Evaluation of a 3D Human System Interface for Air Traffic Control

Andreas Baier
Altran AG
Zurich, Switzerland
Email: andreas.baier@altran.com

Alf Zimmer
Engineering Psychology Unit
University of Regensburg
Regensburg, Germany
Email: alf.zimmer@ur.de

***Abstract* - In air traffic control, events in 3D space have to be managed with the dual goal of safety and efficiency. Due to the fact, that these events have to be constructed from a 2D airspace representation and numerical information, the resulting mental workload for air traffic controllers is very high. An experimental working model of an air traffic control workspace with a 3D airspace representation is evaluated and shown to be a possible means to reduce mental workload and to improve efficiency and learnability while maintaining the present level of safety.**

Keywords - Air Traffic Control; Situation Awareness; Mental Workload; User Centered Design; 3D; Stereoscopy.

I. INTRODUCTION

In 1943, Craik introduced the concept of mental models [1], namely that people interact with their environment not directly, but by means of simplified models of the environment, which consist of sufficiently large sets of knowledge about what is known to be true about the world and of assumptions about the dynamics of processes. This conceptualization of the interaction of individuals with their environment [2][3] has helped to understand and explain, for instance, why people are able to act successfully in a three-dimensional (3D) space while controlling the motion of objects in parallel which, in essence, is the core task in air traffic control (ATC). Mental models furthermore have strongly influenced the field of cognitive ergonomics, especially in the design of human system interfaces, e.g. the mental model is central for Endsley's model of situation awareness [4], as well as in the construction of aptitude tests for the selection and instruction of operators for human machine systems.

What is often overlooked, however, is that mental models can lead to failures because they are too domain specific, too much simplified (e.g. due to the erroneous assumption of linearity), or that they rely on erroneous analogies or over-generalizations (e.g. in the field of naïve physics). Furthermore, mental models are usually elicited by means of verbal protocols. Such protocols, however, are necessarily sequential and cannot properly represent events which happen in parallel and in a 3D space.

For the purpose of designing human system interfaces, this means that the presented information has to be congruent with the tacit knowledge of time and space, and that the mental model that is used leads to a correct understanding of the presented situations. Existing ATC workstations use a two-dimensional (2D) top-view to represent the airspace. Numerical values indicate the elevation of objects. On this basis, the air traffic controller (ATCO) needs to mentally construct an abstract 3D representation of the airspace. Such a mental construction process does not allow to grasping the ongoing events directly which results in a high mental workload and, therefore, is safety relevant. In contrast, an adequate 3D representation that contains all relevant spatial information allows what Gibson calls the direct perception of events [5], which relies on an embodied tacit knowledge of space and time. Especially the advances in 3D visual displays provide the preconditions required for such a direct event perception and therefore allow human machine interactions to go beyond traditional modes of interaction.

In Section II, the importance of situational awareness for ATC is described and it is explained, how it is linked to safety and efficiency. Section III outlines how airspace information is processed using the existing 2D human system interface. In Section IV, results are presented that demonstrate how appropriate stereoscopic 3D visualizations allow for an immediate perception of the dynamic events in the airspace, therewith making the ATCOs task easier to learn, more effective, and lead to a higher efficiency by combining the traditional mental models of ATC with tacit spatial knowledge. In Section V, the impact of stereoscopic 3D airspace visualizations on safety, efficiency, and learning is discussed. Section VI provides suggestions for applying stereoscopic 3D airspace visualizations to ATC.

II. THE AIR TRAFFIC CONTROLLERS' TASK AND THE TRADE-OFF BETWEEN SAFETY AND EFFICIENCY

The task of the ATCO is to guide aircraft safely and efficiently through the airspace. This requires a high degree of situational awareness, namely to build up and maintain an accurate understanding of the current situation and of how it is likely to develop in the near future. Especially in domains such as ATC, where the mental workload of the operator tends to be high, and poor decisions may lead to serious consequences, lacking situation awareness has been identified as a main factor for accidents that are attributed to human error [6]. Because there is a trade-off between safety and efficiency in ATC, safety, for obvious reasons, has a higher priority than efficiency. Therefore, an imminent loss of situational awareness is likely to result in less efficient decisions. Uncertainty about the development of a critical

 ISBN: 978-1-61208-468-8

approximation between two or more aircrafts, for instance, leads ATCOs to immediately implement preventive actions rather than continuing their assessment of the situation in order to reduce the amount of uncertainty and then decide if a more resource intensive intervention is necessary [6].

III. The Existing Human System Interface for Air Traffic Control

The existing human system interface uses a 2D airspace representation combined with alpha-numerical information by means of paper-based or digital strips and verbal communications between ATCOs and pilots. It fails the above described principles for direct event perception insofar, as the aircraft positions are given in two different formats instead of one integrated format. The lateral aircraft positions are shown analogically by a top view onto the airspace on a 2D plane, whereas the vertical aircraft positions are presented numerically. The ATCOs, therefore, cannot perceive the airspace situation directly, but have to mentally construct a 3D representation. In order to understand the critical events in the airspace, additional information about the aircraft is displayed numerically, such as speed, heading, and call-signs. This information is provided within tags attached to the position signifiers of each aircraft. This means that the ATCOs need to combine information that is presented in different formats in order to understand the actual situation and how it evolves in time – a task that requires time and complex mental operations, this can cause a very high mental workload, which may lead to inefficient decisions as a result of uncertainty.

IV. Evaluation of 3D Human System Interfaces for Air Traffic Control

In the line of research presented here, two goals have been pursued; (1) the integration of the spatial information into one 3D representation and (2) the development of a cohesive interaction design tailored to what the 3D representation affords to ATCOs.

In this study three different 3D representations have been compared with a 2D representation similar to the existing 2D human system interface for ATC (see Figure 1) on the basis of safety critical situations involving two aircraft [7]; the existing 2D representation (2D), a 3D view from above (3Da), a 3D side-wise view with vertical drop-lines to the position over ground (3Ddl), and a 3D visualization that is the same as 3Ddl but without the drop-line (3D). All 3D visualizations used stereoscopy combined with a motion tracking system that allowed the adaptation of the airspace visualization to the ATCOs viewing-position in real-time.

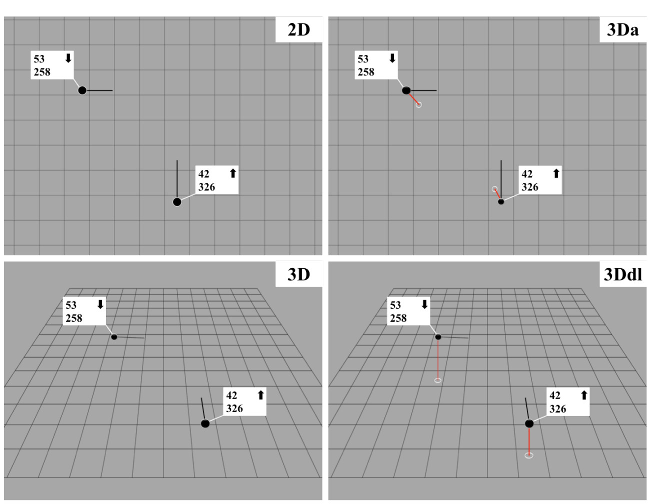

Figure 1. Representations that were compared with each other.

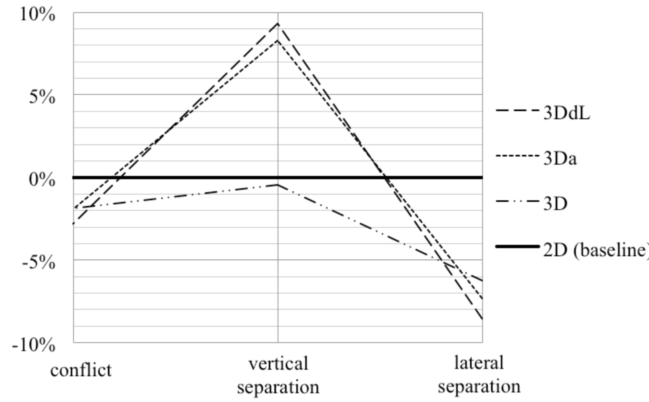

Figure 2. Judgement certainty of ATCOs under high mental workload. With values adjusted to zero 2D serves as baseline.

The situations were systematically created and presented in 50% of the times conflicts, in 25% of the times vertical separations, and in 25% lateral separations. All situations would have either resulted in a conflict or reached the closest point of approximation after 45s. However, each situation was only shown for 10s before the airspace representation was masked by a six-point rating scale that allowed the participants to indicate how certain or uncertain they were about the outcome of the situation. The rating scale ranged from ‘certainly conflict’ to ‘certainly no conflict’ with other categories in between. When the situation showed a conflict, ‘certainly conflict’ was interpreted as 100% certain (‘hit’) and ‘certainly no conflict’ as 0% certain (‘miss’) (vice versa if the situation showed a separation). Responses in between these two extremes were assigned with 80%, 60%, 40% and 20% judgment certainty. 48 participants divided into four groups with an equal number of participants (ATCOs, pilots, trained laypeople and untrained laypeople) participated in this study. The trained laypeople underwent a conflict assessment training that was based on the procedure ATCOs use with the existing 2D human system interface.

This study has demonstrated that the integration of the spatial information into one integral 3D representation can reduce the uncertainty about objects’ vertical positions compared with the existing 2D representation, see Figure 2. This advantage of 3D becomes especially apparent under high mental workload conditions. However, due to the training with 2D as well as due to ambiguities along the line of sight which are implicit in all 3D representations, 2D resulted in higher judgment certainty about lateral object positions. By the selection of an appropriate elevation angle

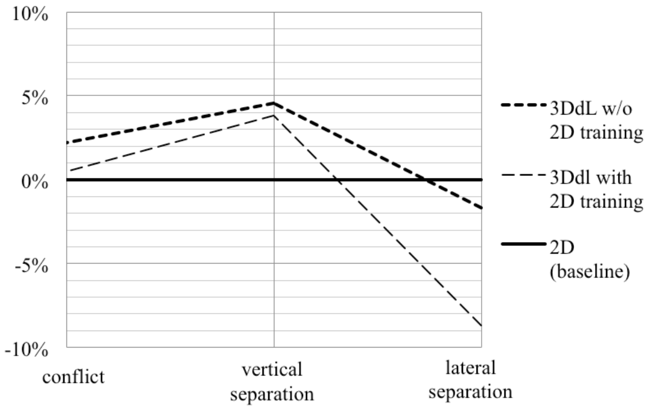

Figure 3. Judgement certainty of trained and untrained participants under high mental workload. With values adjusted to zero 2D serves as baseline.

and the provision of depth cues such as vertical drop-lines connecting the objects and the ground, grid-lines on the base area, and stereoscopy together with motion parallax effects, the disadvantage of 3D representations can be counteracted and its advantage, namely a direct event perception, further augmented.

Furthermore, the performance results show that the 3D representations allow the ATCOs' to assess such situations and discriminate with similar certainty (see Figure 2 and Figure 3) and effectiveness (see Figure 4) between separation and conflict as with 2D, because this assessment always requires processing both lateral and vertical positions. In addition to this, the training of ATCOs for assessing ATC situations with 2D apparently causes a negative effect on judgment certainty with 3D representations, as can be seen in Figure 3, that shows a comparison of the judgment certainty of trained (ATCOs and trained laypeople) and untrained (pilots and untrained laypeople) participants under high mental workload.

Because 3D resulted in an initially higher performance in the group of pilots (who are not trained in assessing ATC conflicts), it is assumed that an appropriate 3D representation allows for a direct perception of events and allows the correct use of existing mental models, see Figure 5. 3D representations such as 3Ddl or 3Da allow the ATCOs' to achieve similar performance as with the 2D representation even after little training [8], see Figure 4. Across 36 situations that were equally divided into three measuring times (MT), the ATCOs' performance rose from 71.2% in MT 1 to 87.9% in MT3 with 3DdL, and from 78.8% in MT 1 to 86.8% in MT 3 with 2D.

Overall, the higher judgment certainty concerning vertical positions promises a higher efficiency of the ATCOs' because today uncertainty about vertical positions lead more often to unnecessary preventive actions than uncertainty about lateral positions [9]. In fact, the predictions (based on the receiver operating characteristics of the ATCOs) made in this study show that with the 2D representation, 75.7% of the interventions would be unnecessary, which is in line with findings from other studies [9][10]. With 3DdL, on the other hand, 62.9% of the interventions are expected to be unnecessary [8], see Figure 6.

Because of these promising results, a cohesive interaction design tailored to what the 3D representation affords to the ATCOs was developed over three iterative development cycles [11]. First, an interactive 3D representation which was a combination of all 3D representations shown in Figure 1 was used to identify the requirements of ATCOs on a 3D Human system interface for ATC.

A total of eight ATCOs with an average of 11 years of practical experience as approach controller participated in this first development cycle in which at any one time one (active) ATCO completed a scenario using a simulator of the existing human system interface while the other (passive) ATCO observed the scenario using the interactive 3D representation. Because of the previously identified advantage of 3D representations regarding the assessment of vertical positions and distances, the ATCOs were asked to complete two different types of scenarios; a holding scenario that required to vertically stack several aircraft within a specified area and an approach scenario that required to guide several aircraft onto parallel approach routes and coordinate them tightly towards a single hand-off point (merge-point) for landing. Both types of scenarios impose particularly high requirements on processing vertical aircraft information. With an average score of 55 (where 0 indicates the lowest and 100 is the highest possible subjective

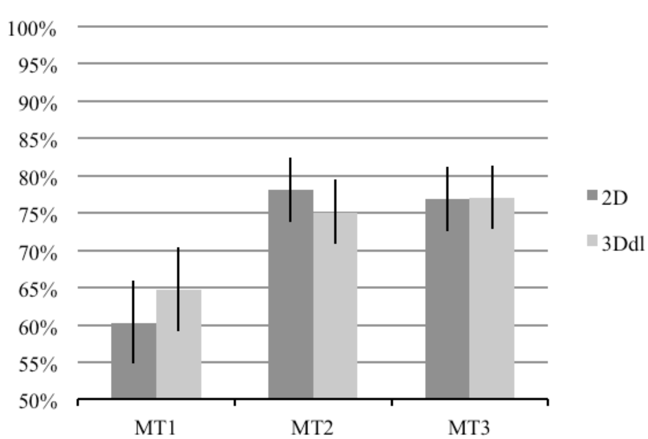

Figure 4. Performance of pilots over three measurement times (MT).

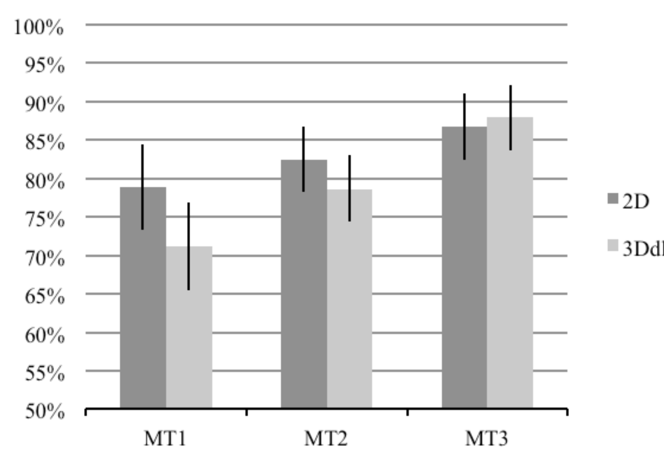

Figure 5. Performance of ATCOs over three measurement times (MT).

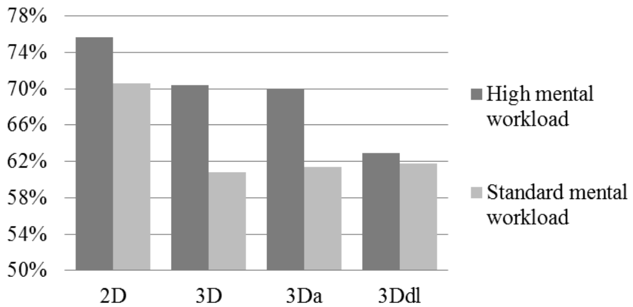

Figure 6. Predicted false alarm rates of ATCOs.

workload) on the NASA task load index [12], the holding scenario was perceived as less demanding compared with the approach scenario that received an average score of 81.

Whereas the subjective workload ratings of the active and the passive ATCOs showed no differences between the 2D and the 3D representation in the case of the holding scenario, the passive ATCOs rated the workload less high with the 3D representation (score 72) compared to the active ATCOs (score 89) who used the 2D representation. The passive ATCOs appreciated the possibility of observing the airspace depending on the situation both from the top-view as well as from the side-view.

An exaggerated representation of the vertical dimension by the factor 7 compared to the lateral dimension was the preferred option of the ATCOs and, according to them, allows obtaining an ideal representation for completing both the holding and the merge-point scenario. Regarding the lateral size of the represented airspace, 80 nautical miles was the preferred lateral airspace size with 3D. In addition to these findings, specific requirements for improving both the visualization and the interaction were derived. One of the most important of a total of 12 requirements that were gathered with respect to the visualization was to keep the font size and the size of aircraft tags constant, independently from how close or far they are represented in the 3D airspace compared to the view-point of the ATCO. Amongst the eight different requirements that were gathered with respect to the interaction with the system was the possibility for the ATCOs to individually adjust their preferred view on the 3D airspace and to save and quickly access multiple views. This function allows to use the full potential of 3D, e.g. by switching quickly from a top-view that allows for the most precise judgment of lateral distances to a side-view in order to determine the best point in time for guiding the lowest aircraft out of a holding stack. Furthermore, the ATCOs mentioned the need to access further and more detailed information on an aircraft whenever required, e.g. its heading, next waypoint on a route, and, if applicable, velocity and altitude that has been advised by the ATCO.

In the second development cycle, a cohesive visualization and interaction concept was developed as static mockups that were based on the requirements that were gathered in the first development cycle. These mock-ups were presented to four ATCOs in order to review the quality of the concept, to gather further ideas for improvement, and to prioritize the functionalities that were to be implemented in the next development cycle. Amongst the total of 11 suggestions for a further improvement the concept was, for instance, to automatically display further information of aircraft that are indicated by the automatic conflict detection system by flipping up the aircraft-tag which, in the concept, usually is manually triggered by moving the mouse-pointer onto it.

In the third development cycle that was based on the two previous development cycles, the improved visualization and interaction concept was realized as an interactive working model with a stereoscopic 3D representation of the airspace for real-time ATC. Figure 7 shows the 3D airspace representation that was used for demonstrating a merge-point approach scenario.

After the ATCOs received a brief introduction into the functionalities and logic of interaction in the 3D interactive working model, a previously recorded merge-point approach ATC scenario was shown to the ATCOs who were asked to explore the working model and to provide feedback. A structured interview procedure was applied during and after the exploration phase in order to evaluate the quality of the working model and to gather further ideas for improvement.

The ATCOs highlighted the usability of the user-interface including the head-tracking system which allows the representation to automatically and continuously adapt to the ATCO's viewing position. Therewith, the ATCOs can resolve occlusions of aircraft identifiers or tags by slight head-movements instead of using the computer mouse as with the current system. Furthermore, the orientation of the aircraft-tags is automatically adjusted to the current viewing position of the ATCO in order to ensure best legibility of their content at all times.

To further improve the interactive working model, the ATCOs suggested using a separate touch-screen instead of a standard computer keyboard to interact with the system to facilitate the selection of the most important functions. Furthermore, the following features were mentioned as desireable: 3D representations of relevant airspace borders, the current weather situation as well as the predicted weather situation, the color-coding for distinguishing in- and out-bound routes, and the display of detailed maps and specific altitude ranges. On the basis of these suggestions, the ATCOs deemed the 3D human system interface ready to be tested in real-time air traffic control.

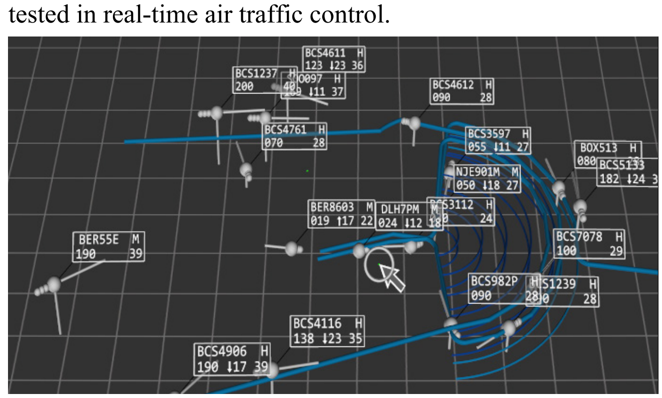

Figure 7. 3D airspace representation for demonstrating a merge-point approach scenario on the interactive working model.

V. DISCUSSION

The experimental as well as the evaluation results reveal that an adequate 3D airspace representation leads to a higher judgment certainty with less mental workload. Of special importance is that this quality of judgment can be achieved after only a short training period. It is plausible to assume that the utilization of an adequate 3D airspace representation from the very beginning of ATCO training might lead to an even more pronounced positive effect of the 3D human system interface.

The singular result that pilots immediately grasp the advantages of the 3D representation indicates the potential for establishing a better shared situation awareness of pilots and ATCOs thereby overcoming possible misunderstandings in their communication because the reference of verbal utterances can be directly linked to spatial positions. Future landing procedures, for instance, which give the pilots more responsibility would profit from this better shared ground in communication.

Immediate effects are to be expected for a better trade-off between safety and efficiency because of the marked decrease in false alarms. In comparison with published data about the given conflict detection and false alarm rates, it has been shown that an adequate 3D airspace representation results in less false alarms while achieving the same level of safety.

VI. CONCLUSION

The experimental data, the qualitative evaluation of the usability including the resulting mental workload, and the evaluation of the working model for visualization and interaction all support the conclusion that an adequate 3D airspace representation for air traffic control allows an immediate perception of danger and urgency in a given situation. Furthermore, according to the air traffic control experts the final version of the 3D human system interface has the full functionality of the existing interface while allowing a more intuitive interaction which apparently leads to a higher efficiency, a lower level of mental workload, and a better learnability. For supervisory tasks, a quick implementation of the system seems to be possible. For subsequent tests it is planned to investigate the potential functionality of the developed version of the 3D human system interface via a ‘shadow mode’ evaluation in real-time air traffic control.

ACKNOWLEDGMENT

This research was funded by the Bavarian State Ministry of Education and Science, Airbus Defense and Space, and DFS. The experiments and evaluations were accomplished in collaboration with C. Avenarius, C. Vernaleken, and J. Vogelmeier.

REFERENCES

[1] K. Craik, The Nature of Explanation. Cambridge: Cambridge: University Press, 1943.

[2] P.N. Johnson-Laird. Mental Models: Towards a Cognitive Science of Language, Inference, and Consciousness. Cambridge: Cambridge University Press, 1983.

[3] D. Gentner and D.R. Gentner, „Flowing waters or teeming crowds: Mental models of electricity,” in Mental models, D. Gentner and A.L. Stevens, Eds. Hillsdale, NJ: Lawrence Erlbaum Associates, pp. 99-129, 1983.

[4] M.R. Endsley, “Toward a theory of situation awareness in dynamic systems,” Human Factors, vol. 37, pp. 32-64, 1995.

[5] J.J. Gibson, The Ecological Approach to Visual Perception. Houghton Mifflin: Boston, USA, 1979.

[6] M.R. Endsley, “Situation Awareness and Human Error: Designing to Support Human Performance,” Proceedings of the High Consequence Systems Surety Conference, Albuquerque, NM, 1999.

[7] A. Baier and A.C. Zimmer, “How 3D-Displays in ATC Permit Direct Event Perception,” 17th International Conference on Human-Computer Interaction (HCI 2015), August 2015, pp. 309-316, ISBN 978-3-319-20372-0.

[8] A. Baier and A.C. Zimmer, “From Spatial Reasoning to Direct Event Perception in Air Traffic Control,” 6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015), July 2015, ISBN 978-1-4951-6042-4.

[9] S. Loft, S. Bolland, M.S. Humphreys and A. Neal, “A Theory and Model of Conflict Detection in Air Traffic Control: Incorporating Environmental Constraints,” Journal of Experimental Psychology: Applied, vol. 15, pp. 106-124, 2009.

[10] A. Bisseret, “Application of signal detection theory to decision making in supervisory control: The effect of the operator’s experience,” Ergonomics, vol. 24, pp. 81–94, 1981.

[11] A. Baier, C. Vernaleken, L. Vogelmeier and A.C. Zimmer, “Machbarkeitsstudie Stereoskopische 3-D-Anzeigen für Flugsicherungsarbeitsplätze: Abschlussbericht zur ersten Projektphase 30,“ unpublished report about a feasibility study on stereoscopic 3D-displays for ATC workstation.

[12] S.G. Hart and L.E. Staveland, “Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research,” in Human Mental Workload, P.A. Hancock and N. Meshkati, Eds., Amsterdam: North Holland Press, 1988.