Looking for the 3D Picture: The Spatio-temporal Realm of Student Controllers

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Abstract. Employing three-dimensional displays in Air Traffic Control (ATC) has been the object of study and debates for numerous years. Although empirical studies have often led to mixed results, some preliminary evidence suggests that training could be a suitable domain of application for 3D interfaces. Little evidence, however, is available to fully support this claim. We attempted to fill this gap with a project that aims at studying and evaluating 3D displays for ATC training purposes. This paper describes the first steps of this project, by reporting and discussing the results of a study aiming at understanding whether ATC trainees form a three-dimensional image of air traffic and at comprehending what the nature of this '3D picture' is.

1 Introduction

Air Traffic Control deals with the management of air traffic by Air Traffic Controller Operators (ATCOs) working at airports and in ATC Centers. For maintaining safe separation vertically and laterally between aircraft, ATCOs use several tools, such as Flight-Progress Strips (FPS), radio communications with pilots, and information gathered through two-dimensional (2D) radar displays. In these displays, aircraft are visualized as moving 'blips', and aircraft information is presented in flight labels in the form of text and numbers. In radar displays the horizontal separation is graphically rendered by the relative position of each 'blip' on the display itself, while assessment of separation by altitude is based on the numbers shown in the flight label. Radar displays use a dynamic 2D picture enriched with symbolic information for representing constantly changing air traffic configurations along 4 dimensions (i.e. three spatial dimensions, plus time). It is not surprising, therefore, that for several years the potential of 3D for ATC has been the object of investigation; however the results have always been quite mixed. Preliminary results emerging from the literature suggest that a suitable domain of application for 3D could be ATC training, however, to our knowledge, this issue appears to have received scant attention, and little empirical evidence is available to fully support this claim. We have attempted to fill this gap with a dedicated project that aims at studying, designing, and systematically evaluating 3D displays for ATC training purposes. The present work describes the first steps taken in this project, specifically we report and discuss the results of an investigation aiming at understanding whether ATC trainees form a three-dimensional mental representation of air traffic (as claimed in some of the pertinent literature) and, if so, at comprehending the nature of this '3D picture'. The paper is organized as follows: first an

M. Kurosu (Ed.): Human Centered Design, HCII 2009, LNCS 5619, pp. 1070–1079, 2009.

overview of related work entailing 3D displays and ATC is given; then the details of the study and the main results are summarized; the some implications for design and future directions are proposed.

2 Related Work

One of the first studies performed in this area was based on a survey (Burnett and Barfield, 1991) whose results revealed that ATCOs tended to prefer 3D perspective displays for "extracting immediate spatial situational and directional information"; however the results of a comparative evaluation of 2D and 3D displays across tasks entailing terrain scenarios (Wickens and May, 1994) found advantages for the 2D displays. Another comparative study involving weather formation avoidance tasks (Wickens, Campbell, Liang and Merwin, 1995) showed some speed advantages for 2D displays and differences between display types were observed in the strategies used to re-direct aircraft around weather formations. In a replication of a study carried out by Tham and Wickens (1993), Wickens and colleagues (1995) found few differences between three display formats (i.e. planar, perspective, and stereo-perspective) across a number of ATC related tasks, namely higher error rate in the perspective display for speed estimation, slower heading judgments with the stereo display, and quickest with the plan-view display, but no differences were found among displays for the conflict detection task. Brown and Slater (1997) discovered that for tasks entailing judging azimuth angle and lateral distances, 2D yielded better performance than 3D. In a series of ATC related tasks, Van Orden and Broyles (1999) discovered that performance with 2D was as good as or better than with 3D and that 3D Volumetric Display seemed particularly well suited for tasks entailing "perceiving complex, dynamic information relationships in a confined 3D space". A comparison between 2D and 3D stereoscopic display across an altitude judgment task (Tavanti, Le-Hong and Dang, 2003) showed that both controllers and ATC experts performed quicker with the 3D display, but no differences were found in accuracy. A disadvantage associated with 3D is that controllers have no familiarity with this display type, and past experience with 2D displays may play a role in the poor performance with 3D. In a few studies involving both air traffic controllers and pilots, it was observed that the costs associated with 3D were more likely to emerge with ATCOs than pilots (Wickens, 1995). ATCOs perform (and are trained to perform) their tasks with 2D planar displays, and this very experience may be a factor influencing performance whenever the nature of the artefacts in use is dramatically changed. Moreover, 3D also has typical drawbacks that can deteriorate performance: for example, ATC tasks may require precise distance judgments, potentially associated with perceptual biases arising from perspective distortions (Boyer and Wickens, 1994), a problem that challenges the fit between the nature of tasks and the chosen representation. Haskell and Wickens (1993) make a distinction between tasks that require the integration among several dimensions and the ones requiring focused attention on a single source and argue that 3D perspective displays may be viable "whenever the tasks to be performed using the display are integrated three-dimensionally". St. John, Cowen, Smallman and Oonk (2001) argue that 3D views are most useful "for tasks that require understanding the general shape of 3D objects or the layout of scenes"; whereas 2D is mostly suitable for tasks that "require judging the precise distances and angles between objects" (*ibid*). These viewpoints were supported by the results of a set of experiments (St. John et al., 2001) entailing shape understanding and relative position judgments, which suggest that 3D perspective view was superior for understanding objects shape, and 2D was advantageous for determining the relative position of objects. These results are of relevance because the idea that 3D views may support the understanding of 3D environments has some continuity with the use of 3D for ATC training. Indeed, employing 3D for ATC training is not an unprecedented concept, as preliminary evidence in support of its potential already exists. Wickens (1995) reports having observed a sort of "asymmetric transfer effect" when 3D and 2D conditions were counterbalanced: improved performances were observed with 2D when this condition followed the 3D, suggesting that 3D could enhance training, improving performance with subsequent 2D displays. Training is envisioned as a promising area of application (Monteleone, 2006; Wong et al., 2008), and during interviews carried out with ATCOs (Tavanti, 2004) it emerged that 3D could be beneficial for preparing trainees for real ATC tasks. An introductory study carried out by Akselsson and colleagues (2000) indicate that virtual reality has a great potential for teaching and explaining holding patterns operations, for enabling the understanding of the geometrical shape of an airspace sector and possibly for supporting the construction of accurate mental representations. ATC trainers, invited to examine and give feedback about an immersive 3D stereoscopic environment for ATC developed by our group (Bourgois et al., 2003; Lange et al., 2004), have commented that 3D visualizations could enhance controllers' training as these representations are similar to the constructed mental models that the trainee seeks to develop. In summary, preliminary evidence appears to point to two main claims: 1) 3D displays could assist the trainees in visualizing the actual 3D nature of the space in which air traffic operates; 2) 3D views may support the trainees in the construction of 3D mental representations required to manage air traffic. The second claim is of particular importance as, if valid, then attempting to understand the nature of this '3D picture' may give insights for the design of three-dimensional tools for training. We investigated this issue in a series of interviews involving ATC trainees, whose details and results are given in the following sections.

3 The Study

The interviews involved 9 interviewees, 8 trainees (2 females and 6 males) and one training specialist; 3 trainees were of Norwegian nationality, while 5 were Swedes; their ages ranged from 24 to 37. All of them had started their training period in August 2007. After having successfully completed the Basic Module (i.e. basic theoretical knowledge of the ATC work, with only a few practical sessions in the radar simulator) the trainees were enrolled in the rating Module 'Approach Control Surveillance with Radar Terminal Control Endorsement'. This second module (lasting about 18 weeks) enables the trainees to qualify for Approach Control Surveillance rating (with Radar and Terminal Control Endorsements). During this module, the simulator exercises are more intense and frequent, and entail the management of complex traffic scenarios (for example, handling emergencies or unusual events); they usually follow theoretical presentations and are followed by debriefing sessions with the instructors. Within this module there are several training objectives, including the handling of departing, arriving, and over-flying traffic, and cooperation between controllers. All the trainees interviewed were approaching the end of the Module (16th week out of 18). All trainees were fluent in English (English proficiency is also a prerequisite for ATC training admission), and English was the language used during the interviews. The interviews, which were semi-structured, lasted approximately 40 minutes and, upon permission from the participants they were tape-recorded. The trainees were asked to talk about the difficulties encountered during the training (up to the moment of the interview); this was done because we wanted to gain an overall understanding of ATC training from a student perspective. In addition, the students were questioned on whether they experienced forming three-dimensional mental representations of air traffic, and/or to attempt to describe these representations (if possible, even by drawing sketches on a piece of paper). The interviews were quite free, and in fact, other issues (probably characterizing the personal concerns and needs of each student) naturally emerged during the conversations. At the end of the interview, each participant was shown a short presentation composed of eight snapshots of a 3D application for ATC developed by our group at Linköping University. The snapshots illustrated the approach area around Arlanda airport (Stockholm) and displayed different visual features and textures, so as to give the flavor of the possible visualization capabilities of the application. The participants could freely inspect the snapshots and were requested to give their feedback and/or envision possible use during ATC training. Qualitative methodologies were used for the analysis of the interviews. Specifically the analysis was based on qualitative content analysis, which employs a step-by-step approach for organizing the material into content analytical units (Mayring, 2000), according to which categories are tentatively derived, further revised and reduced to main categories (*ibid*). No software package was used for the coding, which was essentially done on paper (i.e. the transcripts of the interviews); several means were used to apply the codes, ranging from annotations on the text, to color codes. Following the principles of Grounded Theory suggested by Charmaz (2006) we tried to define pertinent themes (or categories) able to summarize and explain the interviews content. In doing so, each interview was compared with the others, for example the analysis of the second interview was performed with the first interview fresh in mind; thus, as new themes were discovered within the second interview, it felt natural to go back to the first interview and check whether those themes were present, in a loop of constant comparison. Further, we attempted to link and relate the main categories in order to create a 'consistent narrative' explaining the phenomenon. In Grounded Theory, the theory informing about a certain phenomenon should naturally emerge from the available data, thus potential relationships among categories should also naturally emerge, without any forcing. This particular step was quite complex, as continuous tension was experienced between the need to explain events and facts, and the need to maintain an open attitude towards the data.

4 Results and Discussion

In order to summarize the main results of the study, we start by discussing and rectifying the meaning of the '3D picture', and more precisely to define its character. While tackling this question, we were confronted with variable patterns in the responses: whereas some students reported having experienced this '3D picture', notably 3D mental images of certain traffic arrangements in a rather clear manner (even providing drawings and sketches of these images, of which two examples are given in Fig. 1), others did not. A first hint to find a thread that could make sense of these mixed data came from the interview with the training specialist. She reported that '3D thinking' is a characteristic of every controller, and this ability is specifically tested during the initial selection of the candidates. Furthermore, according to the trainer, only if the students "*can do it* [think in 3D] *can they be controllers*". When the trainer was asked if during the course she explicitly encouraged the students to imagine air traffic in a 3D fashion, the reply was negative. Thus, a speculation was that students are left to work out their own way to 'think in 3D'. Seen in this perspective, the data started to make sense. As a matter of fact, while examining the different definitions and examples given by the trainees to define their representations of the so-called '3D picture', it appeared that the inconsistencies present in the contents, rather than being conflicting, were probably characterizing idiosyncratic conceptualizations that each student generated in an rather individual manner. These conceptualizations may not necessarily be linked to visual imagery experiences (which clearly materialized in the descriptions reported in some interviews). For instance, expressions used by the students like "seeing the image", "a flash in your mind", or "picture in your mind" may designate the use of visual imagery; however the use of more or less conspicuous verbal expressions in discussing the issue may simply denote a personal ability in describing experienced visual imagery, rather than being an indication of its presence.

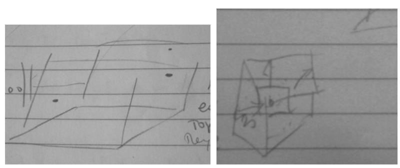

Fig. 1. Two sketches made by students

What appeared more consistently throughout all interviews were the indications hinting at the students' deep understanding of three-dimensional spatial quality of traffic scenarios, a sort of '3D awareness'. The expression '3D awareness' aims at defining the mindful understanding of the spatio-temporal relationships between aircraft, and refers to the comprehension of both current and potential (i.e. anticipated) spatial configurations. Expressions like '3D picture' and '3D thinking' simply denote the underlying awareness that air traffic has an intrinsic three-dimensional spatial quality, involving simultaneous movements of aircraft along three spatial axes. This understanding is essential, but it is not necessarily related to the (personal) propensity to create more or less vivid mental images. The following excerpts of interviews may help to illustrate the fact that the '3D picture' was evoked and described, with more or less vivid expressions and various nuances, but the understanding of the spatio-temporal qualities of air traffic seems persistent. For instance a trainee stated: *"No, I don't have it* [3D picture]...*at least not me"*; but the student's grasp on the 3D spatial character of air traffic unfolds in his words: *"I think I work more with blocks of airspace; for example, if you give an aircraft a flight level 120* [cleared to level 120] *then I just check if that is safe...which means checking that block over the airspace for conflicts, which means if is there another* *aircraft within...if you have a flight that is going in this direction...this block of airspace is unsafe...for another aircraft to travel in it...you can fly outside this box and everything else is safe, but as soon as you want an aircraft to fly through this box then you must be cautious, that's a conflict"*. The *block* and the *box* (three-dimensional shapes) betray a reference to the three-dimensional quality of air traffic spatial relations: checking the block is foreseeing whether certain volumes of the airspace can be safely used or not. Another trainee explained: *"It is like you can see a tube... not a perfect tube, but you see OK, it* [the aircraft] *is over there, it's above, it's below...you have the 2 dimensions on the screen and then you have the information of what heights, it is almost...not a perfect...but some hints at least of some kind of 3D image...You don't have this picture all of it* [all the traffic] *like crystal clear picture, but you have the sense of it...I know when it's all right"*. Another trainee declared: *"Most of the time is usually just dots on the screen and it is like you see a box like you should have a thousand feet the separation around them; but if something occurs, if they get too close, you get like a flash in your mind then you see the two airplanes...or if they are very* [much] *closer than they are supposed to be, and you're keeping the minima, you just see more in 3D than you would"*.

Another issue that emerged from the interviews is that while explaining their personal conceptualization of the '3D picture' the trainees made constant reference to (and provided examples about) assessments entailing current or estimated (i.e. within a certain time window) spatial proximity of aircraft. For instance, one of the students portrayed his own understanding of spatial relationships in terms of cubes and related it to proximate aircraft executing descending and climbing maneuvers, which may require the aircraft to follow crossing paths: *"it is very essential to think in three dimensions...I usually call it to make cubes, you have to make cubes, you have to think about* [that]*...I don't know how to explain but it is just that you have to think in three dimensions, you have to think that you have one* [aircraft] *that is going to go up* [climbing] *and one that is going to down* [descending] *and you have to think about how you're going to make that successful"*. Another trainee explained that when aircraft tracks appear as proximate (on the radar display), then the configuration of the aircraft pair is abstracted into a mental image that encapsulates both lateral position and altitude and that describes the spatial relationships of such an arrangement. A quotation can illustrate this point: *"I had in the simulator an aircraft that was on flight level one hundred I think, and another one descending at flight level one one zero... the second one descending did not stop descending to flight level one one zero so... I saw it was on flight level one zero niner and, I was like...Maintain flight level one one zero!* [mimicking screaming on the radio] *then I got that picture, I saw the actual aircraft descending towards the other"*. It is safety regulations that prescribe the minimum safety distances (vertical, lateral, and in some cases temporal) that must be kept between aircraft. Hence, the use of terms like *cube*, *block* or *box* employed to epitomize the '3D picture' relate to separation minima, and ultimately to safety: *"it's kind of... like a box I guess, but it is hard to explain, but it is 3D in your head. In my head it has to be 3D and so...if this is the dot* [the aircraft] *itself, I imagine it being a 3D box, so I think it is three nautical miles here, three nautical miles there and a thousand feet here, so I just keep it in my head ... I try to imagine it that always, at all time that this is a box"*.

The last theme that emerged from the interviews involves a learning process that occurred during the first weeks of the rating module, the memories of which were only loosely evoked in the students' accounts relating to first experiences with radar practice became apparent. It appeared that trainees experience a sort of shift or modification in the way radar information was comprehended and interpreted. The complex spatio-temporal world, where aircraft move at different speeds within three spatial dimensions, is simplified and split into diverse, multiform representations on the radar display. For instance, the radar may employ more typically pictorial representations (for example the moving tracks and their relative positions within a 2D Cartesian space) but also symbolic (of which notable examples are aircraft level or speed, represented with numbers on the data-block). Different visual features of the radar may be variably subjected to attentive and pre-attentive processes, as some elements of the representation appear to 'stand out', dominating the scene portrayed in the radar, possibly causing confused responses. The radar representation can be perceived as inconsistent with the reality it intends to signify and describe and, for example, two tracks on the same place in the radar may be 'in reality' safely separated if the flight levels are different, using the words of a trainee: *"now it comes natural because now we have been here for such a while, but in the beginning it was new to think that you have two things* [aircraft] *at the same place on the radar, but in reality they are not on the same spot"*. Moreover, the numbers displayed on the aircraft data-block may assume an overshadowed role within the visual scenery; the words of a trainee made this aspect very clear: *"in the beginning for me, it was easy for me to think in two dimensions, because we see two dimensions...it's like I see this dot and where it is going, and then it was easy to forget the levels, because the level is just a number, label tagged by a number"*. Knowledge of ATC basics (covered by the Basic Module) is a pre-requisite to gain access to the rating module in which the participants were enrolled; therefore it is legitimate to state that each participant knew fairly well what the numbers in the data-block stood for. Thus, probably, the meaning of 'flight level' was correctly attributed to the numbers on the display, but the conceptual value assigned to the numbers was unlikely to be. The following quotations will help to discuss further the concept of value attribution: *"in the beginning we just had some dots with labels and the speed, and I can see physically where the dot is going, and then after a while I found that this level is quite essential... it is easy to see when they* [the aircraft] *are quite far apart, but when you're looking at the levels, then you have to make the levels, from a number into a level...so that came second, and then the third part was the speed"*. Thus, understanding levels is 'making levels' out of simple numbers. Progressively, the perceptual information (for example numbers) defining specific spatio-temporal properties of air traffic configurations acquire valuable and specific meaning, and are transformed into conceptual knowledge (levels) associated with a precise role. Although they may appear obvious, three issues deserve to be mentioned further. First, there is a strong temporal quality characterizing the data. The participants used a number of time-related expressions that portray their journey through the training, from the initial impact with radar representations (*in the beginning, then*), up to their current experience thereof (*then, after, now*). Second, the journey does not take place in a void: practical learning occurring during the simulator exercises is the bridge that connects the 'before' and 'nowadays' experiences of the radar representations. Third, the progressive shift towards the generation of concepts from the radar representations is a necessary step to achieve '3D awareness', which seems so crucial for ATC core tasks; but achieving this awareness by gathering air traffic information from 2D radar display is an arduous process. Only with time and practical training, does the perceptual information defining specific spatio-temporal properties of air traffic start to acquire valuable meaning and it is further transformed into conceptual knowledge. Seen in the perspective of design, the initial phases of the practical training could be a suitable niche for exploring the utility of 3D tools. A hypothesis is that 3D displays may provide the students with a more natural view of the spatio-temporal relationships inherent to air traffic, and possibly their use could foster the creation of conceptual knowledge necessary for gaining a thorough awareness of the spatio-temporal relationships of air traffic. This idea was also suggested by the students while inspecting some snapshots of a 3D-ATC application. In fact, a trainee suggested that: *"there's no way of misunderstanding this* [referring to the images of the 3D application]*...you actually see... you see everything much clearer I guess it is really helpful in the start...I think it could be very helpful in the earlier stages... because now we have seen how it works and it is not needed anymore"*.

4.1 Suggestions for Initial Designs

The results of the study along with the feedback given by the students on the potential use of 3D for training can be summarized in a set of initial suggestions for supporting and guiding the design. First, the strict relationship between 3D awareness and safety suggests that 3D representations should focus on the regulations pertaining to separation minima that prescribe procedures and rules to be employed in a number of specific air traffic cases. Suggestions given by the students indicate that using 3D for displaying holding stack management, aircraft sequences in the approach area, aircraft pathways into and/out of airports, may enhance their understanding. In addition, the students declared that sometimes it is complicated to clearly discern from the radar the actual aircraft position during climb and descent maneuvers, making it difficult to evaluate whether aircraft trajectories could cross; 3D representations could help understanding and reasoning on whether aircraft paths intercept. Also, 3D could be used to represent different aircraft behaviors while descending; to use a student's words: *"you'll never know if it* [an aircraft] *is going to* [go] *on a straight* [line]*, probably it is not going to go straight up like this, so even if it is pretty fast up it might going to do like this* [mimicking with gestures a sort of stair-step climbing] *for a while...or climb at different rates of climbing, unless you tell the pilot to climb at 2000 feet per minute, then he has to go straight*". Second, a 3D tool should be (at least at this stage) a 'trainers' device', allowing them to create, add, remove, and modify traffic scenarios on the fly. The simulator exercises usually follow theoretical presentations and explanations, and are followed by debriefing sessions with the instructors. The instructors' explanations may require illustrating and explaining specific traffic configurations on the whiteboard. Thus, the 3D tool could be used as a complement to these explanations *"to illustrate different traffic scenarios, as a demo...I mean teachers and instructors showing us different types of traffic, how you might solve different traffic situations, I mean different solutions... I think that this would be good to illustrate the demos"*. Third, 3D graphical representations should be kept as simple as possible. Students' reactions to a demo of the 3D application were positive overall, but the generous use of colors and the number of features present in the pictures were judged excessive. An idea could be to keep some continuity with the graphical representations of the radar display used by the students, in order to minimize the impact of the transfer between the two representations styles.

In summary, the students provided very helpful suggestions with respect to the potential contents and contexts of use of the 3D display to support training. However, more precise information is needed in order to define in concrete terms some design solutions for the 3D tool. In order to further address these aspects, in the near future, we will involve ATC training specialists and ATC trainees and cooperatively discuss and define in greater detail a few air traffic scenarios and some of the tool's interactive functionalities.

Acknowledgements

"This work has been co-financed by the European Organisation for the Safety of Air Navigation (EUROCONTROL) under its Research Grant scheme. The content of the work does not necessarily reflect the official position of EUROCONTROL on the matter. © 2008, EUROCONTROL and the University of Linköping. All Rights reserved." A special thanks goes to the trainer and trainees who kindly accepted to participate in this study and to Ivan Rankin for reviewing and giving precious feedback on this work.

References

Akselsson, R., Källqvist, C., Bednarek, V., Cepciansky, M., Trollås, A., Davies, R., Eriksson, J., Olsson, R., Johansson, G., Hallberg, B.-I., Håkansson, L.: Virtual Reality in Air Traffic Control. In: Proceedings of the IEA 2000/HFES 2000 Congress, San Diego, California USA (2000)

Bourgois, M., Cooper, M., Duong, V., Hjalmarsson, J., Lange, M., Ynnerman, A.: Interactive and Immersive 3D Visualization for ATC. In: Proceedings of the 6th USA-Europe ATM R&D Seminar, Baltimore, Maryland, U.S.A. (2005)

Boyer, B.S., Wickens: 3D Weather Displays for Aircraft Cockpits. Technical Report (ARL-94-11/NASA-94-4). Savoy, IL: Aviation Res (1994)

Brown, M.A., Slater, M.: Some Experiences with Three-Dimensional Display Design: An Air Traffic Control Visualisation. In: Proceedings of 6th IEEE International Workshop on Robot and Human Communication RO-MAN 1997, pp. 296–301 (1997)

Burnett, M.S., Barfield, W.: Perspective Versus Plan View Air Traffic Control (ATC) Displays: Survey and Empirical Results. In: Proceedings of the 6th International Symposium on Aviation Psychology, Columbus, Ohio State University, pp. 448–453 (1991)

Charmaz, K.: Constructing Grounded Theory: A Practical Guide Through Qualitative Analysis. Sage Publications, London (2006)

Haskell, I.D., Wickens, C.D.: Two- and Three-Dimensional Displays for Aviation: A Theoretical and Empirical Comparison. International Journal of Aviation Psychology 3(2), 87–109 (1993)

Lange, M., Cooper, M., Ynnerman, A., Duong, V.: 3D VR Air Traffic Management Project. Innovative Research Activity Report, Eurocontrol Experimental Centre, Bretigny-sur-Orge, France (2004)

Mayring, P.: Qualitative Content Analysis. Forum Qualitative Sozialforschung/Forum: Qualitative Social Research (2000), http://www.qualitative-research.net/index.php/fqs/article/view/1089

Monteleone, A.: The 3D Technology Applied to Approach and Airport Environments in the ATC Domain. In: Proceedings of Visualization and Distributed Systems Technologies: the A4D Approach and Beyond, Innovative Research Workshop, Bretigny-sur-Orge, France (2006)

St. John, M.H., Cowen, M.B., Smallman, H.S., Oonk, H.M.: The Use of 2D and 3D Displays for Shape-Understanding versus Relative-Position Tasks. Human Factors 43(1), 79–98 (2001)

Tavanti, M., Le-Hong, H., Dang, T.: Three-dimensional Stereoscopic Visualization for Air Traffic Control Interfaces: a Preliminary Study. In: Proceedings of AIAA/IEEE 22nd Digital Avionics Systems Conference, Indianapolis Indiana, US (2003)

Tavanti, M.: On the Relative Utility of 3D Interfaces. Thesis dissertation, Uppsala University, Sweden (2004)

Tham, M., Wickens, C.D.: Evaluation of Perspective and Stereoscopic Displays as Alternative to Plan View Displays in Air Traffic Control. University of Illinois Institute of Aviation. Technical Report (ARL-93-4/FAA-93-1). Savoy, IL: Aviation Res. Lab (1993)

Van Orden, K.F., Broyles, J.W.: Visual Task Performance as a Function of Two and Three-dimensional Display Presentation Techniques. Displays 12, 17–24 (2000)

Wickens, C.D., May, P.: Terrain Representation for Air Traffic Control: A Comparison of Perspective With Plan View Displays. Technical Report (ARL- 94-10/FAA-94-2) Savoy, IL: Aviation Res. Lab (1994)

Wickens, C.D., Campbell, M., Liang, C.-C., Merwin, D.H.: Weather Displays for Air Traffic Control: the Effect of 3D Perspective. Technical Report (ARL-95-1/FAA-95-1). Savoy, IL: Aviation Res (1995)

Wickens, C.D.: Display Integration of Air Traffic Control Information: 3D Displays and Proximity Compatibility. University of Illinois Institute of Aviation. Technical Report (ARL-95-2/FAA-95-2). Savoy, IL: Aviation Res. Lab (1995)

Wong, W., Rozzi, S., Gaukrodger1, S., Boccalatte, A., Amaldi, P., Fields, B., Loomes, M., Martin, P.: Human-Centred Innovation: Developing 3D-in-2D Displays for ATC. In: Proceedings of the 3rd International Conference on Research in Air Transportation (ICRAT 2008), Fairfax (2008)