On the History and Prospects of Three-Dimensional Human-Computer Interfaces for the provision of Air Traffic Control Services

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Abstract

This paper is an essay on the history and prospects of three-dimensional (3D) human-computer interfaces for the provision of air traffic control services. Over the past twenty-five years, many empirical studies have addressed this topic. However, the results have been deemed incoherent and self-contradictory and no common conclusion has been reached.

To escape from the deadlock of the experimental approach, this study takes a step back into the conceptual development of 3D interfaces, addressing the fundamental benefits and drawbacks of 3D rendering. Under this light, many results in the literature start to make sense and some conclusions can be drawn. Also, with an emphasis on the future of air traffic control, this research identifies a set of tasks wherein the intrinsic weaknesses of 3D rendering can be minimized and its advantages can be exploited. These are the ones that do not require accurate estimates of distances or angles. For future developments in the field of 3D interfaces for air traffic control operators, we suggest focusing on those tasks only.

Keywords-3D, Three-dimensional, Interface, ATC, HCI, Human-Factors

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1. Introduction

Since the beginning of commercial aviation, the global air traffic rate has exhibited a fairly positive trend, even through economic stagnation, financial crisis and increased security concerns. According to a prevailing opinion, this trend is unlikely to change in the future, although a number of factors, such as politics, economy, environment, safety and security may affect its actual rate. As a result, the air traffic growth tends to be accepted as a certainty within the industry, especially from a global, long-term perspective [1].

In future scenarios, new forms of co-operation and co-ordination are expected to emerge. These will take advantage of the System Wide Information Management (SWIM) concept [2–4] and rely on the latest Information Communication Technologies (ICT), such as the Global Positioning System (GPS) and Automatic Dependent Surveillance - Broadcast (ADS-B). An '*Internet in the sky*' network will be created [5], providing an information-rich environment for distributing data amongst all air transport stakeholders (including pilots and controllers). With such a wide availability of information, to perform a safe and efficient Air Traffic Management (ATM) will require more and more automated Decision Support Tools (DSTs) and data fusion algorithms. Also, a major shift in the chain of responsibility for en-route collision avoidance and Mission & Trajectory Management (M&TM) is foreseen, in compliance with the '*Free Flight*' and the '*4D Trajectory Management*' concepts [6]. Basically, airliners will take a more active role in M&TM, supported by autonomous systems that will partly replace air traffic controllers. Controllers will continue to monitor the situation, with a policy of intervention by exception [7]. According to Sheridan's classification [8] this will move controller's responsibility from '*direct human control*' toward '*computer-aided indirect control*' [9]. Finally, an improved Air Traffic Flow Management (ATFM) will reduce the number and complexity of the airborne encounters.

From a carrier perspective, the freedom to set courses will outcome in significant time and financial savings, whereas the environment will benefit from the noise and fuel consumption reduction. However, in order to adapt to change, both pilots' and controllers' interfaces will need modifications. As for Air Traffic Control (ATC), this stands to reason, considering that Planar View Displays (PVDs) have been introduced 30-odd years ago and still retain many similarities to earlier Plan Position Indicators (PPIs) – more about this in section 2.

In this paper we investigate the benefits and drawbacks of three dimensional (3D) human-computer interfaces for ATC. Our review is based on the analysis of past related work as well as on the Human-Computer Interaction (HCI) theory.

In order to put in context this issue, we first give different types of ATC background (historical and operational) and a short introduction to the field of computer graphics and three-dimensional human-cumputer interface design.

2. Historical Background

Before the end of the '90s, the introduction of Graphical User Interfaces (GUIs) made computing technologies accessible to a large number of professional and amateur users, in addition to computer scientists and programmers. This made Human Computer Interaction (HCI) a subject of a more general interest. Ever since then, a great effort has been put in trying to fill the gap between the user and what is going on in the hidden and intangible parts of computers [10].

In those years, the early days when the management of a few planes could be left to little more than the pilots' eyesight had been long passed. Controllers had already moved from 'procedural' to 'radar-based' ATC, while the oscilloscope-based Radar Bright Display Equipment (RBDE) – a.k.a. Bright Radar Indicator Terminal Equipment (BRITE) – was in the process of being replaced by the raster-scan PVD. Prior to that, PPIs were used, especially in military operations rooms. However, they were later substituted by RBDE because of their limited brightness.

The transition from the RDBE to the PVD technology heralded the beginning of the data processing era. Indeed, with oscilloscopes-based interfaces, such as PPI or RBDE, the image was not digitally stored, but only displayed on the screen, i.e. fading away as a function of the cathode ray tube persistence. The screen was updated synchronously with the radar sweep, allowing the controller to see echoes, but only for a few seconds before the image would fade out completely. The radar would then make another sweep and refresh the image. On the contrary, by the time that the PVD technology was mature, the radar data was digitally stored and could be used to generate fully persistent images. That is also when User Interfaces (UIs) started to be populated by data-blocks, labels and DSTs. In a PVD aircrafts are represented as dots moving through the radar screen. For each aircraft, selected information is displayed on the screen by means of symbols, data-blocks and labels. This typically includes the aircraft's call sign, type, its altitude and its speed. Further information is available upon request through the UI (e.g. flight plan, historical track, forecasted position, etc.). The radar screen also present information on the airspace itself, such as sectors boundaries, routes, navigational aids, waypoints, fixes, minimum vectoring altitudes and prohibited airspace volumes. As a matter of fact, although the display format is bi-dimensional, a large amount of three-dimensional information is embedded into the interface.

In the meantime, hardware manufacturers met the requirements for real-time 3D rendering. Very soon, 3D compatible hardware was exploited in many fields, such as simulation, data analysis, computer aided design, engineering, medicine, training, entertainment, cultural heritage and archaeology. By now, thirty years of technological advancement have definitively set the hardware requirements for real time 3D graphics to the level of a regular Personal Computer (PC), which perfectly fits the industry needs. On the whole, taking advantage of three-dimensional Computer Graphics (CG) has become less burdensome.

Today, many computer related tasks consist of visually navigating through scenes, searching displays of data and finding things [11]. As a matter of fact, Information Visualization (IV) has become a well-established field of study, covering the design of visual systems that enable humans to explore and understand complex data sets [12]. These are sometimes referred as cognitive support systems [12, 13], which improve the viewer's problem solving capacity by allowing him or her to extract patterns, inspect details, formulate hypotheses and verify theories [14]. This makes it

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possible to spot relevant correlations across data, making sense of them at a perceptual level and lowering the need for high-level cognitive processing – i.e. the cognitive process involved in thinking, reasoning, planning, and so on (e.g. the one required to interpret numerical and textural representations).

Within this context, in the last two and a half decades, a series of studies – mostly empirical – have been performed in order to determine whether or not three-dimensional UIs could be used for the provision of air traffic control services and if there were any point in doing so.

3. Operational background

ATC is basically an exercise in flow control where each controller is responsible for a certain portion of airspace [15]. Airspace volumes can be classified into Aerodrome Traffic Zones (ATZs), Terminal Manoeuvring Areas (TMAs) – a.k.a. Terminal Control Areas (TCAs) – and Control Areas (CTAs). CTAs are further subdivided into airspace sectors. Aircrafts may enter the ATCO's area of responsibility at various points in space and time, according to their flight plan/trajectory profile. As the case may be, they must be guided through the sector, toward take off or up to landing (parking included). This must occur in an orderly and efficient manner, avoiding any risk of collision. Safety is enforced by agreed standards of separation, specified in terms of minimum permitted distances between aircrafts (both vertically and laterally) [15]. Additionally, the aircraft must be placed in a flow which is consistent with the aircraft's route of flight or the airport/TMA departure/landing queue.

En-route air traffic controllers work in facilities called Area Control Centres (ACC) and control aircrafts from the time they leave an ATZ or a TMA to the time they arrive at another ATZ or TMA. When managing en-route traffic, controllers work in teams of two: executive and planner. The executive controller (a.k.a. radar controller) is the one who actually talks to the airplanes, issuing instructions (a.k.a. clearances) to pilots, so that they meet altitude and heading restrictions by specific points. The Planner controller (a.k.a. coordinator) supports the executive controller by planning ahead and coordinating with other ATC units with the aim of (i) establishing how aircrafts should be handled to them and (ii) how they should handle the aircrafts to others. This is done in order to keep conflicts at a minimum. As an aircraft reaches the boundary of a CTA it is 'handed off' or 'handed over' through to the next CTA's ACC. This process sometimes involves a transfer of identification and flight details between controllers or can be 'silent' (depending on local agreements). However, for a 'silent' hand over to be performed, traffic must be presented in an agreed manner. After the hand-off, the pilot is given a frequency change and begins talking to the next ACC. This process repeats until the aircraft is handed off to a TMA control centre (a.k.a. approach control). If a TMA does not exist, the ACC co-ordinates directly with the control tower.

Depending on the TMA complexity, TMAs may be managed by single or multiple ATCOs. However, in the latter case, controllers do not work in teams (as for en-route control). Each of them is in charge of a certain approach/departure phase and manages aircrafts at different flight levels. For instance, a 'feeder' controller is often in charge of lining up and clearing aircrafts for the final Instrument Landing System (ILS) approach. As aircrafts move in and out of the TMA, they are handed off to the next appropriate control facility, such as a control tower or an ACC.

Inside the ATZ, the responsibility of tower controllers typically falls into three main categories: Air Control (a.k.a. Local Control or Tower Control), Ground Control and Flight Data/Clearance Delivery. Ground control (a.k.a. Ground Movement Control) is responsible for all the operations taking place on the airport 'movement' area, which is composed by the apron and the manoeuvring area. The manoeuvring area, in turn, comprises taxiways, inactive runways, holding areas and intersections. Air Control is responsible for the active runways and clears aircraft for take-off or landing. This is done making sure that the prescribed runway separation exists at all times. Both Ground Control and Air Control are also expected to alert airport emergency services in case an aircraft is experiencing difficulties. Clearance Delivery, which is often combined with Flight Data Delivery in controlled airports, issues route clearances and provides pre-flight information to pilots. At extremely busy airports, Clearance Delivery may also plan aircraft push-backs operations and engine starts. This helps to prevent taxiway and apron gridlock. In this case, Clearance Delivery it is better referred as the Ground Movement Planner (GMP) service. Flight Data Delivery provides pilots with the latest information about weather, traffic, outages, delays, ground stops, runway closures and other ground restrictions. At busier airports Flight Data may inform pilots using a continuous broadcast of a recorded loop message on a specific frequency, which is known as the Automatic Terminal Information Service (ATIS).

Alternate ATCOs' activities include supervisory and redistribution of traffic flows, airspace resectorization, holding stack management and provision of Flight Information Service (FIS).

Clearly, to perform all ATC tasks controllers need to extract information from the PVD, check weather, consult Flight Strips (FS), elaborate long term strategies, detect potential conflicts, radio-communicate with pilots, make tactical decisions, coordinate with each-other and look out of the tower window (if any). Also, controllers need to balance cognitive resources and carefully timetable actions [16].

3.1. Flight strips

One of the key aspects of an air traffic controller's job is to make FS useful within the flow of work [17]. Historically, a FS is a piece of paper about one inch wide and eight inches long that is formatted into 'boxes' and provides information on a single flight. In some cases, old-fashioned strips have been replaced by digital strips (a.k.a. electronic-flight strips or e-strips), which make use of touch screens instead of papers. The information printed on the strip is derived from the Flight Data Processing System (FDPS), which is subject to updates, but not continuously. Thus, the FS must be considered as a discrete image of the flight progress not a continuous one [17].

'Pending' strips are submitted to ATCOs several minutes in advance and become 'alive' on the receipt of a radio message from the plane entering the controller's area of responsibility. Both are placed in racks in front of the controller. Through a process referred as '*working the strips'* or '*making the strips come to be at hand*', controllers order the strips in such a way that they reflect the work that needs to be done. For example, based on the Estimated Time of Arrival (ETA), controllers order the strips so that the next plane expected at any point is at the top of the rack. In this way, future activities are scheduled and controllers get a sense of what decisions they will have to

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make in a few minutes [17]. As a matter of fact, each strip becomes a piece of a larger puzzle. Also, ordering the strips contributes to shape controllers' attention in terms of what is likely to happen under their responsibility.

If any problem or situation is spotted, controllers mark out the singularity by slightly lifting the corresponding strips out of the rack, in order to draw attention onto them. This is also known as '*cooking the strip*'.

Another good practice is to note down on the strip all the information related to the aircraft management, including clearances, ETA, coordination, routes and call sign changes. Attention-drawing symbols and convenient signs, such as arrows, crosses and circles may be also jot down on the strip in order to remark uncommon routes, highlight crossovers, emphasize destinations or denote actions about to be taken. ATC centres may follow a precise colour-coded protocol, which shows by whom the note has been written (chief, executive or planner). For instance, chiefs usually write coordination agreements on pending strips, whereas planners update ETAs. In this sense, a FS not only keeps track of the decisions that have been taken, but also indicates by whom those choices have been made.

When an aircraft crosses the final navigation point of the sector (or is finally parked on the apron) the controller puts a cross through the strip to demonstrate that his work has been properly done and that the strip has not just been thrown away.

Exploiting the Verbal Protocol technique [18, 19] several studies have found FSs to be an essential part of controllers working practice [17]. Further analysis suggest that controllers rely on the strips when trying to obtain a general sense of the traffic situation (e.g. when taking over a working position during the shift change) [17]. As a controller once reported "*it would be an impossible job to sit down and look at the radar, and look at all the different blips, and try to avoid them by putting the aircraft into blank spaces on the radar; so you have got to have this information to tell you what traffic is coming into and out of the sector. From your strips you can find out whether there is or not a possible confliction...and what you can do about it, then you go to your radar and look for that particular aircraft*" [17]. These words demonstrate the use of FSs as a primary resource for the creation and maintenance of a mental model that can be used to shape controllers' attention and organise their activity. Once again, the relation between the working memory and the FSs has been properly remarked by a controller himself when he said: "*the strips are like your memory, everything is there*" [17].

To fully investigate the relationship between FSs and controller's mental model (i.e. 'the picture') is beyond the scope of this paper and would be hard to do in absence of further research. However, this aspect should not be neglected in future developments on the subject of 3D interfaces for air traffic controllers.

3.2. The picture

In ATC, '*to build the picture*' is not a detached expression, but one well understood within controllers' culture. For instance, this phrase is often used to depict the regular habit of incoming controllers to spend anything up to ten minutes watching over the shoulder of their colleagues before taking over the position [17].

In [20], Jeannot, Kelly and Thompson report that both theoretical and empirical studies on the *picture* have been carried out since the late 60s, particularly in France [21, 22]. A synthesis can be found in [23]. They also tried to reshape the Situational Awareness (SA) definition so that it would embrace the concept of the *picture,* resulting in a better fit for the ATC domain., During their study, a controller gave the oddest definition, which, unexpectedly, is also the one that we like most: "*SA is what you need to know not to be surprised*" – he said. In [15] Brown and Slater define the picture as the "*overall awareness which enables controllers to carry out their tasks and stay ahead of the game*". Whitfield and Jackson formulated a similar statement, saying that the *picture* is the "*overall appreciation of the traffic situation for which they [controllers] are responsible*" [22]. Further research can be found in [24–26]. On the whole, the *picture* has been described as the holy grail of the controller, the awareness that he seeks and fears to lose.

Recent developments indicate that even if receiving identical information, each controller shapes his or her own SA. Besides, during interviews with both operative controllers and trainees not everyone reported having experienced the '*picture*' as a vivid mental image [27]. Further, the ones who positively reported about its existence had a hard time in describing it verbally [27]. Between the ones negating its existence, a Swedish trainee stated: "*No, I don't have it [the 3D picture]...at least not me*", but later unfolds, in his own words, "*I think I work more with blocks of airspace*" [27]. The block (a three-dimensional shape) is a clear reference to the 3D nature of the ATC problem, which involves the simultaneous movements of aircrafts along three spatial axes. Eventually, the problem becomes 4D, if also considering time. In this sense, the trainee checks 'the block' trying to foresee whether a certain airspace volume can be safely used or not. In [27], a training specialist reported that '*3D thinking*' is a peculiar characteristic of every student, specifically tested during the initial selection of the candidates, but not explicitly addressed later in the course. Thus, each trainee seems to be left to work out his or her own way to '*think in 3D*'.

Many ATCOs organise the *picture* in terms of flight levels, foreground and background traffic or inbound and outbound flows [17]. Also, they take advantage of their knowledge of typical routes and procedures and sometimes focus on non-routine flights [17]. Some evidence suggests that FS play a key ro1e in building and maintaining *the picture* [17, 22]. Other indicates that the mental model is mainly built on top of the PVD image [28, 29].

On the whole, the subjective nature of the *picture* has been found strong and confusing, which makes it difficult to support any definition that relates to a 3D imagery experience that may not exist at all. Instead, we would like to endorse Tavanti's definition: *"[3D picture is] a mindful understanding of the spatial-temporal relationships between aircrafts and airspace, referring to the comprehension of both current and potential (i.e. anticipated) spatial configurations*" [27].

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3.3. *Further working practice*

There are many aspects of controllers' working practice that are probably worth to be mentioned. However, it is beyond the scope of this paper to cover all of them in depth. Some have been discussed in the previous paragraphs; others are summarized below:

- Controllers tend to consider aircrafts in pairs rather than in isolation. In this sense, the information becomes relative (e.g. 'this aircraft is at a higher level than the other one', and not 'this aircraft is at flight level *x*' etc.).
- In order to make decisions, controllers only consider the information they need (e.g. only position and altitude).
- Controllers operate in predictive mode. This was confirmed by observing that when they incorrectly report an aircrafts' position (or altitude), most of the time, they are just forecasting the aircraft behaviour.
- Functional distortions have been found in both the airspace and the radar map (mental) representations, which seems to be related with the traffic load on those elements [20].

4. THREE-DIMENSIONAL USER INTERFACE DESIGN BACKGROUND

Similar to HCI, the field of UI design is an interdisciplinary subject that draws from existing knowledge in perception, computer graphics and cognitive sciences. A 3D UI may be defined as one in which a sense of depth is created along the line of sight into the display (the effectiveness of this being roughly a weighted additive function of the number of depth cues that the interface integrates [30]). Depth cues are frequently classified into two main categories: monocular cues and binocular cues.

4.1. *Monocular cues*

Monocular cues (a.k.a. pictorial cues), are the ones that can be retrieved form a scene by means of a single eye. They are widely used in painting, photography and computer graphics and provide the viewer with a sense of depth and three-dimensionality, to the extent that the content '*looks like 3D*' even if displayed on a 2D media. Here is a list of the most important monocular cues:

- **Linear perspective**, according to which parallel lines converge in the distance.
- **Relative objects size**, according to which large objects are perceived as closer than small ones.
- **Relative height to the horizon**, according to which objects closer to the horizon are perceived as farther away from the viewer.
- **Shading** (a.k.a. shadows and lights). Lights and shadows provide the viewer with some knowledge regarding the objects shape and their relative positioning within the scene.
- **Occlusion** (a.k.a. interposition). This cue derives from the partial overlap of two objects viewed from a certain perspective. The occluding object appears to be closer than the one that is partially blocked.
- **Texture gradient**, according to which a surface texture gets finer and smoother as it distances the observer.
- **Atmosphere**, according to which the blurrier an object is, the more is perceived as far from the observer.
- **Motion parallax**, according to which far objects seem to move less than nearby objects when the viewer changes his or her viewpoint position.
- **Depth from motion**, according to which an object that changes its retinal shape is perceived as moving towards or against the observer. This enables the viewer to estimate the distance from the object in terms of time-to-contact or time-from-contact.
- **Accommodation**. This is the process through which the eye lens reshapes, changing its optical power in order to focus on a certain object. A depth cue is derives from the kinaesthetic sensations of contracting and relaxing the ciliary muscle.

Amongst monocular cues, *linear perspective* is certainly one of the most important. It belongs to the class of projections that make parallel lines converge in the distance. In particular, the projection is achieved by means of straight lines.

Other types of projections exist, which exhibit diverse characteristics other than those of *linear perspective*. For instance, *orthographic projection* (a.k.a. *orthogonal projection*) is a subclass of *parallel projection* wherein the projection lines are orthogonal to the projection plane. As a result, lines that are parallel in the scene remain such in the projection outcome as well. *Orthographic projection* is widely used in technical drawing, Computer Aided Design (CAD) and a few other sectors. For instance, in ATC, an *orthogonal view* is used on the radar screen and comes in handy for distances evaluation and bearing angle assessment (more about this in section 5 and 6).

4.2. *Binocular cues*

Binocular cues, namely convergence and stereopsis, are the ones that require the use of both the eyes.

- **Convergence** allows the eyes to fixate objects. Because the two lines of sight converge at a certain point, the angle formed at their intersection will be narrower or wider, depending on the distance between the eyes and the object. As a result, for close objects the angle will be wider, whereas for far objects the angle will be narrower. Depth information is gathered from the kinaesthetic sensation of stretching the extra-ocular muscles in a similar manner to what happens with accommodation.
- **Stereopsis** (a.k.a. binocular disparity) is based on the slight difference between the images collected by the eyes. Making use of such disparity the human brain is capable of triangulating the distance between eyes and objects with a relative degree of accuracy.

Graphics contents that make use of binocular cues should be referred as '*stereoscopic 3D*' or '*stereo 3D*' contents. On the contrary, graphics contents that do not make use of binocular cues should be labelled as '*2.5D'*. However, it is common practice to name '*3D'* what is actually a *2.5D* render.

4.3. Three-dimensional user interfaces

Generally speaking, 3D graphics is likely to fascinate both end-users and system designers [31]. This is arguably due the ability of easily conveying three-dimensional information [32], "*showing the situation as it really is*" [33] and sparing us (humans) the trouble of collecting and interpreting bi-dimensional information [31].

However, the utility of a graphical interface, either 3D or 2D, cannot be argued *a priori,* nor in absolute terms. Indeed, its pros and cons depend on a number of factors, such as semantics, perception, culture and tasks [10]. Semantics relates to the space representation and the objects' distribution within it. Perception deals with human cognitive abilities. Culture depends on the user familiarity with the interface (including indirect experiences). Tasks relate the user's goals within the current job.

In their review of several human-computer interaction techniques, Andre and Wickens warn system developers about the fact that, occasionally, "*users want what is not best for them*" [34]. In practice, "*they are likely to prefer solutions that hinder rather that hamper performance*" [32]. Therefore, the design of a UI requires a great care and careful optimisation. Non-isolated concerns might include: choice of projection paradigm, choice of depth cues, selection of viewing parameters (e.g. field of view, viewing position, elevation, azimuth and scale), choice of interaction techniques, Human Factors and Ergonomics (HF&E), and further implications for recruitment and training.

4.4. The *'foreshortening effect'* and the 'height constancy bias'

One of the major problems associated with 3D is the difficulty of properly estimating distances and dimensions along the line of sight [10, 32, 35–43]. Reliable judgements on the ordinal relationship between the objects are still possible, provided that enough depth cues are given. However, when it comes to absolute distances estimation, these appear 'distorted' and 'compressed'.

In order to envisage this behaviour, imagine watching a computer-generated image of a vertical pole that is placed in front of you. Now, let the pole slowly rotate around its centre until you can only see the top of it. The length of the pole will appear shorter and shorter, as if it were being compressed [32]. This effect has been given many names in the literature, including '*foreshortening effect*' [44], '*line of sight ambiguity*' [45] or '*projective ambiguity*' [46]. An example is given in Fig. 1.

It is worth noticing that the very same effect exists in bi-dimensional interfaces as well, where it is clearly impossible to estimate distances along the line of sight. However, both designers and final users are aware of this and do not expect anything different.

Going back to perspective 3D, there are further shortcomings that are worth to be mentioned. For instance, for any object, a change of position in the depth direction will be perceived as a smaller move than an equal amount of lateral or vertical displacement [10]. This is known as the problem of '*display resolution*'. Also, the viewer's ability to correctly judge the height of the objects is compromised [10, 36, 47]. In order to better understand this, please have a look at Fig. 2. You will notice that it is hard to determine which of the aircrafts is flying at the lowest or the highest altitude. This uncertainty is known as the '*height constancy bias*', which is truly a combination of the *foreshortening effect* and the shrink of dimensions along the line of sight.

More in depth, the dimensional shrinking *per se* can be calculated mathematically. E.g, let us consider a point of coordinates x_e, y_e and z_e in the *eye-space* coordinate system (a.k.a. *camera-space* coordinate system). For the *x* coordinate, the result of the shrinking operation is given by:

$$x_p = -\frac{x_e * n}{z_e} \quad (1)$$

Where *n* is the distance between the *eye-space* origin (i.e. the field of view origin) and the projection plane, a.k.a. the *near clip plane*. The same calculation applies to the y_p coordinate, but not to the z_p coordinate which is always equal to $-n$.

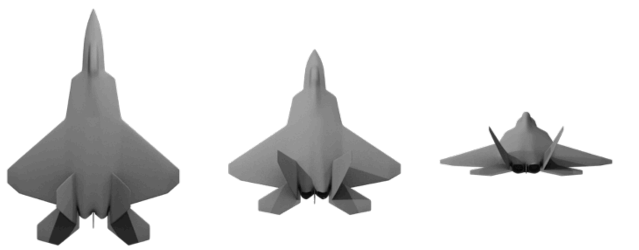

Fig. 1 The *foreshortening effect*

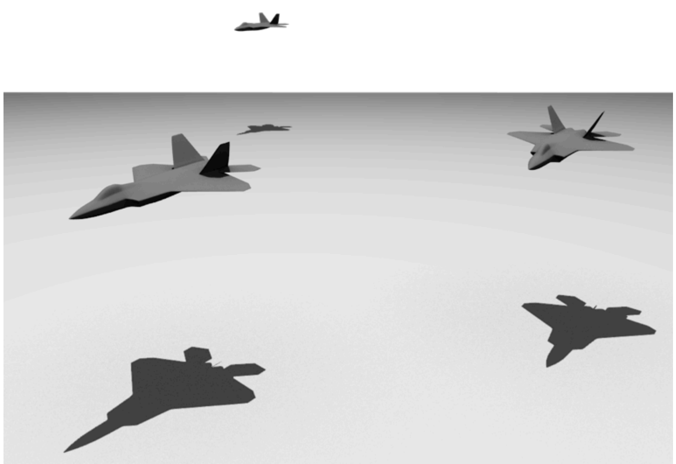

Fig. 2 In this picture, it is hard to determin which of the aircrafts is fliying at the lowest or the highest altitude. This is due to the *height constancy bias* which is truly a combination of the *foreshortening effect* and the shrink of dimensions along the line of sight. Actually, in this particulr case, all the aircrafts are flying at the same altitude.

To be honest, the *height constancy bias* does not only impair decisions on the height of objects, but also prevents reliable judgments on any across-the-line-of-site dimension [48].

4.5. *Interface cluttering*

Obtaining information from the visual subsystem is often depicted as a stream analysis. Within the analysis, a selective process known as '*attention*' is identified, which can be portrayed as a dynamic allocation of the working memory. In order to prove that visual perception is limited in performance, it has been shown that human beings can hold a maximum of three to seven chunks of information in their working memory while operating under normal workload conditions [49] (chunks are small groups of associated data). When operating outside their comfort zone, humans tend to make mistakes, especially if their attention is split among numerous items on the screen. Because of this, the *attention* tries to capture only the most relevant pieces of information. However, the dynamic changes in objects' size, shape, orientation and behaviour take up large amounts of *attention*, leading to carelessness towards the other areas of the screen [31]. All in all, the amount of information that can be easily perceived and interpreted by human operators is limited. For these reasons, *interface cluttering* (a.k.a. *visual overload*) has always been a major concern for HCI developers [33].

In a perspective 3D interface, when many objects are placed in the distance (i.e. near the far end of the scene), they take up a smaller portion of the screen than if the very same objects were positioned closer to the point of view. In some cases, this results in increased clutter. Fig. 3 demonstrates this point.

5. LITERATURE REVIEW

5.1. *Motivation*

With the current HCI model, the ATCO interface seems to have reached a threshold in terms of maximum amounts of information that should be made available to the operator at once [9, 50]. In PVDs, the information is embedded in a 2D fashion by means of characters, numbers, colours, shapes, symbols, size and other features [51–53]. However, this practice has been harshly criticised because it takes too long to the ATCO to calculate the spatial-temporal relationship between aircrafts [54, 55]. Also, this technique seems quite demanding in terms of cognitive resources [54, 55].

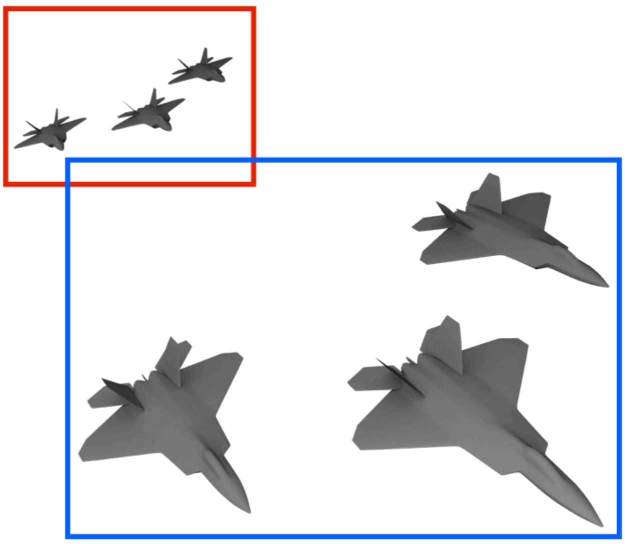

Fig. 3 In this picture, two aircrafts formations take up different portions of the screen, even if they are truly identical. This results in increased clutter for the 'red' formation (which is the one in the distance). The reason for that is the dimensional shrinking that comes associated with the perspectvice 3D interface

It cannot be denied that a substantial amount of the ATCOs work involves three-dimensional problem solving. For this reason, it has been long suspected that 3D graphics may help controllers to reduce their cognitive workload. If this were true, the operator would be able to manage larger amounts of aircrafts and still reduce fatigue, allowing for longer working sessions to be scheduled [56]. Also, a 3D interface would let designers incorporate additional meteorological and topological information such as 3D weather and terrain orography. However, perception is a delicate matter, which is involved in most of the ATC related accidents [57]. Thus, in order not to jeopardise safety, a three-dimensional interface would need to be carefully designed and validated.

5.2. *Design methodologies and evaluation criteria*

With the aim of developing and validating the ideal 3D UI for the provision of air traffic control service, many criteria have been used, namely User Centred Design (UCD), technology-driven design and Ecological Interface Design (EID)

UCD focuses on the user and makes use of a cyclic, human in the loop, validation process. Typically, the design process also includes a number of prototypes, simulations and experiments. However, the 'experimental approach' has several limits and has been harshly criticized because it takes no account for the context wherein test subjects act [58]. In other words, experiments ignore elements that are not measurable (e.g. know how, habits, preferences, social interaction, etc.), but would probably affect the subject's behaviour in a real working environment.

Technology-driven design concentrates on software and hardware prototyping, targeting performance and technological innovation.

EID differs from UCD and technology-driven design insofar it focuses on the analysis of the work domain (a.k.a. Work Domain Analysis - WDA) rather than on the end user or specific tasks. In EID, the *abstraction hierarchy*, which is a 5-level functional decomposition, is used to determine whether or not a certain piece of information should be displayed on the interface and how this information should be arranged. In doing so the designer attempts to make constraints and complex relationships that are already present in the work environment perceptually evident to the end user (e.g. visible, audible), in order to free up some cognitive resources that might be used for other cognitive tasks. As an example, the reader can easily refer to the use of *tunnels in the sky* (a.k.a. *highways in the sky*) for aircraft governance.

Overall, UCD has been the leading methodology. A few times, a complementary approach was chosen, which took advantage of both UCD and technology-driven design [59, 60]. EID was only used in [61]. In [10], an in depth analysis of perceptual, contextual and semantic factors was performed in order to categorize surveys and better interpret results.

For the evaluation phase, several criteria have been used, including performance-based techniques, interviews, questionnaires, observations and queries. According to performance-based techniques and queries the success of a prototype depends on the level of performance objectively inferred during or after the experiment. However, interviews, questionnaires and observations may unveil aspects that numerical and fixed-scale assessment techniques cannot detect. For this reason, a subjective metric must be considered a complement rather than a substitute for other metrics [62].

Occasionally, an alternate design criteria was chosen, which is the *cognitive walkthrough* [63]. In [10] and [59] this method allowed for a fast and cost effective validation process relying on theoretical concepts rather than on physical prototypes.

6. Related work

Ever since the early 90s, a large number of empirical studies have been performed on the subject of three-dimensional interfaces for the provision of air traffic control services. The experiments differed in terms of prototypes, equipment and tasks. Also, different groups of people with all kinds of expertise in ATC were involved, including novices, trained ATCOs and pilots.

In an early study from 1991 [64], Burnett and Barfield found that an altitude extraction task, as well as a conflict resolution task, had been performed faster on a (color-coded) 2D interface rather than on a perspective 3D interface. However, for a conflict resolution task, the mean response time was shorter for the 3D interface, but only at low-level traffic density (maximum seven aircrafts *per* simulation). Apparently, the very same interface provided no benefits when the traffic density was increased up to seventeen aircrafts *per* simulation. It is worth noticing that test subjects did know when a conflict was about to occur beforehand. Thus, they were only asked to choose the most appropriate solution among a pre-defined list. In practice, this task entailed the choice of a conflict resolution strategy, rather than the prediction of the conflict itself. *Post-hoc* interviews revealed that controllers did prefer the 3D interface for collecting horizontal position and heading information. However, speed and altitude were still derived from data-blocks. Also, controllers lamented excessive *cluttering* in the 3D interface.

In 1993, Tham and Wikens [36] found little difference between the PVD format and two perspective 3D formats (2.5D and stereo-3D) when tested against selected tasks. The latter led to a higher error rate for speed estimation, whereas the PVD allowed for quicker heading judgments. No difference was found amongst the three formats with regard to a conflict detection task. On the whole, the PVD format was favoured over the others. This was more obvious for ATCOs than for pilots. Finally, it is worth noticing that Tham and Wickens do not mention any use of color-coding in their experiments.

In 1993, Haskell and Wickens [37] argued that 3D can be useful "*whenever the tasks to be performed using the display are integrated three-dimensionally*".

In 1994, a study by Wikens and May [35] ascertained the advantages of a PVD over a perspective 3D interface for tasks requiring the vectoring of a few aircrafts around a mountain area. On the whole, the PVD allowed for narrower vectors and fewer clearances. Also, decisions were taken faster. The only exception was the judgment of potential penetration threats while flights were not level. In this case, the 3D format brought a little time benefit. The authors ascribed this to "*a more direct spatial extrapolation of changes [that] can be made with the perspective display*". On the contrary, "*a fairly complex extrapolation of changes in digital data tag reading must be performed*" on the PVD. Yet, this benefit was not observed when flights were level because the perspective view disrupted the altitude estimation.

Again in 1994, suspecting that the test subjects' familiarity with a certain interface might influence their performance, Wickens, Miller and Tham, compared six ATC specialists with seventeen pilots trained in ATC [65]. Results confirmed that pilots extracted the information from the PVD as fast as from the perspective 3D interfaces (both 2.5D and stereo-a), whereas controllers were quicker than pilots on the PVD. Also, controllers were erring "on the side of caution", as it happened that they rejected some requests even if these were actually safe. Finally, results were consistent with the ones obtained in a previous study, involving seven controllers and nine pilots [35].

In 1995, a last experiment was performed by Wickens, Campbell, Liang and Merwin [38]. This time, they focused on bad weather. When subjects were asked to assign a single heading vector in order to avoid a weather formation, there was no difference in the response time between the PVD and the perspective 3D interfaces. However, test subjects were less conservative with the 2D interface, meaning that they tried to vector the aircrafts closer to the weather formation. Apparently, in this case, they felt more confident in their distance estimation capability. In a second assignment, having a final destination point as a target, subjects had to clear a set of vectors in order to safely avoid a weather formation. This time both changes in altitude and heading were allowed. When relying on 3D formats, test subjects issued a smaller number of vectors. On the contrary, when dealing with the PVD format, the number of vectors was higher and trajectories were less conservative. To be onset, the authors themselves somehow discredited the results of this study. Indeed, they acknowledged having experienced problems with the stereo 3D interface, which "*had not consistently produced true and 'fused' stereo images*". Also, many test subjects said they were unsatisfied with the 3D interface because of the visual clutter. Nevertheless, the spontaneous comment of a controller showed interest toward this technology. He believed it could be used for training purposes. Interestingly, this supposition found empirical evidence when the authors observed what they called the '*asymmetric transfer effect'*: test subjects who had begun the experiment with the 3D interface, improved their performance in the subsequent trials with the PVD, whereas the opposite effect was not observed.

In 1995, Wikens declared that the overall results of his research program did not provide enough evidence to fully support three-dimensional interfaces over bi-dimensional PVDs [39]. However, he believed that the 'hamletic' question "*3D or not 3D*?" was not fully answered.

In 1996 Azuma, Daily and Krozel presented a perspective 3D interface prototype featuring:

- An interactive navigation system.
- 3D sound capabilities.
- Advanced decision support tools (e.g. collision avoidance alerts).

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Feedbacks were collected from both pilots and controllers. Pilots liked most of the features; especially the use of '*ghost planes*' to represent the aircrafts forecasted position and the visual cues underlining the presence of nearby objects. Reactions to the 3D sound were mixed: some deemed it useful, whereas others judged it irritating. Amongst the military personnel some thought that the 3D format could be useful for sharing information about enemy targets, such as aircrafts, warships, ground troupes, etc. Finally, some suggested using this kind of interface for the '*free flight*' concept. Controllers did not care about the navigation system at all (nor the others advanced features). Most of them chose a fixed viewpoint to watch the traffic from. A few were adamant that 3D interfaces were too confusing, thus, a bad idea. One controller did suggest the use of 3D sound for ground movement guidance. Again, the idea of using the 3D format for training purposes was proposed. Finally, it was hypothesized that the use of a 3D media could possibly shorten the transition time during shift changes.

In 1997, Brown and Slater questioned the controllers' ability of estimating distances and angles in perspective mode. Hence**,** in a preliminary test [15], they asked several former controllers to judge distances and azimuth angles between pairs of aircrafts in both a perspective 3D and a orthographic 3D interfaces. According to the results, orthographic projection allowed for a greater accuracy in the azimuth angle estimation. On the contrary, the distance evaluation task provided to be independent from the type of projection system. However, further drawbacks of the perspective mode were exposed:

- Objects at a greater depth tend to be displayed closer to each other, resulting in increased clutter (cf. sec. IV)
- The dimensional shrinking along the line of sight partially negated the benefits of aircrafts' drop lines for altitude comparison.

As a result, an orthographic projection was set up in the main study. Surprisingly, no test subject commented on the absence of linear perspective. The authors ascribed this to a first time experience with the 3D interface. Within the experiment, two groups of test subjects, namely the *expert group* and the *novice group*, were crossed with three types of interfaces: 2D, 2.5D (3D) and stereo 3D. The *expert group* was made up of trained ATCOs, while the *novice group* was composed of novices (i.e. test subjects unfamiliar with ATC). One of the 3D interfaces incorporated stereopsis, whereas the other was built on top of monocular depth cues only. A spatial ability test [66] failed to detect any difference between the skills of the two groups, somehow negating the results of a previous study [35]. However, clear evidence was found, in the form of answers to questionnaires, of a bias towards the use of data-blocks by ATCOs. This was done out of concerns over accuracy or force of habit, even when relying on a 3D display format. Also, a tendency to separately consider vertical and lateral separations was observed. In practice, tasks were not being performed 'integratively', i.e. exploiting the integrative nature of the 3D interface. As a result, for tasks entailing angles and distances estimation, 2D yielded to better performance. When the test subjects were asked to identify the two aircrafts flying at the lowest and the highest altitude, no benefits were found for the expert group coupled with the 3D format. Finally, a conflict resolution task showed that many trajectories had been incorrectly perceived on the 3D interface. On the whole, many questions remained unanswered: had the task been performed in a non-integrative manner because of an inadequate depth perception? Was this related to the task definition or was it due to the subjects' inexperience with the 3D format? Could they be trained to perform those tasks in a way that exploits the integrative nature of a 3D rendering?

In 1999, Van Orden and Broyles compared four types of displays: 2D top-down displays (PVDs), perspective 3D displays, stereo 3D displays, and volumetric displays (laser-based) [67]. For a series of tasks, such as velocity assessment, altitude judgement, vectoring and collision avoidance, performance with the bi-dimensional display was at least as good as with the others display formats. Also, they believed volumetric 3D to be well suited for tasks entailing the perception of "*complex and dynamic information relationships in a confined 3D space*".

In a few of studies between 2000 and 2010, Persiani, Liverani, Bagassi and De Crescenzio found 3D features to be useful for specific tasks, such as flight phase recognition and conflict detection [9, 68, 69]. Thus, they conclude: "*the positive acceptance, evidenced in the evaluation phase, shows how the increased readiness of computer graphics and virtual reality technologies can push the adoption of such techniques in the design of innovative interface*".

In 2001 [32, 42], Smallmann, John, Oonk and Cowen compared the effectiveness of representing 3D in a 3D space and 3D in a 2D for an altitude and path determination task:

- 3D in a 3D space: flight levels and flight paths could be inferred from a 3D icon moving in a 3D space.
- 3D in a 2D space: the same information was presented by means of 'analogic' symbols 'attached' to the aircraft (e.g., a dynamic bar whose length indicated the flight level).

The '3D in 2D' representation proved to be the quickest source. This demonstrated that the availability of analogical information might have a bigger impact on information acquisition than the choice of the display-format (e.g. 3D). However, the advantages of 3D graphics for tasks entailing 3D thinking and shape understanding remained unquestioned. In a later study, John, Smallman and Cowen found a combination of 2D and 3D to perform better than strict 2D or sole 3D for tactical routing [70]. The task consisted in deploying a chain of antennas across a swath of terrain while avoiding the enemy's sight.

In 2003, Tavanti, Le-Hong and Dang [50, 71] compared the performance of several ATCOs in a series of tasks entailing the use of 2D and stereo 3D display formats. Results showed that participants achieved better performances with the stereo 3D display, with no detriment for accuracy. Yet, it is worth noticing that test scenarios did not display a very deep area. Thus, the *height constancy bias* was not remarkable. Also, the authors expected the acquaintance with the 2D planar interface to negatively affect the performance with the stereo 3D interface. However, this hypothesis was not confirmed.

In 2009, a study by Tavanti and Cooper [27] revealed that ATC trainees did not foresee the use of perspective 3D for tasks entailing typical radar monitoring, such as approach or en-route air traffic control. In general, controllers showed "*distrust and diffidence towards novel and (or) 3D interfaces*". However, they suggested testing 3D against different tasks, such as the provision of air traffic control service from the control tower, the holding stack management, the traffic allocation between sectors and the training of young ATCOs.

In 2010, Cooper, Fridlund, Andel, Bojan and Hardy provided some evidence in favour of the perspective interface concept [56]. In their study, a standard training scenario was more easily solved thanks to the 3D interface. However, for some people, the very same interface was found confusing. Indeed, during the test, a couple of controllers became very bewildered about the lateral separation between two aircrafts and had a hard time trying to solve a situation which was actually quite simple.

According Cooper et al. the use of a semi-immersive 3D virtual environment resulted in both quantitative and qualitative benefits [72]. In their study from 2005, fourteen former controllers were engaged in a judgment task, i.e. the detection of critical flight levels within a certain air traffic scenario. Results showed that controllers performed tasks faster using the stereo 3D display format rather than the PVD and were at-large satisfied with the 3D rendering system. However, the experiment was based on a low-level traffic density, which critically reduced the possibility of errors. Also, qualitative results were self-esteemed.

In [73], some ATC trainers invited to examine and feedback a stereoscopic 3D interface commented: "*3D visualization could enhance controllers training as these representations are similar to the constructed mental models that the trainee seeks to develop*".

In 2006, Abadir et al. reported that their perspective 3D interface was judged time-consuming: both ATCOs and untrained subjects complained about the presence of too much information, which, according to Sternberg's similarity theory [74], "*made it more difficult to distinguish the important stimulus*" [75]. Most importantly, the interviewed ATCOs argued they "*had no difficulty visualizing the airspace mentally and therefore found 3D unnecessary for operative use*". All in all, the authors suggest focusing on more suitable areas for 3D, such as training and accident/incident analysis.

6.1. Further development: the effort toward 2D-3D integration

The complexity of the ATC task and the awareness of the pros and cons of a 3D rendering lead some authors to believe that both 2D and 3D views were needed at the same time [32, 38, 70]. A relatively straightforward way to achieve this was to place the conventional PVD alongside with a three-dimensional display. Alternatively, both 2D and 3D views could have been integrated in a multi-frame setup to be displayed on a single screen. In any case, the user would have needed to integrate the information from two different sources and balance his or her attention between them. This is the kind of process that requires a number of fast eye movements known as '*saccades*', which can be a cause of visual fatigue [76]. Also, during saccadic movements, humans are more likely to miss noteworthy events that are displayed on the screen, which is sometimes referred as '*change blindness*' [77]. Thus, they will commit more errors if they divide their attention among several displays (or frames).

A further commitment toward the consolidation of 2D and 3D views was made by the "3D-in-2D Planar View Display" project, sponsored by EUROCONTROL in the framework of the third CARE-INO program (Co-operative Actions of R&D in EUROCONTROL, 2007-2009) [61]. In this project, ten concepts were developed, trying to find the most effective ways of combining the "*3D and 2D views of the air traffic (i) allowing the controller to benefit from the mutual capabilities of the two displays; and (ii) minimizing the effort when moving from one view to the other*"[78]. Concepts were mostly implemented in the Augmented Reality Toolkit (AR-Toolkit) [79], with a maturity level corresponding to the early stages of nine-point NASA Technology Readiness Level (NASA-TRL) framework [80]. Some had been actually drawn from an earlier FP6 project named "AD4 - Virtual Airspace Management" [81]; however, the majority was derived from a two-way 'combination display', in which the project partners correlated numerous 'display techniques', such as *3D in 2D Symbols*, *Multi-Windows*, *Rapid Zooming*, *Distortion*, *Overview Plus Detail*, *In Place*, *Filtering* and *Multiple Coordinated Views*, with several 'display formats', such as *Strict 3D*, *Side By side*, *2D/3D Multi-View*, *Exo-Vis and In Place View* [82, 83]. The 'display techniques' determined how the information was rendered, whereas the 'display formats' dictated if and how 3D and 2D blended in. Regrettably, at the end of the first year, the Eurocontrol Innovative Research Advisory Board (IRAB) redirected the project. For this reason, only low-fi prototypes were developed and no time was left for concepts integration.

It is beyond the scope of this paper to discuss each concept in depth. However, we would like to comment on the first year prototypes at large. On one hand, we have really appreciated the effort toward a groundbreaking integration of 2D and 3D views. Also, we acknowledge that some early prototypes seemed quite promising, especially if coupled with certain tasks. On the other hand, we believe that some aspects that had been initially theorized were not adequately discussed later in the study. These are namely the human mapping capability, the contextual awareness and the limited attention bandwidth. In the absence of new developments, it would be hard to further comment on this study.

7. Analisys and discussion

Conventional PVDs use bi-dimensional maps and standard symbology as an interface between the Air Traffic Control Radar Beacon System (ATCRBS) and the ATCO. With the exception of the ground coordinates and the heading information, this practice involves a high level of abstraction in the traffic representation. Controllers need to interpret symbolic data, manage flight strips, interact with pilots and possibly coordinate with colleagues. At the same time, they need to stay focused on the job and maintain an adequate SA of the overall traffic situation.

It has been long suspected that the 3D format may provide a 'natural' and intuitive representation of the airspace, allowing for the spatial information to be easily grasped and processed by the operator. For this reason, a great effort has been put in creating the ideal three-dimensional UI for the provision of air traffic services. However, empirical studies have shown that fine-grained metric judgments along any particular direction are not possible in perspective 3D, leading to cognitive errors when trying to assess the objects' absolute or relative position

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[10, 32, 35–43, 47, 48]. A more precise estimate might be given by navigating the virtual environment, looking for the most appropriate viewpoint (which is often the one perpendicular to the distance itself). However, this would increase the complexity of the interaction system [5]. Similarly to what happens with the distances, it has been shown that judging absolute and relative angles may be problematic as well [15, 35, 35, 38]. In order to minimize these biases, several DSTs, such as widgets, rulers, grids, drop lines and scales can always be added to the interface [5, 15, 78, 82, 84]. However, this would increase the interface clutter [15, 38, 64]. Finally, the use of a perspective 3D camera system cuts out of the display those objects that do not reside within the camera field of view. In other words, a close up to a specific location inhibits the view of the global dataset. As a result, the controller's awareness of the overall traffic situation is reduced, possibly leading to spatial disorientation [85, 86]. Also, because the controller must elaborate both 'focused' and 'contextual' information, the overall cognitive load increases. Of course, a comprehensive view of the scene can be used, which would provide an adequate SA. But then again, this may lead to unacceptable levels of *cluttering* and *display resolution* issues [10, 15, 38, 64].

Due to the absence of linear perspective, in a 2D top-down interface the assessment of horizontal distances and angles is a relatively straightforward task. Also, there are no open issues associated with a complex navigation system and all the aircrafts are always in sight. Nevertheless, the decision making process requires the integration of information that is only exposed by means of non-spatial codes (i.e. alphanumeric data-blocks). This includes the flight level or the altitude information. In order to convert the data-block information into conceptual knowledge, demanding arithmetic must be performed by the ATCO. This kind of process is typically referred as a '*controlled'* process, because it requires a great care and must be executed sequentially. With a great deal of practice, some *controlled* processes may become '*automated'*, i.e. executed unconsciously and performed in parallel. For instance, it has been proven that the establishment of a spatial relationship between the aircrafts becomes a partially automated process when relying on the PVD [27]. This happens as a result of the extensive training to which air traffic controllers are subject and was confirmed several observing how controllers took advantage of the PVD interface over pilots and ATC trainees [5, 36, 65].

On the whole, as the '*Proximity Compatibility Principle*' by Wickens and Carswell asserts [87], whether or not a 3D interface suits a certain task depends on whether the task itself is integrative or not in space and time [88]. If the task requires the integration of multiple sources of information, performance will be best supported when those sources are displayed in close 'proximity' (e.g. closeness in space, resemblance of colour, dimensional integrity, etc.). On the contrary, if the task requires the user to focus on a single source of information, performance will be best supported by a disjoint representation. In this regard, some evidence was found that many tasks in ATC may not require integrated spatial judgements [15], which would somehow negate the advantages of a three-dimensional interface. If this were true, the design of a good interface would be made more difficult by the fact that air traffic control requires the execution of both 'integrative' and 'attention-focused' tasks at the same time.

Concluding, we believe there is no such question as "*3D or not 3D?*" [39]. The utility of a graphical interface, either three-dimensional or bi-dimensional, cannot be argued *a priori*, or in absolute terms. On the contrary, it is relative and dependent on a number of factors, such as rules, goals, perception, culture, semantics and tasks [10]. Hence, a different question must be formulated: given a certain domain, under which rules, circumstances and tasks can a particular 3D interface contribute to human performance?

8. Recommended Fields of Application

Based on the previous review, we can assert that 3D graphics can adequately convey only the qualitative aspects of the airspace, such as shapes, trajectories, orography, weather conditions and traffic layouts. In turn, these are easier to grasp, as they make sense at a perceptual level.

In this section, those tasks that suffer less from the cognitive shortcomings of 3D rendering will be identified. These are the kind of tasks that do not involve precise coordinates or heading estimations.

8.1. Vectoring under the Minimum Vectoring Altitude or throughout prohibited airspace volumes.

The Minimum Vectoring Altitude (MVA) – a.k.a. Minimum Flight Altitude (MFA), Minimum Radar Vectoring Altitude (MRVA) or ATC Surveillance Minimum Altitude (ASMA) – is the lowest altitude Above Mean Sea Level (AMSL) that can be issued by an ATCO to a selected aircraft [89]. For each airspace volume, this value is presented on the radar screen in the form of a numeric label. More detailed information (e.g. terrain orography) can be found on paper or electronic maps, which should be available at the controller's workstation. However, maps can be cumbersome, as they do not integrate the traffic information [35].

Most of the time, MVAs are extremely conservative. This prevents controllers from vectoring the traffic into large amounts of airspace, a fact that can hinder performance and worsen delicate (dangerous) situations [35]. The same occurs with prohibited airspace volumes, which are often over simplistically represented on the radar screen.

In the unfortunate event that an aircraft finds itself flying under the MVA, and requires assistance to escape, an air traffic controller would need to integrate both the elevation map and the radar image into his or her mental model, resulting in either expensive or inaccurate cognitive process. In this scenario, the temporary adoption of a perspective 3D interface, featuring the aircraft's position, heading and speed, along with a truthful representation of the aircraft's surroundings, may improve the controllers' ability to deal with the situation.

Such an interface could also be used for tactical routing in military operations.

8.2. Weather formation avoidance or escape

Bad weather is a huge contributing factor to the incidents and accidents rate for both commercial and military flight operations. For this reason it is considered to be one of the greatest threats in aviation [38, 89]. Besides jeopardizing safety, it contributes to delays, fuel consumption, passenger dissatisfaction and airports congestion.

On the radar screen, bad weather is seldom represented. Hence, controllers must gather this information from a separate display, resulting in either expensive or inaccurate cognitive process.

In an early study from 1995 Wickens, Campbell, Liang and Merwin compared the integration of 3D weather information in a perspective 3D interface against the integration of 2D weather information in a PVD [38]. On the whole, they commented negatively on the performance of their prototype. However, further research is needed to ascertain this outcome. For instance, the conclusion might change if considering the vectoring of a single aircraft of instead of a complex air traffic management situation. This could be the case of an aircraft requiring assistance in order to escape or circumnavigate a weather formation, or the one of a military tactical vectoring. The availability of new weather information thanks to the SWIM network supports this idea.

8.3. Control tower operations

When working in the control tower, controllers are instructed to gaze out of the tower's windows as long as the weather condition allows it. Hence, during daylight and fair weather conditions the Airport Surveillance Radar (ASR) and the Surface Movement Radar (SMR) are considered to be of secondary importance. On the contrary, during night shifts and Low Visibility Conditions (LVC) the radar equipment becomes of primary interest. In these circumstances, a perspective 3D interface, either of the virtual or augmented reality type, might become a strategic asset to the ATCO, especially if compared to the image provided by the radar interface, which can be sometimes over simplistic.

8.4. ATC training

In their training programs, controllers attend both theoretical and practical classes. During the course, instructors make use of books, whiteboards and other equipment (e.g. ATC simulators) in order to speed up the learning process and achieve the desired quality goals. The effectiveness of this practice has never been precisely estimated, at least not in comparison to others. On the whole, several months of training (typically more than a year) are needed for controllers to become fully operational.

In [90], Akselsson et al. have shown that virtual reality (VR) holds a great potential for ATC training. This claim was also supported by [10, 27, 56, 68, 81, 84]. For instance, a VR tool can be developed as a repository for air traffic management examples. Also, the very same tool could be used for virtual debriefing and post-hoc simulation analysis, allowing instructors and trainees to run through a recorded simulation. This tool would explicitly and unequivocally describe the four-dimensionality of the ATC problem, preventing trainees from developing different or inaccurate mental models [27] and resulting into a better trainer-trainee communication. However, further evidence is needed to fully support these claims and there are many questions that are yet to be answered. For instance, how would controllers perform because of this kind of training? How would the air transport system benefit from that? Will it be possible to increase safety, efficiency or capacity?

8.5. Holding stack management

Holding stack is a common queuing method that requires aircrafts to fly a 360 degrees racetrack pattern at a given altitude, waiting for a landing 'window' to free up. During the holding pattern, an aircraft spends one minute flying straight in a given direction, one minute performing a 180 degrees standard turn, one minute flying straight in the opposite direction, and one minute performing the final turn, which is symmetrical to the first one. In the end, the aircraft returns to its starting point every four minutes. On the radar screen, the small size of the holding track and the frequent overlap of the stacked aircrafts (and their labels) make the stack management problematic. For this reason, a pair of controllers often works together on such occasion. One will take responsibility for the stack management, releasing aircrafts from their holding patterns and possibly leading them up to a certain point in the approach procedure. The latter will guide the aircrafts to the Final Approach Point (FAP) so that they can intercept the glide slope of the Instrument Landing System (ILS). Normally, the holding stack is cleared from the bottom and filled from the top. Given that controller's perception of the stack situation is limited, this happens by design. No space is left for discretional behaviour, which makes the stack management a rather procedural task.

As a matter of fact, the stack management procedure requires the ATCO to make judgments on vertical arrangements, rather than preserve horizontal separations. Exploiting 3D graphics, it may be possible to visualize the stack in a more intuitive way, including the location of each aircraft within the racetrack patterns. In this way, controllers should be able to process the stack more effectively or even issue exit clearances to selected aircrafts other than the one at the bottom of the stack (e.g. the ones closer to the exit point).

8.6. Glide slope intersection during Instrument Landing System approach

In an instrument approach procedure, an ATCO will guide the aircrafts down to a certain point (i.e. a certain altitude) so that they can intercept the glide slope (a.k.a. glide path) of the ILS. In order to do so, the aircrafts must be heading to a certain direction with a relatively low degree of freedom; otherwise they won't be able to 'establish' the procedure. Due to the complexity of this manoeuvre, both pilots and controllers often report incidents involving ILS 'miss-locks' [84].

One of the contributing factors to the 'miss-locks' phenomenon is that the glide scope, which is basically a three-degree inclined plane extending above (and beyond) the runway, is not represented on the PVD. Thus, the ATCO must determine whether the pilot(s) will be able to 'establish' the ILS procedure based on a host of information, such as the aircraft's altitude, its rate of descent and its ground speed. This is definitely no easy task, especially when dealing with other flights at the same time.

Again, a 3D interface that features a symbolic representation of the glide slope and a clear view of the aircrafts' forecasted trajectories may help controllers to deal with ILS approach procedures.

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8.7. Traffic allocation and coordination

Supervisors and planners are responsible for the traffic allocation between and within sectors respectively. Supervisors make sure that individual sectors are not overloaded, whereas planners minimize potential conflicts and optimize efficiency for aircrafts approaching, leaving, and flying through the sector. For these tasks, a larger picture and a longer-term view are needed, with respect to the one of the tactical (a.k.a. executive) controller. As a matter of fact, the traffic allocation activity requires controllers to explore and organize the traffic from a 'global perspective', rather than to get into exact metric judgments. Thus, in [84] a perspective 3D interface of the table-top type was conceived and judged useful for balancing traffic among airspace sectors. This concept was further inspected to the extent of being depicted as a device that could possibly change the entire nature of ATC.

8.8. Continuous Climb Operations

A Continuous Climb Operations (CCO) is flight procedure allowing a departing aircraft to fly an optimised trajectory immediately after taking off, resulting in both noise and fuel consumption reduction [91]. From an ATCO perspective, it is hard to ascertain whether a departing aircraft will be able to climb above the arrivals without bridging the separation minima. This task entails the integration of several data for at least two aircrafts, including altitude, rate of climb (or descent) and ground speed. At the same time, the controller needs to keep an adequate awareness of the global traffic situation.

We speculate that a 3D interface may both speed up and improve the controller's ability to judge whether a certain CCO should be authorized at a particular time. Also, it would be better if the aircrafts' forecasted trajectories were explicitly represented on the screen.

8.9. Free Flight, Trajectory Based Operations and conflict resolution

In both the '*Free Flight*' and the '*Trajectory Based Operations*' concepts, aircrafts will set their own courses and possibly solve conflicts autonomously [5, 6, 92]. Under certain conditions, such as a Reference Business Trajectory (RBT) or a Controlled Time of Arrival (CTA), pilots will be entitled to select or negotiate their preferred path, resulting in significant time, fuel and financial savings for commercial airlines. When facing the risk of a future conflict, aircrafts will try to solve the situation by themselves, without a direct intervention of an air traffic controller. Consequently, the role controllers will shift from active control to passive monitoring, with a policy of intervention by exception.

In this context, we speculate that a 3D interface might be useful to display and solve potential conflicts, such as the ones that will be detected by future Flight Management Systems (FMS) or any other kind of Collision Avoidance Systems (CAS). Indeed, both pilots and controllers will mostly care about the inbound collision rather than the global traffic condition. Thus, an egocentric perspective might ease the conflict resolution. Also, the fact that pilots are already used to this kind of perspective supports the idea.

9. Conclusion

This paper has discussed the relative utility of three-dimensional interfaces for the provision of air traffic control services. Results have shown that any use of 3D graphics that involves accurate estimates of distances and angles must be rejected, including those tasks that strongly rely on radar monitoring, such as en-route and approach control. For these assignments, 3D will only produce detrimental effects, especially if tested against high traffic conditions.

With the aim of reducing perceptual biases, corrective measures can always be taken, such as the use of widgets, rulers, grids, drop lines and scales. Also, a complex navigation system can be set up. However, these measures increase clutter and result in higher cognitive workload.

An alternative approach is to combine 3D with those tasks that do not suffer from the perceptual shortcomings associated with it. This is what we have proposed in section 8, where several tasks have been identified, including:

- Vectoring under the Minimum Vectoring Altitude or through prohibited airspace volumes
- Weather formations avoidance or escape.
- Control Tower operations.
- ATC training.
- Holding stack management.
- Glide slope intersection during ILS approach.
- Traffic allocation and coordination.
- Continuous Climb Operations.
- Free Flight, Trajectory Based Operations and conflict resolution

We suggest focusing on these assignments for future developments in the field of three-dimensional interfaces for the provision of air traffic control services

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