance tools this concept can be applied more frequently [6]. In simulations a traffic load of up to 80% of the declared capacity was handled [7]. But the results showed that additional workload was induced by the large number of new assistance tools. As a consequence, the “digital controller” was introduced that not only supports the human air traffic controller, but issues commands directly to aircrafts [8]. In the operational concept, the digital controller operates the flights which are within its capabilities. All other flights are handled by human controllers. This leads to cases where digital and human controller operate flights in the same sector and must coordinate with each other.

This paper evaluates the most appropriate design for the coordination interface between human and digital controller. Therefore, three different approaches are presented. Out of the three approaches, two are tested in human-in-the-loop studies with controllers and ATM experts. The major finding of this study is the inclusion of the HMI in the existing display or a very close positioning with a visual representation of the situation.

2. Related Work

2.1 State of the art

A sustainable HMI in the context of air traffic control must fully cover the information requirements of the human controller, but also counteract possible excessive demands. Studies show that the transparency of algorithmic decisions, and their traceability are highly relevant for the acceptance of automated systems [9][10]. The HMI should therefore not only display results, but also reveal the algorithm's decision-making process. In addition, interactivity of the interface is essential in order to give the human controller the opportunity to intervene in the processes or adjust at any time. The HMI should preferably depict human-like action patterns in order to make the behavior of the automation comprehensible[10]. In terms of visual design, aspects of effective attention guidance are highly relevant. Equally important is a graduated alerting system that conveys information according to urgency without unnecessarily disturbing situational awareness [11][12].

The spatial and functional positioning of the HMI has a significant impact on the effectiveness of human-machine interaction. A central display, such as the radar screen, which allows a clear, reductionist representation of the airspace situation, remains indispensable even in the age of automation [13]. Supporting systems must be integrated in such a way that they are perceived as a natural extension of the main workstation. Controllers prefer to determine the layout of their working environment themselves. A customizable design can therefore both improve usability and increase acceptance [14]. Furthermore, the HMI must be designed in such a way that it enables seamless handovers between human and digital controllers [15].

The workload is a key challenge in the design of a digital controller. Studies show that both overloading and underloading the human controller can lead to human errors [16]. Systems must therefore be designed to automate routine tasks while leaving critical tasks to humans to maintain situational awareness [17]. A balanced level of automation can be achieved by introducing different levels of autonomy [18]. For example, support from the system starts with pure information, followed by suggestions and ends with a co-operative decision-making process. It is crucial that the human controller always retains the final decision-making authority. In addition to cognitive relief, it is important that the system's error behavior is defined. In the event of malfunctions, a safe backup system must be able to intervene automatically in order to ensure a consistently high level of safety in air traffic control [13].

2.2 Methodologies for evaluating the HMI

A practical, user-centred approach is crucial for evaluating the HMI of a digital controller. Simulation-based tests with realistic prototypes are particularly suitable [19]. It is important that the test subjects have no previous experience with the system in order to obtain uninfluenced feedback on first impressions, integration, and situational awareness.

Another established approach is the scenario-based evaluation model S.A.D.E. (Standardized Application for Automated Driving Evaluation) [20], in which users use live ratings, questionnaires and interviews to assess how comprehensible, and controllable the system is. Such procedures are supported by quantitative methods such as in the AR-HUD (Augmented Reality-Head Up Display) evaluation [21], where criteria such as readability, visual fatigue and layout are assessed in a standardised scoring system. The targeted isolation of critical scenarios is suitable for simulating extreme situations [22]. These can be tested realistically, even if real flight data is missing. In addition, user experience via photoplethysmographic (PPG) signals [23] provides methods for the objective measurement of attention distribution, for example through eye tracking and heart rate analysis. A combination of interviews, performance data and scale evaluations, allows for a comprehensive assessment. The added value of expert evaluations in early concept phases is also emphasised.

To summarise, an effective evaluation method for the digital controller combines different approaches: realistic simulations, objective parameters and subjective user feedback. In this way, the user-friendliness and efficiency of the HMI can be assessed in a well-founded manner.

3. Methodology of the evaluation

Main aspect of this validation is to measure the efficiency and usability of the interfaces. To achieve the key measurements different indicators can be used (Figure 1) [24]. Key indicators for the efficiency are the amounts of clicks, time needed to solve the situation and the situational awareness during the usage of the interface. To measure the usability, it is necessary to get the feedback of the persons using the interfaces.

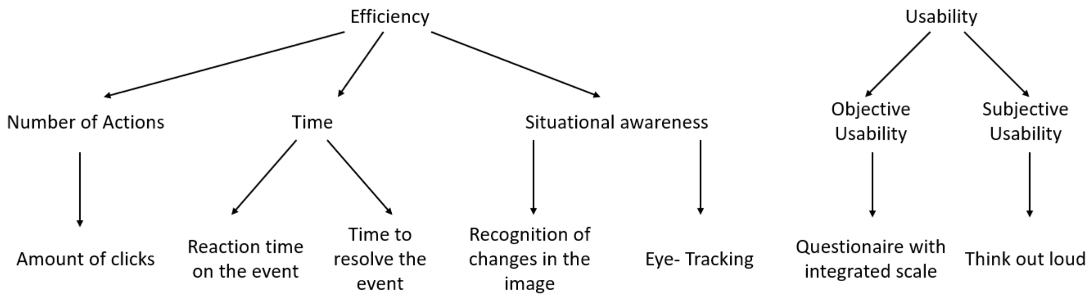

Figure 1: Validation tree for Efficiency and Usability

The evaluation of the different HMI designs can be separated into two different phases. A Workshop for getting feedback and improving the designs for further implementation in prototypes. The implementation of the designs will be validated by a test with prototypes of developed interfaces.

3.1 Workshop

In an early phase of the development feedback of persons known to the challenges of interfaces for an ATCO is necessary to improve existing ideas and conclude which designs are preferable. In order to achieve the uninfluenced opinion of ten experts the workshop was designed in a way to present the designs within the chosen three different scenarios direct, conflict and emergency. The scenarios were chosen by the extremes of time-based interaction and the lead of the interaction (pilot/ATCO) [25]. The scenarios occur mainly in en route operations, where the digital controller should support the center controller. During these scenarios the digital controller requests actions by the human ATCO resolve the problem. The collected thoughts of the experts were added by a few questions which guide the gathered information to the structure of the interface, the positioning, the kind of interaction and the advantages of the different interfaces. In order to track the improvements of each interface a rating on a scale from zero to ten was given by the experts.

For this phase of the validation three different designs were chosen, which are supporting the primary radar display. A conservative choice for such an interface is to implement the new features in an existing HMI known to the human ATCO. Known but less used in recent years is the flight strip display. For the validation of the different designs the flight strip display is reduced to necessary information while adding tools to interact with the digital controller. The given information is reduced to be shown in text and answered the same way. To indicate new information are given by the interface, a sound will be given to the human ATCO to inform him/her on the need of his/her action.

The flight strips (Figure 2) are marked by different color to indicate the human ATCO which aircraft is under the control of the digital controller (green) and affected by the situation (orange). To interact with the digital controller the human ATCO can see the planned actions in the bottom comment box which provides next to it the option to accept and decline the planned action.

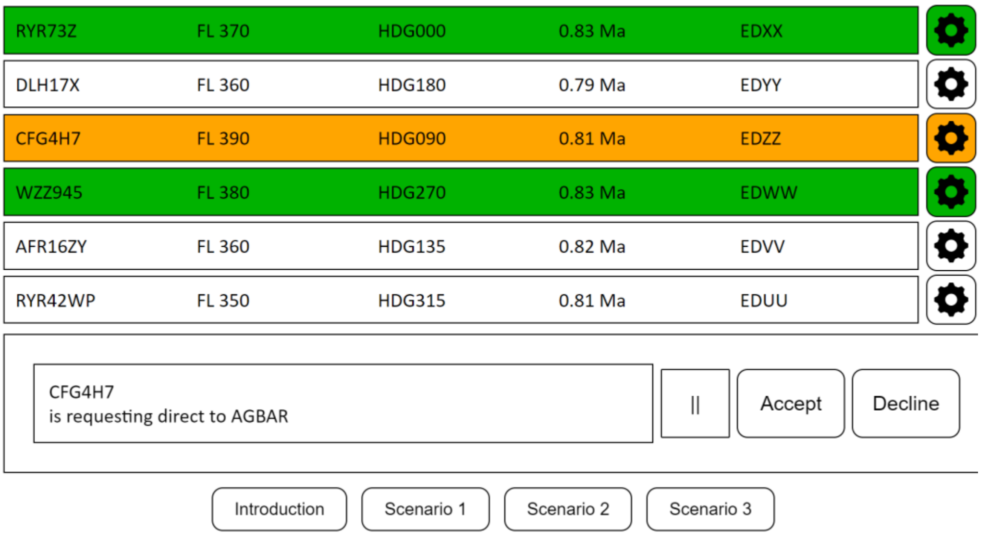

Figure 2: Flight strip-based design of the HMI

In comparison to the familiar design of a flight strip interface the more progressive interface would be a newly designed one (Figure 3). Based on this approach the usage of a separated display is used to show the needed information. The information given to the human ATCO are shown by a replication of the radar display with the addition of the information given by the digital controller to solve the problem.

The design consists on a setting section on top with the option of different control modes of the digital controller as area based, time based, airplane-based operation. The mid-section is the replicated radar display showing additional information. To specify the intentions of the digital controller a textbox with a short description of the planned actions and the problem is given in text. Based on the planned action by the human ATCO the buttons on the bottom enable different action of the digital controller.

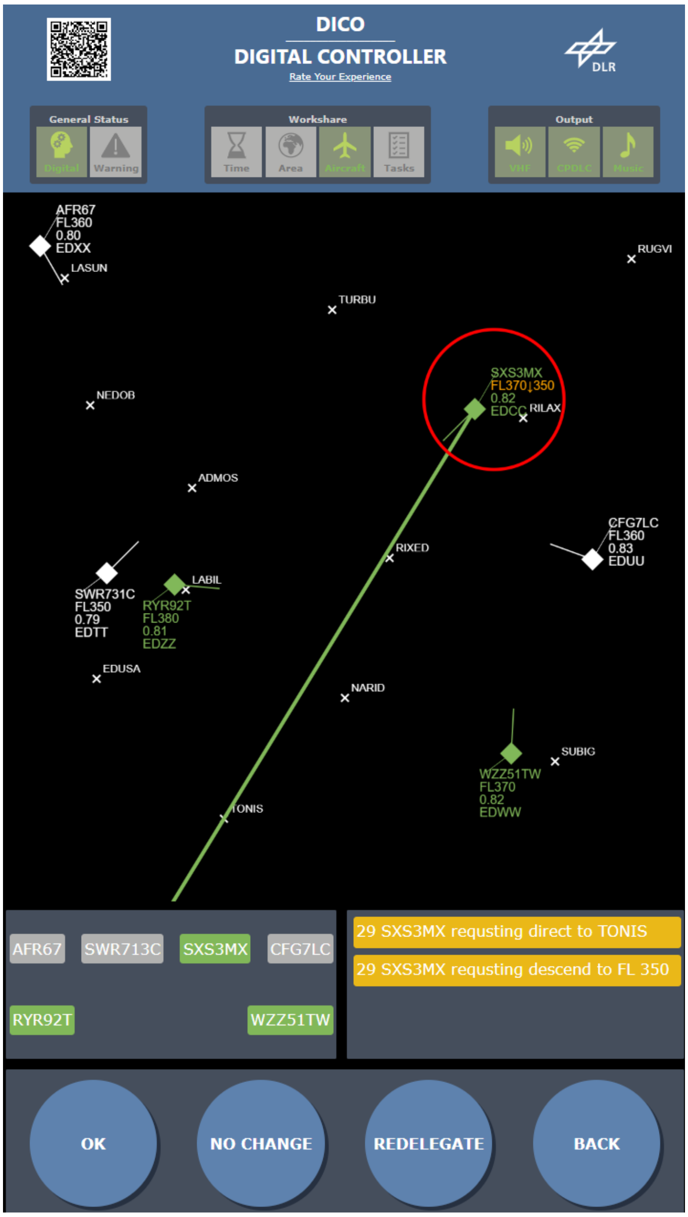

Figure 3: HMI design on separated display

The third interface is to interact with the human ATCO with audio communication. Based on the separated display design as backup for the human ATCO the audio communication is the main way to interact with the digital controller. Beside the audio communication the ATCO can also interact with the display.

3.2 Test with prototypes

Based on the feedback from the workshop validation, the audio communication interface was not developed further because the sounds disturb the concentration of the ATCO. The other two designs were improved and adapted to the feedback of the experts, but no major changes of the interfaces were implemented.
The setup of the prototype test consists of a primary display showing an abstract scenario as an image. Next to the scenario, the flight strip/separated display is placed on the right side. The separate display interface is in the form of a robot, resulting in the idea of representing a human being to interact with. The process of validating both

interfaces consists of three separate runs, each representing one of the scenarios conflict, direct or emergency. For each run the following procedure is carried out by the subject of the validation:

1. Focus on the primary display,
2. Signal tone of the digital controller
3. Interaction between human and digital controller,
4. Focus on primary display with changes in the original image,
5. Identifying the difference in the image by the test person,
6. Feedback by a questionnaire.

To measure the wanted data about the efficiency and usability different parameters were measured like:

- Clicks used,
- Reaction time on the event,
- Time to solve the event,
- Recognition of the changes in the image,
- Time of the recognition,
- Number of gaze changes.

To collect these data, the screen was recorded using eye-tracking to follow the person's gaze. The questionnaire used for the subject's feedback was developed from the SUS questionnaire [26]. In order to make the questions more specific and to detect the differences in the interfaces for air traffic control, some questions were modified.

Removed questions

- I think that I would need the support of a technical person to be able to use this system
- I would imagine that most people would learn to use this system very quickly
- I needed to learn a lot of things before I could get going with this system

Added questions

- The amount of given information was enough to solve the situation
- The situation could be solved quickly
- The situational awareness was maintained any time
- I recognized the importance of the situation

In order to compare the interfaces from the questionnaire, the statements were separated into positive and negative connotations and added up to obtain a comparable rating. The positive connotations
Additional to evaluate the changes made from the workshop a scale was added and two question boxed were added collecting open feedback.

- What is needed to improve the interface?
- What was the main problem with the interface?

4. Results

4.1 Design of the interface

Based on the feedback from the workshop, the interface with audio communication was not further developed and evaluated by the scale rating at the end of the workshop. Due to the scale rating in the workshop and the prototype test, it is possible to see the development in both interfaces and to compare them regarding their general rating. Ten experts in the field of ATM were involved in the workshop. In the prototype test, four ATCOs and six ATM experts were involved. The results of the scale indicate a better performance of the separated display design in the workshop phase as well as in the prototype test (Figure 4).

Validation phase	Flight strip design	Separated display design
Workshop	4,3	4,9
Test with prototype	5,5	6,6

Figure 4: Scale rating (0-10) for the interfaces in the different validation steps

The use of eye tracking allows the measurement of different indicators for each interface from the beginning of the scenario to the detection of the change:

Indicator	Flight strip design	Separated display design
Average amount of gaze changes	2,9	1,2
Average processing time	19,6 seconds	18,9 seconds
Rate of recognized errors	67%	63%
Average duration of error detection	13,7 seconds	13,6 seconds

Figure 5: Collected data out of the eye-tracking

While most of the data have results in the same range, the number of gaze changes (looking from primary display to HMI and back) in particular indicates that the understanding of the interface is better in the separated display. A lower amount of gaze changes is given when the test person got a better understanding out of the HMI. This is confirmed by the open-ended questions in the questionnaire.

Regarding the results in processing time and number of gaze changes, the different performance of the flight strip design in detail is revealing. While in the scenario of a direct request the interface performs better than the interface as a separate display, in the scenario of an emergency it performs in the range of the other design. For the conflict scenario, the flight strip design performs worse. Analyzing the error detection (Figure 6), the average time of each scenario is close to each other while there are differences between the scenarios. The reason for this can be found in the type of changes made in the different scenarios.

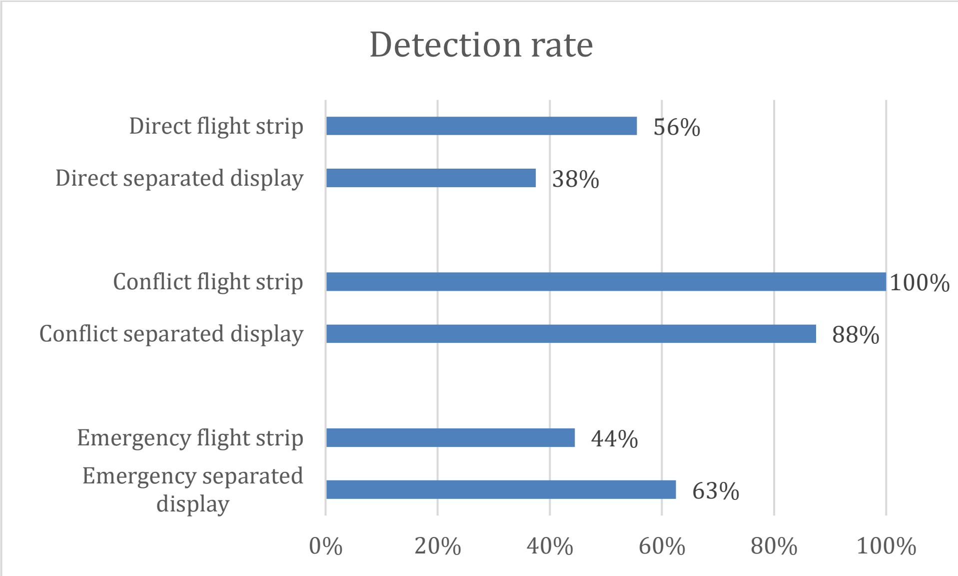

Figure 6: error detection rate for each scenario

From the open-ended type of questions in the questionnaires, the feedback can be grouped into different topics which include the color scheme, sonification, and the work separation between human and digital controller.
For the work separation, a hard cut in the upper airspace at flight level 365 received positive feedback, while the hard cut itself was suggested as complicated and unnecessary in events that require quick action by the human ATCO, such as the emergency. For higher altitudes than flight level 365 the digital controller is guiding all aircrafts and interact with the human ATCO if he can't solve a situation or is guiding an aircraft lower than flight level 365. For complex situations the human ATCO doesn't expect the digital controller to be able to solve the situation, which is the reason he prefers to guide the aircrafts by himself/herself.
The color scheme used with the separation between green and white was considered to be useful, while more highlighting for details is needed to show the human ATCO the prioritized action needed.
For the sonification, the feedback given concluded that a signal tone is useful to guide the attention of the human ATCO while maintaining focus on the tasks he is doing. The idea of an interface with its only feature being audio communication is not includable in the existing working position while maintaining the existing work tasks of the human ATCO.

4.2 Positioning of the interface in the working position

From the data collected by the eye tracking and the closed questions from the questionnaire, there are no indications about the positioning of the HMI possible. The open-ended questions provided some feedback on positioning. The test participants wanted an implementation in the primary display, which would eliminate all gaze changes between the displays. In addition, the human would be in contact with the digital controller all the time and could interact without the required sound notification. If the digital controller gets a separate display, a visual explanation of the situation is needed for the human ATCO to get into the situation as quickly as possible.

5. Conclusion and Outlook

The objective of this research and validation was to identify an interface for a human ATCO to work with his digital twin. Given the substantial number of subjects, the results are noteworthy, but they should be regarded as general tendencies of the data. The separated display design is preferred by the ATCO and the experts. However, in the scenario of a redirection of a specific aircraft, the collected eye-tracking data show a better performance of the flight strip design. The feedback from the prototype concludes that the HMI to be used later in the co-working position of human and digital controller should be implemented in a single display, while the functions and design tested should be influenced by the separate display design. An explanation for the human controller should be visually displayed and solvable without further knowledge. Highlighting important information while showing the future outcome of the situation will help the human controller solve the situation in the most efficient way.
Further research on HMI for human ATCO collaboration with its digital twin should focus on human-in-the-loop validation for data representing daily work in the future. New designs tested should use questions from the modified questionnaire to ensure comparability with the interfaces tested in this study.

References

[1] EUROCONTROL. "EUROCONTROL Think Paper #19 - ATC Mobility and Capacity Shortfalls." (2022) https://www.eurocontrol.int/publication/eurocontrol-think paper-19-atc-mobility-and-capacity-shortfall

[2] DFS Deutsche Flugsicherung, "Mobilitätsbericht 2023," 2024. https://www.dfs.de/homepage/de/medien/publikationen/

[3] Meier, Jana und Finke, Michael und Ohneiser, Oliver und Jameel, Mohsan (2024) Flexible Air Traffic Controller Deployment with Artificial Intelligence based Decision Support: Literature Survey and Evaluation Framework. In: Deutscher Luft- und Raumfahrtkongress 2024. https://doi.org/10.25967/630258

[4] Finck T., Névir M.-C., Kluenker C. DESIGN & VALIDATION OF A FLIGHT CENTRIC WORKLOAD MODEL INCLUDING ATC TASK CHANGE & CONSIDERING INFLUENCING FACTORS (2022) 33rd Congress of the International Council of the Aeronautical Sciences, ICAS 2022, 9, pp. 6416 - 6428 https://www.scopus.com/inward/record.uri?eid=2-s2.0-85159665859&partnerID=40&md5=21e9d94cf329debb05628c23074f5d2a

[5] FAA/EUROCONTROL "Principles of Operations for the Use of ASAS" 2001 https://www.eurocontrol.int/care-asas/gallery/content/public/docs/po-asas71.pdf

[6] M. Jameel, L. Tyburzy, I. Gerdes, A. Pick, R. Hunger and L. Christoffels, "Enabling Digital Air Traffic Controller Assistant through Human-Autonomy Teaming Design," 2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC), Barcelona, Spain, 2023, pp. 1-9, doi: 10.1109/DASC58513.2023.10311220.

[7] Hunger, R.; Böhm, J.; Materne, L.J.; Christoffels, L.; Tyburzy, L.; Mühlhausen, T.; Kleinert, M.; Pick, A. Increased Safety Goes Hand in Hand with Higher Cost Efficiency: Single-Controller Operation Showcasing Its Advantages. Aerospace 2025, 12, 321. https://doi.org/10.3390/aerospace12040321

[8] Gerdes, Ingrid und Jameel, Mohsan und Hunger, Robert und Christoffels, Lothar und Gürlük, Hejar (2022) THE AUTOMATION EVOLVES: CONCEPT FOR A HIGHLY AUTOMATED CONTROLLER WORKING POSITION. In: 33rd Congress of the International Council of the Aeronautical Sciences, ICAS 2022. ICAS. 33th Congress ICAS 2022, 2022-09-04 - 2022-09-09, Stockholm, Schweden. ISBN 978-171387116-3. https://elib.dlr.de/190172/

[9] D. S. A. ten Brink, R. E. Klomp, C. Borst, M. M. van Paassen and M. Mulder, "Flow-Based Air Traffic Control: Human-Machine Interface for Steering a Path-Planning Algorithm," 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC), Bari, Italy, 2019, pp. 3186-3191, doi: 10.1109/SMC.2019.8914030.

[10] , R. E., Riegman, R., Borst, C., Mulder, M., & van Paassen, M. M. (2019). Solution space concept: Human-machine interface for 4D trajectory management. In Proceedings of the 13th USA/Europe Air Traffic Management Research and Development Seminar 2019, ATM 2019: 17/06/19 - 21/06/19 Vienna, Austria.

[11] M. Nylin, J. Lundberg and J. Johansson. (2020). Attention Support with Soft Visual Cues in Control Room Environments. 160-165. 10.1109/IV51561.2020.00035.

[12] O. Ohneiser, H. Gürlük, M.-L. Jauer, Á. Szöllősi and Dóra Balló. (2019). Please have a Look here: Successful Guidance of Air Traffic Controller's Attention. 9th SESAR Innovation Days, 2019-12-02 - 2019-12-05, Athen, Griechenland.

[13] I. Gerdes, M. Jameel, R. Hunger, L. Christoffels & H. Gürlük, "THE AUTOMATION EVOLVES: CONCEPT FOR A HIGHLY AUTOMATED CONTROLLER WORKING POSITION," 2022

[14] S. Huber, J. Gramlich, S. Pauli, S. Mundschenk, E. Haugg and T. Grundgeiger. (2022). Toward User Experience in ATC: Exploring Novel Interface Concepts for Air Traffic Control. Interacting with Computers. 10.1093/iwc/iwac032.

[15] M. Jans, C. Borst, M.M. van Paassen, Max Mulder, Effect of ATC Automation Transparency on Acceptance of Resolution Advisories, IFAC-PapersOnLine, Volume 52, Issue 19, 2019, Pages 353-358, ISSN 2405-8963, https://doi.org/10.1016/j.ifacol.2019.12.087.

[16] . Edwards, T., Homola, J., Mercer, J. et al. Multifactor interactions and the air traffic controller: the interaction of situation awareness and workload in association with automation. Cogn Tech Work 19, 687–698 (2017). https://doi.org/10.1007/s10111-017-0445-z

[17] G. A. Mercado Velasco, C. Borst, M. M. van Paassen, and M. Mulder. Solution Space Decision Support for Reducing Controller Workload in Route Merging Task. Journal of Aircraft 2021 58:1, 125-137. https://doi.org/10.2514/1.C035852

[18] X.-B. Hu, "A Methodological Framework of Human-Machine Co-Evolutionary Intelligence for Decision-Making Support of ATM," 2020 Integrated Communications Navigation and Surveillance Conference (ICNS), Herndon, VA, USA, 2020, pp. 5C3-1-5C3-8, doi: 10.1109/ICNS50378.2020.9222913.

[19] Flohr, Lukas & Janetzko, Dominik & Wallach, Dieter & Scholz, Sebastian & Krüger, Antonio. (2020). Context-Based Interface Prototyping and Evaluation for (Shared) Autonomous Vehicles Using a Lightweight Immersive Video-Based Simulator. 1379-1390. 10.1145/3357236.3395468.

[20] N. Schömig, K. Wiedemann, A. Wiggerich und A. Neukum, "S.A.D.E.—A Standardized, Scenario-Based Method for the Real-Time Assessment of Driver Interaction with Partially Automated Driving Systems," Information, Jg. 13, Nr. 11, S. 538, 2022, doi: 10.3390/info13110538.

[21] Yunuo, C., Xia, Z., Min, Y. et al. Usability Evaluation of in-Vehicle AR-HUD Interface Applying AHP-GRA. Hum-Cent Intell Syst 2, 124–137 (2022). https://doi.org/10.1007/s44230-022-00011-1.

[22] H. Alghodhaifi und S. Lakshmanan, "Autonomous Vehicle Evaluation: A Comprehensive Survey on Modeling and Simulation Approaches," IEEE Access, Jg. 9, S. 151531–151566, 2021. doi: 10.1109/ACCESS.2021.3125620. [Online]. Available: https://ieeexplore.ieee.org/document/9605690

[23] Z. Lei, S. Han and Q. Zhao, "User experience evaluation based on PPG for human-vehicle haptic interaction," 2020 Chinese Automation Congress (CAC), Shanghai, China, 2020, pp. 1810-1813, doi: 10.1109/CAC51589.2020.9327439.

[24] Böhm, Julian (2024) Entwicklung einer Evaluationsmethode zum Vergleich der Benutzbarkeit und Effizienz unterschiedlicher Interaktionsschnittstellen für den digitalen Fluglotsen. Masterarbeit, TU Braunschweig. https://elib.dlr.de/209616/

[25] Böhm, Julian (2024) Untersuchung unterschiedlicher Interaktionsschnittstellen für digitale Lotsen. Studienarbeit, TU Braunschweig. https://elib.dlr.de/204706/

[26] Brooke, John. (1995). SUS -- a quick and dirty usability scale. Usability Eval. Ind.. 189.