Low-Fidelity Prototyping for the Air Traffic Control Domain

Gernot Rottermanner[1], Markus Wagner[1], Martin Kalteis[1], Michael Iber[1], Peter Judmaier[1], Wolfgang Aigner[1], Volker Settgast[2], Eva Eggeling[2]

Fachhochschule St. Pölten[1]
Fraunhofer Austria Research GmbH[2]

[1]vorname.name@fhstp.ac.at, [2]vorname.name@vc.fraunhofer.at

Abstract

In the next 20 years, significant changes in air traffic control are planned (SESAR, 2015). Next to an increase in air traffic, reduction in delays and improvement of safety, 4D trajectories will ensure flights on the most direct route to the destination airport. Within the research project VAST (Virtual Airspace and Tower), the team wants to explore the design space of future air traffic control interfaces. Three low-fidelity prototypes were developed to evaluate them as early as possible with the target group, namely Air Traffic Control Officers (ATCOs). They will be described in this paper in more detail.

1 Introduction

As described in the Air Traffic Management Master Plan (SESAR, 2015), significant changes will impact the way European air traffic is handled in the future. While in 20 years, the amount of air traffic should have doubled and delays both on the ground and in the air should at the same time be reduced by 30%. Overall safety should also have been improved. Instead of using standard airways, the implementation of 4D trajectories will ensure flights on a "practically unrestricted, optimum trajectory for as long as possible […] to meet very accurately an arrival time over a designated point" (SKYbrary, 2017a). To be able to handle these innovations, Air Traffic Control Officers (ATCOs) need appropriate tools, especially for the visualisation of 4D trajectories. Developing software for the safety-critical working environment domain turns out to be very challenging, because operational errors can cause fatal accidents. It is necessary to work with the user group as close as possible to get to know their requirements and develop solutions that have a chance to be accepted among these expert users. Within the research project VAST (Virtual Airspace and Tower), new concepts for visualising and sonifying complex air traffic scenes will be explored. The team followed a user-centred design process (Norman, 2013), and developed three low-fidelity prototypes to evaluate them with ATCOs as early

Veröffentlicht durch die Gesellschaft für Informatik e. V. 2018 in
R. Dachselt, G. Weber (Hrsg.):
Mensch und Computer 2018 – Workshopband, 02.–05. September 2018, Dresden.
 https://doi.org/10.18420/muc2018-ws12-0401

as possible. The low-fidelity prototypes are based on preliminary work such as an extensive literature research of state-of-the-art technologies, tools and projects in Air Traffic Control, feedback from interviews and a focus group discussion with ATCOs (Rottermanner et al., 2017) as well as on-site visits of approach and terminal control centres.

This paper is structured as follows: Section 2 provides background information concerning the primary target group (ATCOs) and scenarios to convey a basic understanding of the focus of the low-fidelity prototyping phase. Section 3 presents related work of research in air traffic visualisation and sonification. Section 4 describes the low-fidelity prototypes in more detail in terms of challenges, flight data generation, auditory display design, user interface design and interaction design. Section 5 summarizes the outcomes of the prototyping phase.

2 Air Traffic Control

Air traffic control (ATC) is subdivided in several responsibilities, such as en-route control, approach & terminal control and ground control (Mensen, 2014). Within the project, ATCOs responsible for approach and terminal control are identified as the primary target group. They control departing and arriving air traffic, as well as overflights around the airport up to a certain height. It is their task to ensure that airplanes are at an appropriate altitude when they are handed off to another control responsibility, and that they arrive at suitable intervals to start the landing processes. Among many other tasks, ATCOs must respond and act in situations/scenarios which may become critical, e.g. when a Level Bust or a Loss of Separation is imminent. A Level Bust is defined as any "unauthorised vertical deviation of more than 300 feet from an ATC flight clearance" (SKYbrary, 2017c). They for example can be caused by too fast climb and sink rates of an airplane. A Loss of Separation can occur between two airplanes "whenever specified separation minima in controlled airspace are breached" (SKYbrary, 2017b). In case of an actual conflict, the ATCO instructs the affected airplanes with a course or altitude correction and informs the pilots of the traffic situation.

The main tool used for controlling air traffic is the RADAR (Radio Direction and Ranging), which visualises ground and airspace by two-dimensional top-down bird's eye view. This representation is used for decades, is well established and ATCOs are very well trained in working with this visualisation. The altitude of an airplane is represented only indirectly, using digits. ATCOs are trained to mentally construct a 3D representation which requires high cognitive workloads (Baier & Zimmer, 2016). With the introduction of 4D trajectories, the required cognitive workload will increase even further, since airplanes will no longer follow standard airways and allow free route operations. Conflicting points will not be at fixed locations anymore, which is in contrast to the current situation, where conflicts mostly appear at specific points where airways are crossing. ATCOs are then required to envisage complex combinations of parabolic trajectories. Route and altitude changes can have an impact on the whole trajectory as well as on other trajectories and need to be executed accurately (SKYbrary, 2017a).

3 Related Work

Studies exist in displaying the air traffic three-dimensionally, e.g. with the use of stereoscopic displays. Bourgois et al. (2004) describe a stereoscopic representation which includes concepts for navigation, weather information, positional audio and presentation of conflicts. They compared it with a 2D representation. Objective measurements in a study with former ATCOs indicated that "controllers were quicker in identifying the target in the 3D stereoscopic than in the 2D condition". Also, subjective data showed that the controllers estimated that their performance was better with the 3D stereoscopic interface. Baier & Zimmer (2016) compared three different stereoscopic 3D representations with a similar 2D interface. It reveals that "an adequate 3D airspace representation for air traffic control allows an immediate perception of danger and urgency in a given situation".

Regarding sonification and auditory displays, Ngo et al. (2012) performed a modified air traffic scenarios test, which is a low-fidelity, simplified air traffic control simulation to compare the performance of en-route delay, handoff delay, simulation errors, and conflict resolution delay in four testing scenarios: visual display only, and visual display in combination with an auditory, audio-tactile, or vibrotactile cue. The test results showed a significantly faster response for the tests including auditory and audio-tactile cues with equal accuracy than the visual cue alone. Rönnberg et al. (2016) pursued a musical sonification approach primarily addressing periods of low to mid air traffic to increase situation awareness when controller's attention may tend to decrease.

There is a lot of research that focuses on a specific part of ATC, including 3D visualisation of air traffic. Only few studies exist that pursue a holistic approach of user interface and interaction design and sonification for the most important situations/scenarios to improve situation awareness and conflict-detection, which the research project VAST tries to accomplish.

4 Low-Fidelity Prototyping

In a user-centred design process (Norman, 2013), low-fidelity prototyping serves for the validation of design ideas at very early stages. Prototyping for the safety-critical working environment can be challenging because it is a field were operational errors can cause fatal accidents. ATCOs are highly trained experts in using their tools and therefore reluctant in accepting changes or new solutions. Consequently, the requirements on prototype evaluation are much higher. Commonly, low-fidelity prototypes are implemented as paper or screen mockups, for which the development does not take much time (Rogers et al., 2011). But, a focus group with ATCOs revealed that concepts in 2D and 3D traffic visualisation which are visualised only with paper mockups were difficult to discuss. The ATCOs struggled with envisioning how the interfaces would look like and could be used in practice. This had a negative effect on their acceptance ratings (Rottermanner et al., 2017). Compared to other domains, ATCOs must have a clear picture not only of the static interface elements itself, but also how it is changing and reacting in case of events over time. Also, when evaluating a concept with ATCOs, objective measurements with paper prototypes are not possible or only with a very high effort. To make testing as real as possible, one way can be to integrate existing tools and visualisations, already used by ATCOs into a simulation, but this turns out to be very difficult. Often, they are proprietary, inaccessible or costly, and cannot be adapted to the required research functionality (Prevot et al., 2018). Prototyping is essential to test the most important usage scenarios. Therefore, it is necessary to simulate air traffic realistically to make profound decisions about the quality of the concepts. For air traffic data, there are APIs (Application Programming Interfaces) and data sets available, but they are often costly and do not fit for the (conflict) scenarios that should be simulated. For the evaluation, not only the subjective opinion of ATCOs, which is based on their user experience is important. Measurable parameters related to conflict-detection and situation awareness must be used. The ability to measure standardized and objective data according to the situation therefore allows for a comprehensive discussion and decision of the quality of the concepts.

Given these challenges, the following requirements have been formulated for the low-fidelity prototyping phase: (R1) The prototypes shall be implemented digitally and interactively; (R2) The prototypes shall be implemented from scratch, are reduced in functionality and features and are tailored to essential scenarios; (R3) Flight data shall be represented realistically and based on existing airways but can be adapted easily to fit the evaluation needs; (R4) The prototypes allow quantitative and qualitative measurements in terms of situation awareness and conflict-detection.

4.1 Flight Data Generation

For realistic air traffic routes, waypoints were taken from standard arrival and departure charts of the airport of Dublin[1]. Since these charts use polar coordinates, it was necessary to transform them to a Cartesian coordinate system, which is the basis of the simulation. In a first step, the coordinates from the sexagesimal system were converted into decimal numbers. The second step included the calculation of the distances between the waypoints and the runway. By applying the trigonometric functions, the angles to the origin of coordinates (runway) could be determined. Thus, a two-dimensional coordinate system was generated. By adding the heights from the charts, the trajectories were mapped into a three-dimensional Cartesian coordinate system. The aircraft speeds were also taken from the charts. The flight data for each airplane is stored in a separate csv-file which is loaded into the simulation. Each data record contains the values listed in Table 1. While loading the data, they are transferred into the internal metric structure of the simulation for further processing. As there is one .csv-file loaded for each plane, it is easy to add or change an airplane or change route data. In the .csv-file there are only waypoints defined and the simulation interpolates each movement between two waypoints. In the low-fidelity prototypes the aircraft positions are updated every two seconds.

[1] Standard arrival and departure charts of Dublin airport: http://iaip.iaa.ie/iaip/aip_eidw_charts.htm;

Value	Description	Unit
Start time	Time, the airplane appears in the scene at (x seconds after starting the prototype)	seconds
Call sign	Airplane identifier	text
Waypoint x	Distance airplane to airport on the x-axis	kilometres (km)
Waypoint y	Distance airplane to airport on the y-axis	km
Height	Planned height of airplane	km
Speed	Planned speed of airplane	km/h
Deviation	The current deviation of an airplane from the planned height.	km
WTC	Wake Turbulence Category, based on the maximum certified take-off mass of the airplane.	L, M, H, S

Table 1: Variables of data record.

4.2 Spatial Auditory Display

With the implementation of auditory display as an additional perceptual channel, the team intended to increase general situation awareness and to decrease the response time of the operators in case of critical events. It chose an auditory display design based on continuous sonification in favour to intermittent auditory alerts (Watson, 2006), which had been implemented in air traffic control consoles before (Cabrera et al., 2005). Continuous sonification integrates well into workspace environments by slow and subtle level changes. It is less intrusive than discrete sound events and allows operators to follow their colleagues' communications. In a dual task process monitoring experiment, Hildebrandt et al. (2016) demonstrated that continuous sonification outperformed both, information display based on solely visual display as well as in combination with intermittent, i.e. event based sonification. As several studies have shown (Brock et al., 2008; Brock et al., 2002; Roginska, 2012), directional information does not only improve the localization of an event but also increases the number of simultaneously perceivable discrete sound sources. The low-fidelity prototypes focus on two types of critical situations: Loss of Separation and Level Bust. Both were represented by sonification models. Loss of Separation alerts were encoded by a pulsating sound generated by two resonant filters with distance dependent frequency ranges (20-200Hz, 100-150Hz). By the restriction to a rather low frequency range, the generated sounds do not have any negative impact on the required speech intelligibility. The speed of the generated pulses as well as the sound level were redundantly mapped to the distance parameter. A synthetic wind model derived from (Farnell, 2010) served as basis for the auditory display of bi-directional Level Bust alerts. To support the localization of alerts, the team implemented vector-based amplitude planning (VBAP) and planar ambisonics to be played back on a four-channel loudspeaker setup. To avoid confusion, the directional orientation was always north-bound.

4.3 Prototypes: Setup, User Interface & Interaction

In this project, the low-fidelity prototypes were developed to make a design decision to reduce three concept ideas to a final one (Buxton, 2007). The features were implemented based on literature research, feedback from interviews and a focus group discussion with ATCOs (Rottermanner et al., 2017) as well as on-site visits of approach and terminal control centres. The project team developed three different visualisations of air traffic[2]: P1 visualizes the air traffic in an enhanced two-dimensional way (see Section 4.3.2). P2 combines a two- and three-dimensional representation of the air space (see Section 4.3.3). P3 enhances the two-dimensional representation with an abstract visualisation of height and arrival time (see Section 4.3.4). The spatial auditory display was fully implemented in all three prototypes.

4.3.1 Setup

For the implementation of the prototypes, the game development platform Unity is used. It was the first choice as the project team includes developers who are familiar with the platform and programming language C#. Also, real-world scenes can be built up with less effort and reused with different camera settings, which is particularly useful for showing air traffic both two- and three-dimensionally. For the prototypes, only one plugin to transmit data over the OSC (Open Sound Control) protocol and one driver for the 3D mouse is needed additionally. The auditory display is implemented with Max MSP. Whenever a specific event occurs in the simulation, it is also transmitted via OSC, so that the Max MSP patch is aware of it and can react. Further, the following hardware setup is used: A 28-inch UHD monitor, a PC, a standard keyboard, a mouse and a 3D mouse (3Dconnexion SpaceMouse). For the spatial auditory display setup, four speakers are used.

4.3.2 P1: 2D View

As already mentioned before, the main tool used for controlling air traffic is the RADAR. ATCOs are highly familiar with this type of two-dimensional visualisation. Based on the findings in the preliminary research (Rottermanner et al., 2017), the prototype "2D View" is not a completely new interface but extends the two-dimensional view with additional information elements and interaction described below.

User Interface (see Figure 1): An ATCO is responsible for a certain sector, which is in this prototype highlighted with a darker grey background colour. An airplane is visualised as a circle with four different fillings. Fill patterns indicate the Wake Turbulence Categories as either Light, Medium, Heavy or Super Heavy. Next to the circle, the so-called airplane label is positioned. It shows the call sign (airplane identifier), the current altitude, as well as an arrow indicating if the aircraft is ascending or descending. A solid white line shows the route still to be flown to or from the airport. Additional information is shown on the bottom of the scene: A description of the Wake Turbulence Categories, the current system time, a scale indicating the current zoom level and a compass pin pointing north. For better orientation when zoomed in, a mini map shows the current part visible in the whole scene. If a Loss of Separation or

[2] High-resolution images of the prototypes are available for download here: http://mc.fhstp.ac.at/projects/vast

Level Bust occurs, the affected airplane labels change their colour to red and get a white background.

Interaction: For zooming and moving, the prototypes make use of common interaction principles for navigating in maps. By using the mouse wheel, zooming in and out is possible. By clicking and holding the left mouse key, the scene can be moved to the top, bottom, left and right side. By clicking on an airplane or on the airplane label, the flight path is coloured blue and the label shows a blue border. When selecting a new airplane or when clicking into an empty space, the old one will automatically be deselected. The interactivity is tailored to the defined scenarios and is therefore limited. The routes are pre-defined, it is not possible to change the flight behaviour of an airplane during the simulation. Based on the feedback of the ATCOs, rotating the view is not possible, the north is always on top.

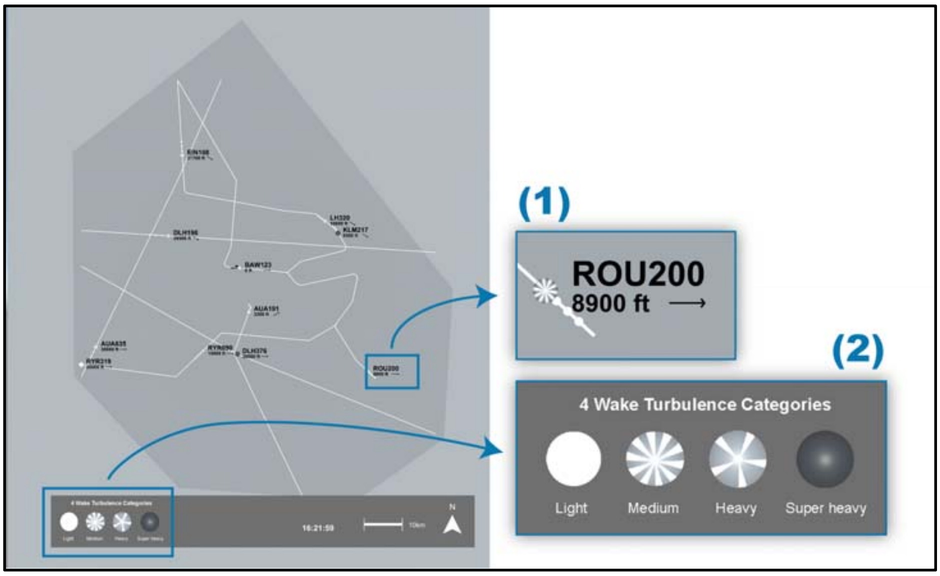

Figure 1: User Interface of prototype P1 2D View which visualizes the air traffic in an enhanced two-dimensional way. Zoomed interface elements: (1) Airplane with the following information: Wake Turbulence Category, call sign, current altitude, arrow indicating if the aircraft is ascending or descending. (2) A legend describing the four different Wake Turbulence Categories.

4.3.3 P2: 2D & 3D View

User Interface: This prototype enhances the already described 2D view with a three-dimensional view of the air traffic (see Figure 2 left). The spatial representation allows better indication of deviations from the planned flight route and visualises the airspace in a more vivid way. The spheres that are representing the airplanes are connected to the ground with lines. They allow for a more precise perception of height differences. In the mini map, the position in the scene where the viewer is located is shown as a green pin.

Interaction: In addition to the interaction described in Section 4.3.2, a 3D mouse is used to allow a more precise navigation in all three axes in the 3D view. This makes navigating in space more convenient for the user. Also, the normal mouse (for interacting) and the 3D mouse (for navigating) can be used at the same time. Selecting an airplane first and pressing "Z" on the keyboard performs an auto zoom onto the airplane in the 3D view. By pressing "up" on the keyboard, the camera angle can be changed in the 3D view. By pressing "down", the previous camera position will be active.

4.3.4 P3: 2D & Abstract View

User Interface: This prototype enhances the already described 2D view with an additional information layer visualising the heights (split into departing and arriving aircraft) and the estimated landing times of the airplanes (see Figure 2 right). This view makes use of the concept of Parallel Coordinates (Inselberg & Dimsdale, 1990). For departing aircraft, only the height axis without an arrival time is shown. The visual changes to red for Level Bust and Loss of Separation are shown in both views.

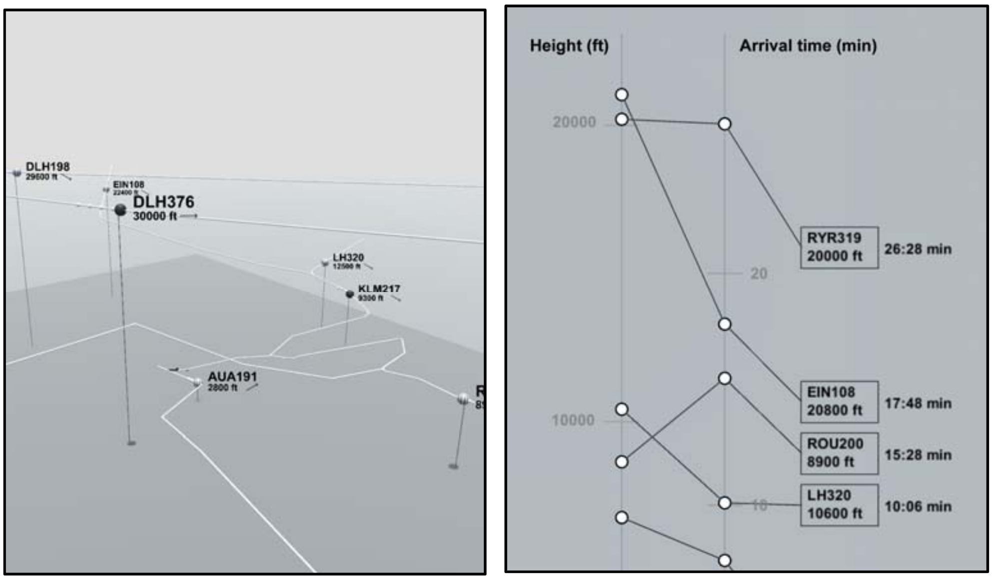

Figure 2: Left: Three-dimensional representation of air traffic. Right: Additional information layer showing the heights and the estimated landing times of the airplanes.

5 Reflection & Discussion

This paper presents three low-fidelity prototypes considering the planned innovations in Air Traffic Management in the next years. For the prototyping phase, four requirements were defined: (R1) The prototypes shall be implemented digitally and interactively; (R2) The prototypes shall be implemented from scratch, are reduced in functionality and features and are tailored to essential scenarios; (R3) Flight data shall be represented realistically and based on existing airways but can be adapted easily to fit the evaluation needs; (R4) The prototypes allow quantitative and qualitative measurements in terms of situation awareness and conflict-detection. Regarding R1 and R2, early results - the analysis is not fully finished yet - of a user test with five ATCOs and six air-traffic affine persons show, that the level of visual representation and interaction is necessary to get meaningful results in terms of conflict-detection and decision-making. Regarding R3, access to air traffic data sets for simulations is very limited, the integration complex and costly. For this reason, a data set was created on its own, which is highly adaptable for evaluation purposes and therefore allows a realistic evaluation. Both the prototypes and the data sets can be used for research activities to better compare and evaluate similar visualisation approaches. They are available for free on the project website. Regarding R4, the prototypes were developed with the aim to collect profound quantitative and qualitative data. Early results show that the prototypes P2 & P3 performed worse than P1 regarding the subjective ratings in terms of situation awareness and conflict-detection, but both performed better in objective measurements.

In conclusion, the degree of complexity described in this paper is necessary to make profound design decisions in this field. Therefore, the effort put in the low-fidelity prototyping phase proved to be worthwhile. And only relying on subjective data in the evaluation can lead to inadequate design decisions, so both subjective and objective measurements must be considered.

Acknowledgments

This work was supported by the Austrian Research Promotion Agency, FTI-Initiative "Take Off" via the "Virtual Airspace and Tower" project (FFG 855215). We would also like to thank all stakeholders and Air Traffic Control Officers who have agreed to volunteer in this project.

References

Baier, A., & Zimmer, A. (2016). Evaluation of a 3D Human System Interface for Air Traffic Control. https://doi.org/10.13140/RG.2.1.4153.1283

Bourgois, M., Cooper, M., Duong, V., Hjalmarsson, J., Lange, M., & Ynnerman, A. (2004). Interactive and immersive 3D visualization for ATC.

Brock, D., McClimens, B., Trafton, G., McCurry, M., & PERZANOWSKI, D. (2008). Evaluating Listeners Attention to and Comprehension of Spatialized Concurrent and Serial Talkers at Normal and a Synthetically Faster Rate of Speech.

Brock, D., Stroup, J. L., & Ballas, J. A. (2002). Effects of 3D Auditory Display on Dual Task Performance in a Simulated Multiscreen Watchstation Environment. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *46*(17), 1570–1573. https://doi.org/10.1177/154193120204601709

Buxton, B. (2007). *Sketching User Experiences: Getting the Design Right and the Right Design* (1 edition). Amsterdam: Morgan Kaufmann.

Cabrera, D., Ferguson, S., & Laing, G. (2005). Development of Auditory Alerts for Air Traffic Control Consoles. Presented at the Audio Engineering Society Convention 119, Audio Engineering Society. Retrieved from http://www.aes.org/e-lib/browse.cfm?elib=13300

Farnell, A. (2010). Designing Sound. Retrieved 7 March 2018, from https://mitpress.mit.edu/books/designing-sound

Hildebrandt, T., Hermann, T., & Rinderle-Ma, S. (2016). Continuous Sonification Enhances Adequacy of Interactions in Peripheral Process Monitoring. *International Journal of Human-Computer Studies*, *95*.

Inselberg, A., & Dimsdale, B. (1990). Parallel Coordinates: A Tool for Visualizing Multi-dimensional Geometry. In *Proceedings of the 1st Conference on Visualization '90* (pp. 361–378). Los Alamitos, CA, USA: IEEE Computer Society Press.

Mensen, H. (2014). *Moderne Flugsicherung: Organisation, Verfahren, Technik* (4th ed.). Springer Vieweg. Retrieved from //www.springer.com/de/book/9783642542930

Ngo, M. K., Pierce, R. S., & Spence, C. (2012). Using Multisensory Cues to Facilitate Air Traffic Management. *Human Factors*, *54*(6), 1093–1103. https://doi.org/10.1177/0018720812446623

Norman, D. (2013). *The Design of Everyday Things: Revised and Expanded Edition* (Revised, Expanded edition). New York, NY: Basic Books.

Prevot, T., Callantine, T., Lee, P., Mercer, J., Palmer, E., & Smith, N. (2018). Rapid Prototyping and Exploration of Advanced Air Traffic Concepts.

Rogers, Y., Sharp, H., & Preece, J. (2011). *Interaction Design: Beyond Human - Computer Interaction* (3 edition). Chichester: Wiley.

Roginska, A. (2012). Effect of Spatial Location and Presentation Rate on the Reaction to Auditory Displays. *Journal of the Audio Engineering Society*, *60*(7/8), 497–504.

Rönnberg, N., Lundberg, J., & Löwgren, J. (2016). SONIFYING THE PERIPHERY: SUPPORTING THE FORMATION OF GESTALT IN AIR TRAFFIC CONTROL.

Rottermanner, G., Wagner, M., Settgast, V., Grantz, V., Iber, M., Kriegshaber, U., Eggeling, E. (2017). Requirements Analysis & Concepts for Future European Air Traffic Control Systems. In *Workshop Vis in Practice - Visualization Solutions in the Wild, IEEE VIS 2017*. Phoenix, Arizona USA: IEEE.

SESAR. (2015). European ATM master plan - The roadmap for delivering high performing aviation for Europe: executive view : edition 2015.

SKYbrary. (2017a). 4D Trajectory Concept. Retrieved 13 March 2018, from https://www.skybrary.aero/index.php/4D_Trajectory_Concept

SKYbrary. (2017b). Loss of Separation. Retrieved 26 March 2018, from https://www.skybrary.aero/index.php/Loss_of_Separation

SKYbrary. (2017c, November 3). Level Bust. Retrieved 28 February 2018, from https://www.skybrary.aero/index.php/Level_Bust

Watson, M. (2006). Scalable earcons: Bridging the gap between intermittent and continuous auditory displays. Retrieved from https://smartech.gatech.edu/handle/1853/50645