CARE INO III

3D IN 2D PLANAR DISPLAY PROJECT

D4-4: COCKPIT: DISPLAY DESIGN EVALUATION REPORT (LOT NO. 5, WP 4)

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Table of Contents

1. INTRODUCTION

This document reports on the outcome of the evaluation we conducted on the concepts that were prototyped in Year 2 of the 3D-in-2D Displays for ATC project. Originally, this year was meant to focus on the development of the ATC prototypes developed in year 1. However, the IRAB re-direction in December 2007 asked us to focus examine the possibility of using these prototype methodologies in a cockpit context. Two cockpit prototypes and one display prototype were developed in year 2, and the purpose of this evaluation is to evaluate their potential utility and usability.

The approach in this evaluation was significantly different from the ATC prototype evaluations carried out in Year 1. In the earlier ATC prototype evaluations we had access to four ATC experts that help situate the display designs intended for ATC controllers, providing assessments of the utility as well as usability. However, for the evaluation of cockpit display prototypes, we have so far been unable to gain access to pilots. We had approached airlines such BA, Alitalia, and Lufthansa, and pilot training schools such as CAE. The frequent reply was that due to the current economic climate they were not prepared to release their crews for the evaluation. We were however, fortunate to be able meet with the cockpit displays manager and some of his design and development team at Airbus France. At this meeting, these Airbus cockpit display designers provided us with some very useful feedback. Although this session was brief (3 hours) and was not intended to be scientifically rigorous, it was sufficient to gain some insight of the expectation that one of the main airline developers thought of the viability of the cockpit visualisation and interaction concepts we presented.

The display prototype was not sufficiently advanced for usability testing, so we instead held in-depth qualitative evaluations with usability experts. This is known in the industry as “expert evaluation”. We employed a form of Cognitive Task Analysis that was a modified form of the Critical Decision Method. The CDM is intended to elicit expertise and decision making strategies from experienced practitioners. We adapted the technique to instead provide expert insight about the usability of the prototype interfaces. 10 experts were asked a questions that informed us about the advantages and disadvantages of the display prototype, and gave us suggestions relating to potential opportunities and pit-falls in future development. The goal of this evaluation was to shorten the future development cycle by focussing development on areas that are likely to bear fruit. The expert panel consisted of 10 Master’s in Interaction Design students from UCL, aged between 22 and 30.

The rest of this report will briefly describe the Year 2 Prototypes, the specific evaluation method and procedures, and our findings from the evaluation about the anticipated difficulties, the advantages that the prototypes have over existing methods of visualisation and interaction, the opportunities these prototypes create through either in combination or modification in some way, and the potential these prototypes have for defining the nature of future controller work by enabling new forms of work.

2. THE CONCEPT PROTOTYPES TO BE EVALUATED

This section reports the Innovative concepts which the evaluation focused on and is intended as a reminder only of the display shown to the users. For a full description of (i) the rationale for focussing on energy, (ii) each concept, (iii) their intended use, (iv) the expected benefit for the pilot, (v) the anticipated drawbacks for the pilot, and (vi) its implementation, the reader can refer to D4.2: Cockpit Display Concepts and Software Prototypes.

2.1 The Energy Management Problem

In our work last year (D4.2, D4.3) we concluded that energy management is a key task carried out by the pilots in relation to air traffic control. The management of the potential and kinetic energy of the aircraft as it approaches the runway is important to ensure that the airliner does not come in “too high and too fast” for a safe landing. For example, BA regulations state that the airliner needs to arrive at a point such as the approach or final ‘gate’ at 3,000 ft at 140kts with the right glide slope in order to land safely on the runway. What is crucial is the gradual dissipation of the aircraft’s energy over the path that leads to this final gate. The length of this path, or the ‘track miles’, is the actual distance travelled. This could be a longer curve rather than the straight line between the current point and the final gate. If this can be managed well, it can facilitate controlled descent and minimise fuel consumption on approach, in line with the concepts of Reference Business Trajectories and Controlled Time of Arrival under SESAR. Energy management underlies the coordination of many activities between pilots and ATC, especially during the approach phase. To that end, we addressed the work concept of energy management to facilitate the planning for arrival at target points in space in a timely and safe manner.

We also identified the main planning and execution activities during a flight:

- Planning (both before a flight, pre-flight, and during a flight, in-flight)
- Execution
- Re-planning to adapt to changing circumstances

The distinction between the different planning stages emphasises where we focused our development work. Through this we identified a ‘gap’ in the support provided to both pilots and air traffic controllers for reasoning about the aircraft energy levels during the in-flight planning and re-planning phases. We recognize the already advanced nature of the work by Amelink and colleagues (Amelink, Passen, Mulder, & Flach, 2003) that addresses energy management during the real-time flight control of aircraft. Figure 2.1 shows an example of their Energy-augmented Tunnel in the- sky display, reproduced from their paper.

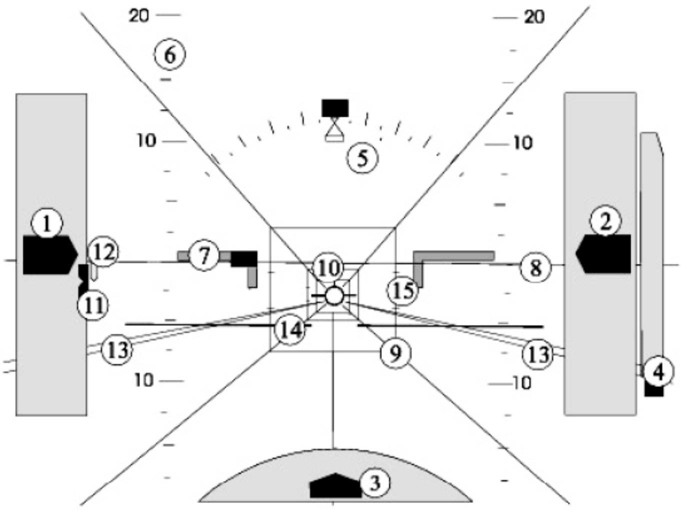

Figure 6. *Symbols found in the Energy-augmented Tunnel Display: (1) speed tape, (2) altitude tape, (3) compass, (4) vertical speed indicator, (5) bank angle and slip indicator, (6) pitch ladder, (7) aircraft symbol, (8) horizon, (9) perspective tunnel, (10) flight path vector symbol, (11) speed bug, (12) speed trend vector, (13) perspective TERP, (14) energy angle symbol and (15) speed marks (Amelink, 2002).*

Figure 2.1. The Energy-augmented tunnel Display (from Amelink, et al, 2003), designed for use during the real-time flight control phase.

2.1.1 4D Tubes and Rings

To address the problem of energy management, we developed a prototype consisting of tubes and rings. A user can manage the energy and time of arrival of aircraft at a point in space, by dragging points on the trajectory and moving the rings. The energy profile of the aircraft is presented in the graph at the top right corner of the display represented by a filled circle on this graph; it currently shows that the changes made will result in the aircraft arriving late at the desired point, and with too much energy. This means that what was once a complicated set of verbal instructions is now described visually by the computer for use by pilots or autopilots.

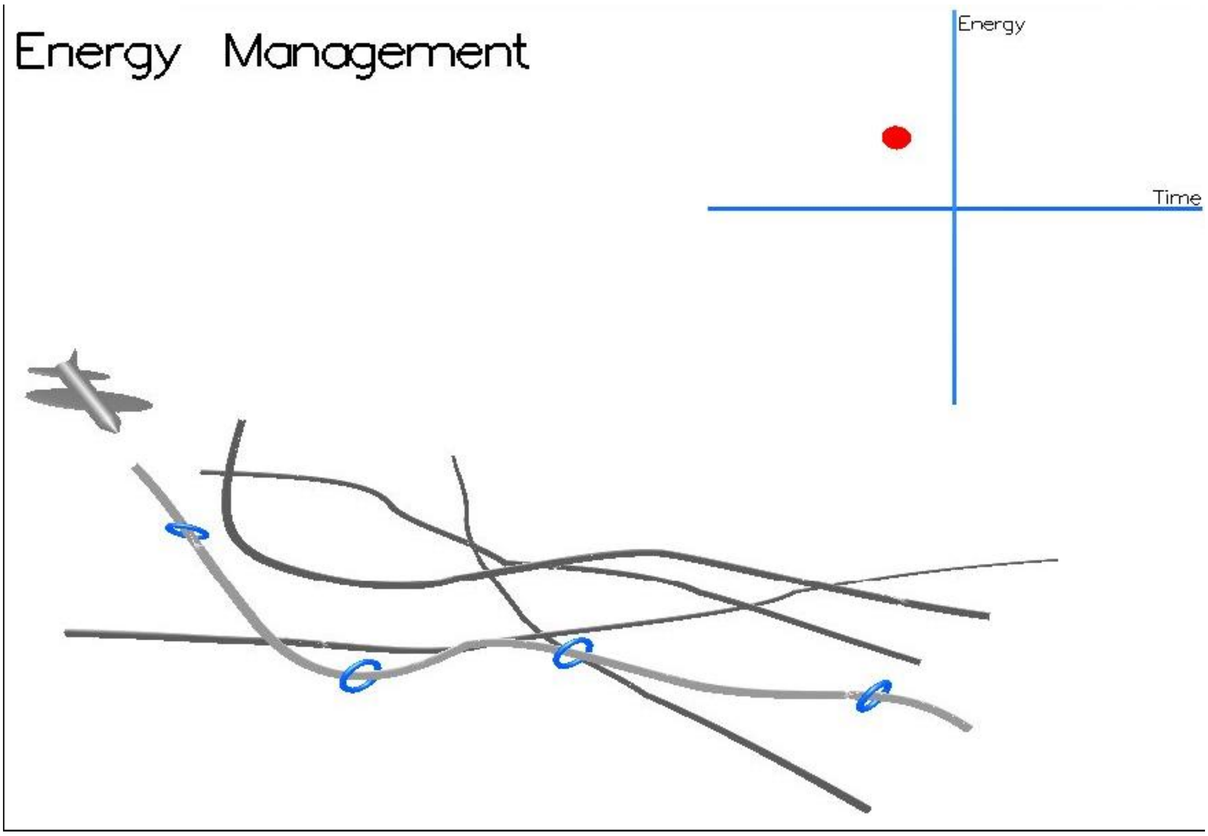

Figure 2.2. 4DET using 3D tubes and rings

These "energy rings" have an additional benefit. Pilots also need a way to determine the effects of deploying various control surfaces and drag effects – slats, flaps, gear etc – in order to devise approaches that are efficient and have minimal environmental impact. In Figure 2.2, each of the 3D "energy" rings can be moved along the future trajectory of the aircraft and will reflect the location where a given drag element should be deployed in order to estimate the energy of the aircraft and arrival time at a point in space, as shown in the above algorithm. Moreover, as aircraft performance and other flight parameters on a navigable trajectory, we can manage energy profile by regulating aviation route. The graph in the top right corner of the display immediately shows the effects of any change upon how the aircraft will meet its targets. In Figure 2.2, as an example, moving suitable waypoints on the tube will result in a variation of the flight trajectory, and thus we can adjust energy profile at the desired gate point from aircraft arriving early with too much energy in the left-hand figure to aircraft arriving in time with target energy level in the right-hand figure. By combining the tubes and the rings, controllers and pilots can manage the energy profiles in a more efficient fashion, reducing missed approaches, improving arrival time accuracy and thereby increasing airport efficiency.

2.1.2 The 'Can I do it?' display

We found that pilots often need to make rapid assessments of whether they can dissipate their energy quickly enough to accommodate a re-routing that reduces their remaining track miles. In other words, they need to determine whether the reduced distance to fly means they will arrive at the point in space and time "too high and too fast". Currently, pilots use a "3 times table" heuristic to estimate track miles needed to dissipate the aircraft's energy. The altitude in thousands of feet is multiplied by three to give the required track miles. For example, if the altitude is 12000ft, the aircraft needs 12 x 3, or 36 nautical miles to dissipate its energy. The heuristic is a rough estimate of their "stopping distance" which is often used to answer the question, "can I do it?" i.e. can the pilot arrive at a point in space at a particular time without being too high or too fast?

When pilots are flying the downwind leg of their approach phase, they commonly use TCAS to determine where the aircraft ahead of them are being turned inward to intercept the ILS. The location and magnitude of the turn can be used to determine the remaining track miles (Figure 2.3).

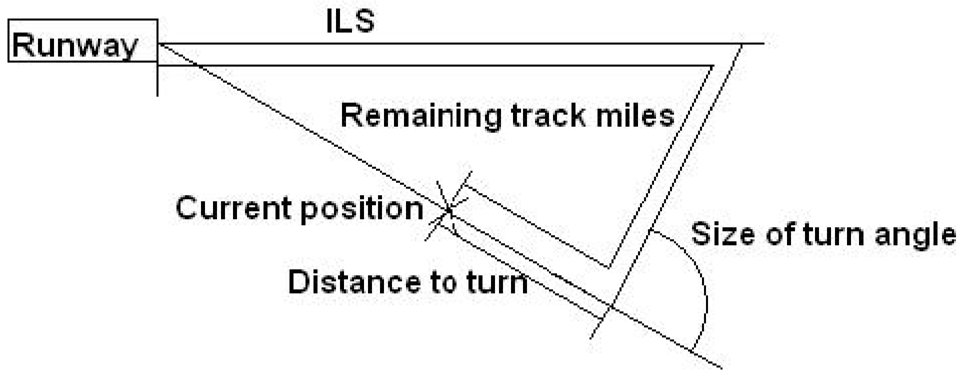

Figure 2.3. A diagram how turn size and distance to turn relate to track miles remaining

The "can I do it?" display graphs the relationship of energy to the position and angle of the turn (Figure 2.4). Turns resulting in angle/distance combinations on the middle line are perfect for the current energy. Combinations that are above the top line are impossible.

Combinations between the top and bottom lines are possible, but may require unusually rapid or unusually slow energy loss. Combinations below the bottom line will require thrust to achieve. This implementation uses variations of the 3 times table heuristic to implement.

Future implementations will reflect physics more accurately. The display constantly updates to reflect the state of the aircraft. Future implementations will reflect physics more accurately.

The permanent nature of this display means that the pilot can respond to a request by a controller without needing to interact with the system at all – they can simply read the suitability of the instruction from the display.

Note that this display does not require any of the capabilities defined under SESAR, but simply reflects the current state of technology. The simplicity of the display means that it could conceivably be implemented in the near future.

Starting Altitude	6000
Vector to airport	20
Distance to airport	10

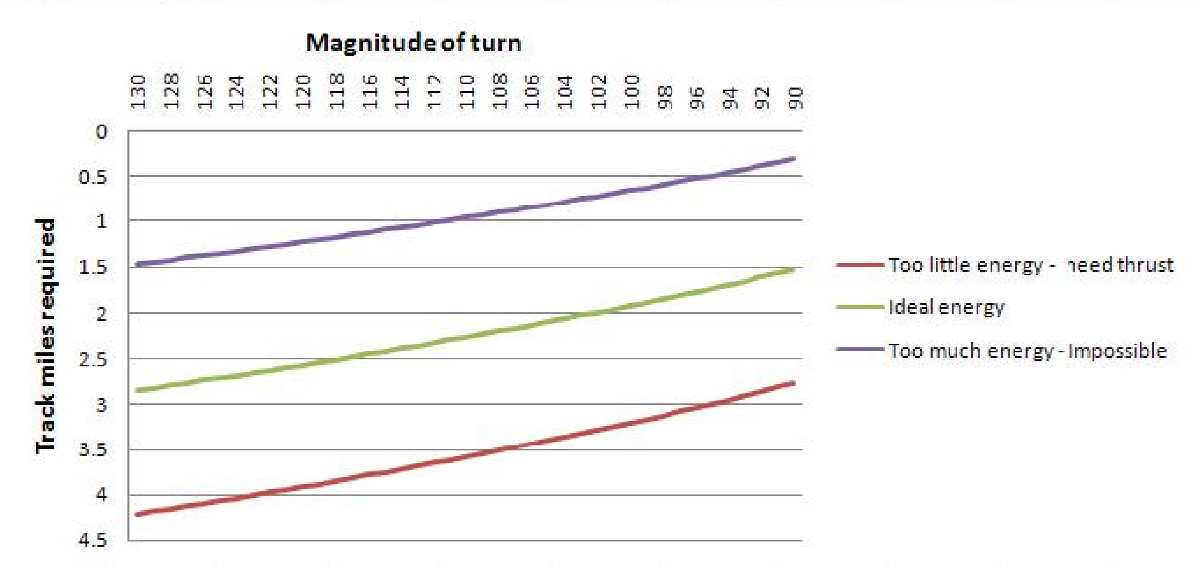

Figure 2.4. The "Can I do it?" display. The distance to the turn and the angle of the turn are used to calculate the suitability of the energy profile

2.2 Interacting with containers

Before computers, humans used their head and eyes for exploration, their feet for movement and their hands for manipulating. In the modern world, we overload the use of hands. For example, the mouse as a 2D interaction and control device is often used for all three purposes, with the function of the eyes reduces and the feet eliminated. While adaptable, it is difficult to use the mouse in, say, 3D spaces or in spaces that require movement and selection of multiple objects in depth. We applied a number of new techniques that are based on adapted commercially-off-the-shelf tracking systems (such as the Wiimotes) creating new spatial interaction techniques with various contents that allow some degree of accuracy to select points in the multi-dimensional space, while allowing users to return to the more natural division of labour.

2.2.1 Fish-tank Virtual Reality

When a person views a scene through a window, the view of the scene changes as the user moves their head. In this sense, a window is very different from that on a computer screen. Additional cues like motion parallax mean that users can perceive depth more effectively (Deering 1992). The feeling is much more realistic, and is one category of desktop virtual reality (VR). Careful use can even provide the illusion that objects are in front of the screen (Figure 2.5).

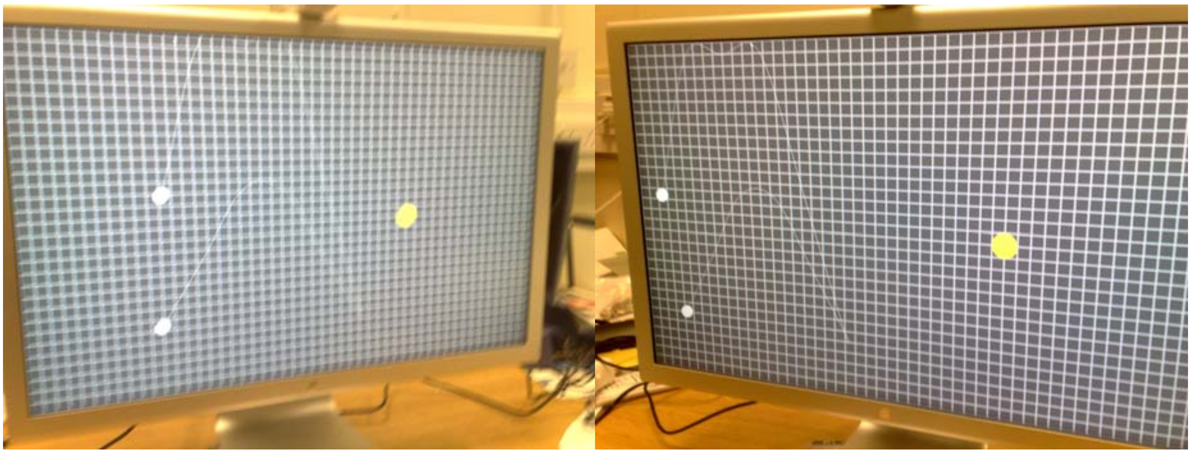

Figure 2.5. The Fishtank VR display. The two images show the same set of tubes from different points of view. The user changes the view by moving their head.

By combining the Nintendo Wiimote and the Mogre graphics engine, we created a 3D desktop VR environment that allows cheap and rapid prototyping of display and interaction concepts. We have also used anaglyph stereo effects to make the effect even more powerful. While the anaglyph technique limits the colours that can be used in the display, we are exploring recent display technologies to overcome this limitation. In the future it is hoped that we will be able to move towards visualization technologies that do not encumber the viewer at all. This concept allows the user to use head movements to explore the environment in a way that is both far more intuitive and powerful.

2.2.2 Wii Balance Board Navigation

Modern computer users do not use their feet very much. This limitation is unusual, considering the utility of foot controls. Drivers use foot pedals to shift the load of speed control away from the hands. Pilots use feet to control the rudder, organists use their feet to press pedals, and controllers may use their feet to control the radio, or not at all.

The Nintendo Wii Balance Board allows users to control the computer with their feet (Figure

2.6). Using our test environment, users can navigate through and around their environment by shifting the weight of their feet on the board, meaning that the workload on the hands is drastically reduced.

The users move forward by putting their weight forward, backward by putting their weight backward. More weight on the left foot means that the user moves left, and more weight on the right moves right.

To turn left, users put weight on the front of their right foot and on the heel of their left foot. Weight on the front of the left foot and heel of the right foot will turn right. This metaphor is similar to the distribution of weight found when a standing person rotates their shoulders left or right.

Figure 2.6 provides a pictorial description of the balance board controls.

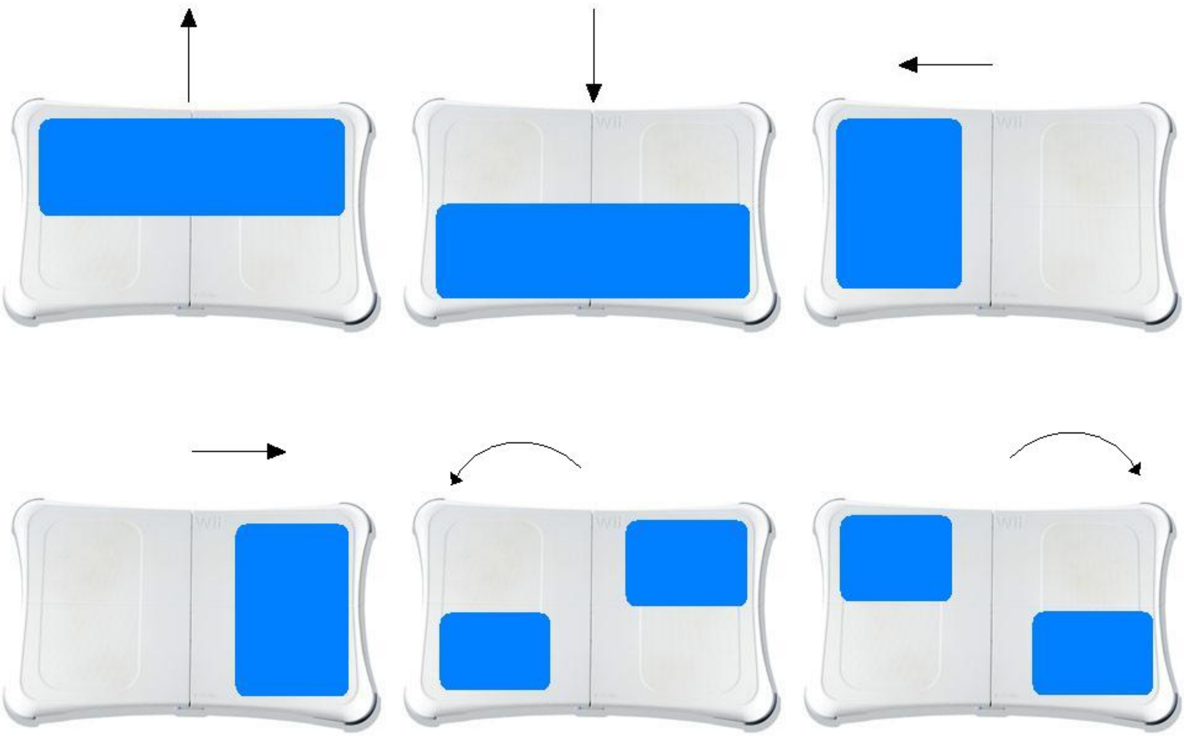

Figure 2.6. The relationship of weight distribution to motion. Leaning forward moves forward, leaning back moves back, leaning left moves left, leaning right moves right. Putting the weight forward on the right and backward on the left turns left. Putting weight forward on the left and backward on the right turns right.

2.2.3 Spaceball5000

The Spaceball 5000 (Figure 7) has a ball that allows isometric translation or rotation to control the position of the screen pointer. Twelve buttons also allow gestures for different types of on screen object selection. Unlike the other interaction technologies described here, the user’s hand remains on the desk, much like using a mouse. While the mapping between movement and the effects on the screen may be less intuitive, it may be found that the interaction is less tiring and more suitable for long periods of use.

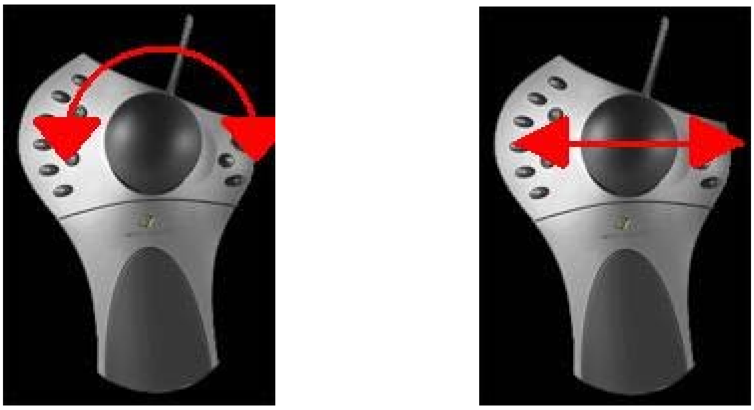

Figure 2.7. The Spaceball 5000. The Spaceball can rotate (left) around the three principle axes.

Translation is achieved by pushing the ball through its central moment (right).

In our prototypes, the user manipulates a ball in three dimensional space using the three translation axes of the Spaceball (Figure 2.7). Rotation is available, but is not implemented in any of our prototypes. In the second prototype, the ball on the screen takes on the roll of the mouse cursor in traditional interaction. user is able to select points by pressing button 1 and to change the selection targets by pressing button two.

2.2.4 Pinch and pull interaction

As much of this work is still at early stage, the prototypes currently require desk mounted devices for hand interaction. It would be interesting to examine the potential for isomorphic interaction, in which the hands are tracked in 3D space, and users interact directly with the virtual world. Although such interfaces have been studied in larger virtual environments and found to be incomplete or unsuitable (Bowman, Kruijff, LaViola, & Poupyrev, 2004), the data regarding interaction in desktop VR situations is less well understood.

In the context of the Tubes and Rings for Energy Management (Section 3.1.1) the interaction could be something like a “Pinch and Pull” (PnP) method, in which users pinch the section of the line they want to move and pull it to the new location. Such interaction could take the form of a tracked data glove, a light pen, or a new technology. We attempted to make a data-glove interaction with the P5 Glove, but found large, systematic, non-linear errors that prevent the kind of precise needed in the desktop VR scenario. We have begun development of a stereoscopic tracker that might allow this kind of interaction.

3. THE EVALUATION APPROACH

3.1 Utility Evaluations

The utility of the energy management concepts were evaluated in a meeting with Airbus. There was no precise method employed, rather the concepts were presented and demonstrated, and the participants in the meeting provided feedback.

The utility of the designs will be systematically explored in evaluations with pilots from Air France, to be added to this report later.

3.2 Usability Evaluation

The interaction prototypes are not sufficiently advanced for utility evaluation with users. It is difficult to obtain opportunities to interview expert pilots and controllers, and these chances would be wasted if the users are presented with a low quality prototype that may be rejected because of usability, as opposed to utility, limitations. To this end, we performed a usability evaluation that might allow us to perform a more complete utility evaluation later this year.

Two separate concepts were evaluated: The viability of the display and interaction metaphors, and their usefulness in a simplified version of the Tubes and Rings for Energy Management (Section 3.1.3).

The first virtual environment consisted of the “Skill tester” display shown at the EUROCONTROL INO Workshop 2008. Users see a green helix on a ground plane that intersects a standing human figure. (Figure 3.1). Users can move a ball in 3D space using the Spaceball and can navigate using the Wii Balance Board. The virtual world is displayed in the desktop VR environment with anaglyph stereo. The environment appears lit with vertically incident lighting and the objects cast realistic shadows.

The second virtual environment is a simplified version of the Tubes and Rings for Energy Management prototype discussed in section 3.1.3. Although the initial prototype used tubes, lines require much less processing power to render, and as such, if they are sufficient for perception and interaction then they would be preferred. There is no attempt to graph

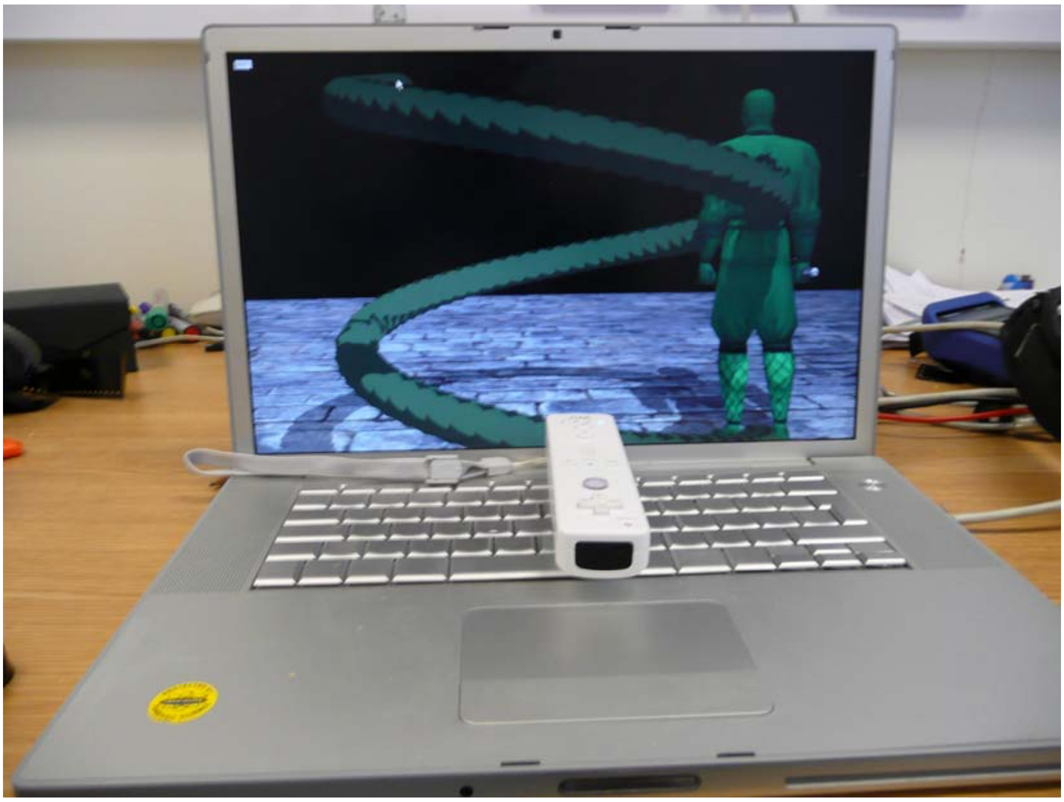

Figure 3.1 The 3D Virtual World Prototype

energy or arrival time, since the focus was on the usability of the VR environment and the interaction methods. This display is shown in figure 2.5.

The 3D-in-2D concept calls for the presentation of general 3D views with precise 2D views as support. This is likely to produce significant background visual nose. To test the effect of background visual noise, the there was a backing grid of dark grey squares with light grey lines.

Users are able to manipulate the lines with the use of the Spaceball, and the prototype is presented in a desktop VR environment with anaglyph stereo. The environment is only lit with ambient light, and there is no attempt to produce shadows.

The experts were also asked to speculate about the possibility of PnP interaction, and whether that would be of significant benefit.

We hoped to learn from these prototypes if:

- The desktop VR environment was compelling, reliable and useful
- The three dimensional effect remained in the absence of a ground plane and lighting effects

- Three dimensional tubes are necessary, or if dimensionless lines are sufficient for spatial tasks
- Background noise will have an effect on the perceptual experience
- The Spaceball was an effective 3D manipulation tool
- The PnP design was worth implementing
- The balance board interaction system was a useful addition

EVALUATION METHOD

In this section we describe the methods and procedures we used in the evaluation.

The controls and containers described in section 3.2 are not mature enough for evaluation with users, and doing so would require significant investment of resources that may be misdirected. The goal of this evaluation was to identify flaws in the current designs and to identify improvements that could be useful. We also wanted to examine the potential utility of the PnP (Pinch and Pull, Section 3.2.4) concept. To that end, we evaluated the display with usability experts, in the form of MSc students from the UCL Interaction Centre (UCLIC). Evaluations were carried out individually with each of the ten participants in a quiet room at the UCL campus. Participants were presented with two separate implementations of the desktop VR environment, and briefed on how to use them. The setting for the evaluation is illustrated in Figure 3.2.

Figure 3.2. Setting of the evaluation

3.3 **Subjects**

Subjects were 9 MSc students and one graduate from UCL Interaction Centre (UCLIC). There were 5 females and five males, aged between 22 and 35. Participants were recruited by email, and were paid for their participation.

3.4 **Procedure**

We carried out the evaluation using a semi-structured, open-ended interview technique. In this section, we explain the principles that guide the design of this evaluation.

Step 1: Play and explain

Participants were invited to explore the each prototype in detail, exploring the visualisations and interactions available. We (1) explained the tools being presented, (2) what they were designed to do, hence some operational context and purpose of the device, and (3) hands on practice that allows the users to explore the interaction capability and limits of the tool. Appreciating the context and purpose of a tool provides the evaluator with a frame of reference for assessing how well the tool will be able to assist a user in performing that task. Due to the specific constraints of this evaluation, it was necessary to give the expert some time to familiarize himself or herself with the interface, and time to consider in a principled way, the effectiveness of the interface. We also explained that, although planned, there is no operating interaction device working with this yet, but consider devices such as light pens, data gloves and other devices that support gestural interaction that could be used to implement the concepts.

Step 2a: Expert Review of Interaction Issues

In this step, the intention is to understand the strengths and limitations of the different interaction devices to control tasks such as pointing, dragging, pulling, picking up, manipulating a particular type of object vs types of data. In this step, we were interested in determining from an expert evaluator’s perspective. We were especially interested in problems with *learning* to use the prototype, since this is a useful metric for judging longer term performance from short evaluations.

(a) whether it was hard to learn to use or was really simple,

(b) what made it hard to learn to use it,

(c) what could make it easier to work with

Step 2b: Expert Review - reflection on interaction issues

In this step, we carried out an analytic evaluation by asking them to reflect on their experiences in interacting with the interface. To assist the expert in articulating their insights, we asked them, as experts, what kinds of difficulties or problems they (the expert) would anticipate a novice user is likely to encounter. We also asked them what mistakes they, as experts, would anticipate a novice or someone with less experience will be likely to make.

Step 3: Expert review of visualisation issues

We are aware that there is already a lot known about the limitations and capabilities of 3D visualisation reported in the literature, and the extent to which they can be made convincing, perspective problems, parallax problems. While they are important, they are not the issues of primary concern. Instead, in this step, we are concerned with the informativeness of the visualizations. Issues include:

(a) How informative were the 3D presentation of the aircraft tracks?

(b) What kinds of information could be sensibly or advantageously incorporated into the display?

(c) Specifically looking at our display, what in the 3D display works well, e.g. able to distinguish values, able to see trends or patterns, able to see conflicts readily.

The whole procedure took approximately 30 minutes per participant. Interviews were recorded with a video recorder, and notes were also taken to highlight important points and record information.

Table 3.1 summarises the questions we used as a guide for evaluating the usability of the various interaction and visualisation aspects of the prototypes.

For the Spaceball in general	Was hard to _learn_ to use or was really simple,
	What made it hard to learn to use?
	What could make it easier to work with?
Specifically regarding selecting a point,	Was hard to _learn_ to use or was really simple,
	What made it hard to learn to use?
	What could make it easier to work with?
Specifically regarding dragging a point	Was hard to _learn_ to use or was really simple,
	What made it hard to learn to use?
	What could make it easier to work with?
For the balance board	Was hard to _learn_ to use or was really simple,
	What made it hard to learn to use?
	What could make it easier to work with?
Concerning the Pinch and Pull concept	What kinds of difficulties or problems would you anticipate that a novice user is likely to encounter?
	What mistakes would a novice or less experienced user is likely to make?
Concerning the Visualisations presented here:	Was the display good?
	For the track information we are intending the system to be used for, is the 3D visualisation informative?
	What kinds of information could be sensibly / advantageously incorporated into such a display?
	Specifically looking at our display, what in the 3D display works well (e.g. able to distinguish values, able to see trends or patterns, able to see conflicts readily ...)

Table 3.1 The probes presented to participants

4. RESULTS AND ANALYSIS OF THE EVALUATION

4.1 Utility of the Year 2 prototypes

Since we have been unable to secure the services of pilots to evaluate the utility of the Can I Do It (CIDI) display, we met with Airbus France to discuss the display's potential. While they do recognise that energy management is a significant problem, and that missed approaches are a problem for many pilots, they felt that the primary problem was a failure on the part of controllers to understand the energy constraints of aircraft.

4.1.1 The Tubes and Rings for Energy Management

While Airbus felt that the prototype was interesting and informative, they said that it was mainly a tool for use by a controller.

They also expressed concerns about 3D displays in general, since a 3D view that cannot be verified by both pilots at once is unlikely to pass the certification process.

4.1.2 The Can I Do It Display

They argued that the display would not be useful in a cockpit because pilots do not want a separate instrument for this problem – they want energy information integrated into a central display. To this end, they have developed a set of "energy circles" that provide the same information as the CIDI display without requiring a separate tool.

Airbus mostly felt that the primary advantage of the CIDI display would be to help controllers, rather than pilots. Communication with Vu and Mark B. suggests that there is a solution already worked out for this problem – we should look into that more closely before pursuing this display with controllers.

4.2 Usability of visualisation and interaction methods

4.2.1 The Spaceball 5000

In general, the users liked the Spaceball, finding it easy to learn and easy to use:

User 1	"When you get used to it, it's kind of like a mouse."
User 2	It was easy to learn.
User 3	"I need to find some way to get a grip on the ball" - the most comfortable way isn't intuitively obvious.
User 3	[Would a novice user make any mistakes] "No, I think it mapped quite well. When I moved it, it did go where I wanted it to. It was very direct in, you want it to go there and it went there straight away, there's no time lag so that's fine, you could see because it's direct manipulation, there was no "I wonder if I've put it where I wanted to. It very much went where I wanted it to go."
User 3	It would be easier if it were a lightweight thing that you could pick up and move it with you. There are all these opportunities to move your head, but you have to be able to reach the ball.
User 3	Spaceball lifted of the desk when participant tried to pull up. Not immediately obvious that you need to keep your hand on the board.
User 4	I think it would be easy to learn to use, it's just that I'm not used to it so it would take a while, but that's the same as for a mouse. I mean when I used a mouse for the first time it took me a while, I suppose, to learn it.
User 4	It was not easy to drag where I wanted something, but I think I

	would learn in a week. I would be quite proficient I would say.
User 4	Without [the experimenter] some people might not actually understand that this is a control device. It doesn't have any obvious affordances.
User 5	It was pretty easy to grab the points.
User 5	It was pretty easy to move the lines where I wanted them to go. It all worked like I would expect.
User 6	Once you'd grabbed a point, moving it around was easy.
User 7	I don't have anything to base it on, but it was difficult to get over my initial feelings that it was hard. But then it was easy.
User 7	That was very simple. You could see the connection and where it was going, yeah.
User 8	The stiffness of the device, having to move it around is not so easy... Because it's not moving around, it doesn't really feel intuitive. I would like it if it was more like a mouse
User 9	I thought it was easy to learn to use. I thought the ball was quite intuitive, but I wanted to be able to twist it as well.
User 9	It didn't seem to be a problem.
User 9	That was fine, there didn't seem to be any problem. The fact that I was just playing, I can't be sure if it was that accurate, but it seemed to respond the way I would expect.
User 10	It was not hard to learn, the mapping is very natural

One recurring problem was the tendency to rotate the ball when using it, rather than pushing through the centre of mass.

User 2	Initially it was a little hard, because I felt like I wanted to turn it. Because it's round, it kind of make you want to treat it like a ball. Whereas if it had been kind of a linear thing I would have mapped it to linear motion.
User 3	Participant rotated the ball instead of pushing through the centre.
User 5	I had trouble learning that it is not a joystick. You need to remember to push rather than rotate. Once you've got that it's easy
User 7	Why is it a ball? Why does it rotate around the centre?
User 8	It was slightly harder to use because I'm used to [rotating around the centre] but once I worked that out, yes, I would say it was better because it maps to 3D space.

Users also reported frustration with the nature of the buttons:

User 4	The worst part was the placement of the buttons, because I would expect them to be - I don't know because it seems that I should click it with [my little] finger, which is quite awkward. So

	this is quite difficult. If you are moving the Spaceball, if you are controlling something, and at the same time you want to do some precise clicking, how would you go about it? This is not really a good position [for the buttons] I would even expect to be clicking with my left hand. Especially if I were performing some precise tasks. Because since you are moving your whole hand [to control the Spaceball] all your fingers are actually moving. If you have a mouse, you move your whole hand, but the buttons stay constant relative to your fingers.
User 5	Also moving your hands off the ball to press the buttons is quite difficult. I would like to maybe use my left hand. It breaks the flow.

In some cases the users indicated dissatisfaction with the Spaceball, but this was most likely caused by deficiencies in the visualisation.

User 3	The first time I used the Spaceball, I made the mistake of moving too far forward, and the ball was in front of the point. There was no feedback to say that you'd picked the point up. That could be a problem in PnP too. You don't get the same thing when it's too far behind, because you can see the point in front of the ball.
User 7	Initially it was hard to select a point. I understood it was a 3D space, but sometimes the technology wasn't good enough for my mind to understand where that ball was in 3D space. If it was a smoother experience I think it would be much clearer.

4.2.2 The Wii Balance Board

The balance board was also popular with the users.

User 1	Cool
User 2	It was easy to use.
User 3	Going forward and back was easy, and going left and right was okay, because that kind of, um, maps with your natural movements.
User 4	It was really easy. I was basically doing what I would do in real world. If you were strafing left and right, that's kind of of what you would do. Going forward, backward, that was straightforward. The rotation - even though the mapping was not so straightforward, but I got it the first time so it was really easy to learn, because it kind of felt natural. That was easy, I would say, yeah. It was quite natural, like if someone would ask me to design a tool to allow you to navigate in a 3D environment, I think I would be thinking about something really similar, for forward, backward, the rotation is a bit more difficult. But like I said, when I saw you doing it, I got it straight away.
User 5	I really don't get how to do it, I'm not really good in orientation. I just forgot the commands
User 6	It was quite easy to learn because as soon as you put your feet

	on it, the idea of moving forward is common sense. It's what you do.
User 7	Speed is an issue. It would be good to move faster.
User 7	This is really easy to use. You could learn it easily; there are only a couple of things to do. Because I've done snowboarding, I've always turned with that particular movement.
User 9	I found it quite interesting using the board and controlling it. And I'm not particularly well coordinated, so I don't think it was too difficult.
User 10	It was a lot of fun using the board to explore the space

Most of the users considered rotation to be the most difficult aspect of using the balance board, with most users reporting difficulty coordinating the use of their feet.

User 1	But the one where you had to go forward with the left and back with the right, or vice versa, I felt that I was going in the opposite direction to what I expected. I expected to go anticlockwise, and it span clockwise. So it actually operated in what was counterintuitive to me... There was no obvious direction of which would have been which. That's something that, once you'd done it a few times, you would learn. It's just that, to go left, it's really obvious that you go left, whereas to steer around and its one forward and one back, there's no indication of which one that would be.
User 1	it was harder to learn than the Spaceball, because your left and right foot had to do different things. Going forward and back was easy, and going left and right was okay, because that kind of, um, maps with your natural movements. Having to turn meant doing different things with your feet.
User 2	In a stress situation where things are happening really quickly and you haven't got time to think, if both feet are doing the same thing that's a lot easier to remember than trying to remember which foot is supposed to go forward and which is supposed to go back.
User 3	[Rotating] is not really intuitive.
User 3	It might be easier to point both feet in the direction you want to turn. Like when you're driving, both hands turn in the same direction, and you kind of point where you want to go.
User 3	Maybe if you twist your feet to both one side or the other, it might be better.
User 3	The participant turned to look at something off-screen while keeping her feet on the board. She looked back and had moved a long way by accident.
User 5	I can't really understand how to turn... It was very hard to learn to use. It was not the way that I would normally move my feet. It was a lot for me to remember I would rather just [swivel my feet in the direction I want to go]. It's like when you drive a car, you point in the direction you want to go.

User 5 Twisting was a bit harder, because that's not how you normally turn. You'd fall. It was perceptually easier to use the translation.

User 6 Takes me back to snowboarding, that does.

User 7 Relative to the ball, it was harder, because you have to coordinate both feet. If you were able to turn using just one foot, that would seem more natural.

User 7 The Wii board you shifted your weight forward to move forward, you shifted it left to move left. I had to be instructed in how to turn in place. I didn't have a problem with it because I'm a dancer, and you do make that gesture to turn your body on the spot, but I still needed it explained to me. I probably wouldn't have done it on my own.

Two users reported the need for a “dead zone” in which the board does not register small amounts of feedback.

User 1 It was hard because there was no dead point, you’re always moving forward or backward. Easy to learn though.

User 9 I couldn't let my feet rest on it, because it would react to that. It needs to be able to carry the weight of your feet without reacting.

4.2.3 The Pinch and Pull Concept

4.2.3.1 General Usability

The users were almost unanimous in their support for the concept:

User 2 I don't think someone would need to learn to use it, because it's what people do with their physical bodies.

User 3 It would be better and easier to learn.

User 4 That would be way easier, because that's natural, yeah, they will not have any input device, I don't think they will feel like they have any tool, because the data glove is quite unobtrusive, so I think that will be quite natural, and after five minutes people will forget that they actually have an input device. They will think that they are actually directly manipulating the objects. People are used to manipulating objects in the real world by just using their hand and just moving things around

User 5 That would be really good.

User 6 That's a good idea, cool.

User 7 I think that would be much easier. It's the directest manipulation you could possibly achieve.

User 8 Cool. Would you get visual feedback?

User 9 That would be really interesting

User 10 [While thinking about the Spaceball] I'm just thinking if there's a way to manipulate the tool directly in 3D. Maybe you could reach in and grab it like a 3D version of a touch screen.

4.2.3.2 Feedback

They did, however, feel that more feedback would be needed, in order to avoid the problems found in the current visualisation:

User 6 If you have some kind of tactile feedback it would be really easy, just like manipulating something in real life. With the ball, you have to learn how to handle that, but if it's direct and the points on the screen map to points in space it would be easy to learn to use.

User 8 As long as there was feedback given, I don't think it would be hard to use. You want feedback given because otherwise it would be hard to use. Obviously you would want tactile and visual because you are doing a 'physical' task in this virtual space. Even if you have a visual feedback I think a novice would be able to use it, like you see it squeezed in, or you see it change colour.

User 10 You might need to provide some kind of tactile feedback, like a vibrate, some kind of feedback so you know you've got it.

4.2.3.3 Occlusion

Users were also worried about the hand occluding the screen.

User 1 "You could move your hand somewhere else and show a virtual hand on the screen. That way you could move behind things. Since you aren't actually touching the screen, I think it would be better to have a virtual representation of the hand. If you have a cursor, it won't matter where your hand is."

User 2 If you have got two lines and you start moving them around with your fingers, you're going to have the problem of cutting into things with your hands.

User 3 Is occlusion a problem in 3D?

User 6 The first time I used the Spaceball, I made the mistake of moving too far forward, and the ball was in front of the point. There was no feedback to say that you'd picked the point up. That could be a problem in PnP too.

User 7 "You're going to have the occlusion problem, because your hand is going to hide the point you are reaching for, and that's something that doesn't happen with a mouse... A mouse pointer is tiny, so you can see what's around it. It's way smaller than your hand. You start reaching for things; you're going to have some trouble. "

4.2.3.4 Accuracy

User 4	Fine manipulations might be a problem if the system isn't accurate. It depends how big the display is, how small the targets are. If the targets are really small and you have to do some fine manipulation with your fingers it might be problematic working out which of those items you want to actually select. Maybe it would be good if you were able to zoom it. For example like a Mac - with a very information dense display, then you would probably like to do something like an IPhone, to zoom with a gesture
User 6	Maybe changing things around could be difficult.
User 7	I think the problem would be the same as I already have. Can you see this 3D hologram type thing in front of you well enough so you could work out where it was in the space? Because, if that isn't clear enough, then people will be moving their fingers all over the place trying to grab hold of it.

4.2.3.5 Fatigue

One user expressed concern with pinch and pull use over a long period of time.

User 1	"[It would be easier to use] for a short time. Your shoulder would start to get tired after a while. But for interaction, that would be much easier. Because the mapping [on the Spaceball] of how hard to push and pull to get the distance right is really hard to learn. It seems to jump suddenly – I pull and 'what happened.' It would definitely be easier."

4.2.4 The Desktop VR environment

4.2.4.1 The 3D environment

General impressions were good:

User 1	"It's beautiful, it's wonderful"
User 2	It was quite fascinating the way that you got the 3D effect, that was quite nice,
User 3	[The first prototype] was very compelling. It really felt like 3D.
User 4	I liked the ability to see different perspectives, to look at it from many different directions
User 4	It's quite real, quite vivid.
User 5	In this case, it was really three dimensional. Like, I had the 3D sensation very strongly.
User 5	It feels like real 3D, especially [the spiral]
User 6	I liked the first one definitely; you could see the pipe in 3D. The colours were a bit boring. I was a little bit confused by

the red green. It was a little difficult to use initially.

User 6 It was good, it was clear, you could see the spiral going around; you got a sense of size. It was more immersive.

User 6 It's good, it's enjoyable.

User 6 It's very interesting. It's not too much of a problem, but it's not entirely comfortable.

User 6 The first one seemed clearer.

User 7 It's fascinating stuff. I'm excited to see what the end product of this stuff will be in the future.

User 7 Without a doubt, moving the head was a useful feature, because it helped me understand the space I was in... You have this whole big space with the freedom to explore and experiment which you don't have with computers. The exploration of space and the movement, direct manipulation of items.

User 8 I liked being able to move my head, but I want to be able to rotate the head.

User 8 It is convincing.

User 9 It's cute... The first one was good. I wanted to play with it more and I was disappointed when we had to move on. The second one I struggled with a bit, it was a bit difficult to tell which line was in front of which. I wouldn't say I found it an easy thing to see... I liked being able to move my head around the whole thing. I think it would definitely be useful - it depends on the circumstances, but I can't see why it would hurt.

User 10 I think it's easy to learn to use. The movements are very natural.... The first one, you could see very clearly that it was 3D... I found the way of moving with my feet was a really good metaphor. It's normally how you move around space, so that's good.... The view is very good.

However, some users felt some discomfort:

User 2 [The glasses] "do make you go slightly cross eyed when you take them off. Like you've had a few... but I felt that my vision was slightly off, as I said, it made you feel a little bit drunk. It might be that I've got quite bad eyesight - with glasses on top of glasses... It's hard to say. I also found that my right eye became really dominant, and I was kind of by the end, only using my right eye.

User 3 The glasses are certainly a problem for anyone who wears glasses. Obviously, because I haven't tried it with contact lenses instead of glasses, I can't speak from the other perspective of what it would have been like. But definitely, if there were an option to have it without any glasses that would be great.

User 6 It feels a bit strange, a little uncomfortable. The red one seems to be making me feel a bit funny. I realise that I use my right eye more and my left one less, so that might be why.

User 1 “The glasses are kind of a problem. They’re a problem because they screw up the view when you’re looking around the rest of the room. It would be good to have glasses that are 3D when you’re looking at the screen, and are clear when you are looking around the rest of the room. Polarized lenses would be fine.”

The only suggestion was for a more realistic horizon:

User 5 The ground doesn't look 3D because it doesn't finish at a horizon, it just stops.

User 8 I would suggest you have more things along the horizon, instead of just a blank wall.

4.2.4.2 The Simplified Trajectory Manager

The user experience was not generally as good for this prototype:

User 1 “It helps getting right behind the ball and coming forward until it covers the point.”

User 1 “The visualisation is informative until the lines cross [in 2D, not 3D] then you can’t tell whether they intersect... You’re going to have to keep looking like this [moves head to get different points of view]. It wouldn’t be a problem if the computer was able to display intersections, or near intersections, as things in a different colour. It’s going to be obvious when they’re a long way apart, but when they get closer you’re going to need more information.”

User 1 Had difficulty finding the correct point in space – ball in front of point.

User 2 [The user seemed to have difficulty determining the position of the ball in space relative to the target points - both in front and behind.]

User 3 [On trying the task a second time] You can only really see the altitude, you can't see the separation in like [gestures along the axis out of the screen] I can tell whether it's behind or in front, but it's hard to be accurate. I can't place one line so it exactly crosses over another.

User 3 I let them cross over and it didn't really tell me that I was doing anything wrong. It was visually obvious though. It would be useful to have more information.

User 3 I liked that it's simple and clear, it's not cluttered. It just gives you the basic information that you might need.

User 3 It's obviously quite clear at the moment

User 3 Yes it was informative. You definitely got the feeling that it would tell you when one aircraft was in front of another - you could check separation in all dimensions.

User 4 [Is it informative?] I would need some domain knowledge to be sure, but I would say that having those lines is enough to detect some possible collisions. I think it's enough if you can distinguish two lines and whether you can locate them in 3D space. With more planes it might be really complex, and then you might want to be able to actually rotate the plane or just see it from all different perspectives.

User 5 I found it more compelling than the [first prototype] because it was more simplistic. The lines are very clear. The other display did not seem very real.

User 5 It was easy to tell when the lines were conflicting or not conflicting. [Tries the display again] Right now, no it's not easy to know when they collide, because when the lines are crossing in 2D space, they are quite hard to see. The closer they are, the harder it is to see, especially because they are thin lines.

User 6 I couldn't really tell if the lines were crossing or not.

User 6 I didn't necessarily see the right information. It was very hard to see the 3D.

User 6 It's very difficult to select the points on the line. I can't locate the ball in space.

User 7 I've got one line and another line; do I know that they are separate? Yes. Because I can immediately tell they were two different lines, one in front of the other. [After having another go] At that point I can kind of tell I've come forward, because I know I've come forward. I can kind of see this line is coming over the other line, but it's not quite clear enough to be precise. Yeah, I can see well enough to tell when they definitely aren't close.

User 7 The depth is the most important thing here, so different ways of indicating when things are closer or further away. Doing that with 3D glasses isn't quite enough for beginners. The lines getting bigger as they get closer would be good. Maybe bigger and lighter as it gets close to you?

User 8 I can see the 3D effect, but I also see a trace - it's not really 3D. It's not as convincing, the nearer one looks a little closer, but it's not as convincing. [Experimenter moves screen closer] Yeah, that's better.

User 8 The issue I have is that I can't see when these two lines intersect. For air traffic control you want it to be more apparent than looking at these tiny lines and wondering "Did I make it, did I not?"

User 9 That looks weird. It totally looks like I'm closer to [the front point] than [the rear point]. It's hard to tell.

User 10 It doesn't look very 3D... The ball on the screen covers the point; you can't tell if it's in front or on it. What I do is start behind it and come forward until it disappears. That's the only way I can do it. I can see it if I move my head a lot, but it's not easy to do.... I can't really see if they are crossing. I can't tell if they are touching in 3D.... No, it wasn't informative. It was so hard, and even at the end I wasn't sure if what I was seeing or what I think I was seeing was accurate.

Users felt that the grid was distracting:

User 4	The grid gives too much noise, it's too dense.
User 6	The display wasn't much better than a normal display; it was hard to see things. The grid lines didn't add much.
User 8	I think what threw me off was even though these two trajectories were in 3D space, the way the grid was set up behind it, it kind of conflicted with it, and it didn't feel like a 3D space.

They also felt that the lack of addition 3D cues, especially the dimensionless nature of the lines, was a major problem:

User 1	The small balls should change size more with the distance
User 1	Novices wouldn't realise that the trajectories are actually 3D trajectories, because they don't change size when they come closer to you. There's no shadow, texture, colour changes as they come closer to you, so that took me a while. The other problem is the trajectories are really thin. It's really eye-straining using them over more than a couple of minutes. For this kind of interaction it's got to be much more friendly. The kind of lighting, texturing and size that was in the first prototype was better.
User 2	[Did you find the 3D informative] The first one yeah, this one no. That's because there was no change in colour and texture and stuff.
User 3	The 3D is useful, but with my eyesight... I think you have to have it, but I think that for someone with eyesight like mine it would need to be a bit improved so that it wasn't quite so... So that I wasn't so cross-eyed. The first display was much clearer - it was bigger and coloured better.
User 6	The thin lines were difficult to see. Perhaps if they were bigger, there would be more to cross and it would be easier to see.
User 8	Didn't at first, but when I manipulated it, it did. I think the lines were too thin, and that made it difficult to differentiate these lines and these trajectories in space.
User 8	I do like the grid concept, in the sense that I can ground the lines relative to the graph, but I had difficulty seeing 3D because of how thin the lines were.
User 9	I'm seeing 3 dots in this one
User 9	I'd consider making the lines more 3D by having shadow, perhaps if one cast a shadow on the other as well.
User 9	The ball didn't appear very ball like, it was very flat. It would be easier if it and the points were more ball like.

5. CONCLUSION AND KEY FINDINGS

5.1 The Spaceball 5000

The Spaceball was found to be a useful, if imperfect tool. Users found that, after some practice, they were able to accurately manipulate the position of an object in 3D space using the Spaceball. However, there were some major issues identified.

When learning to use the device, the users often tried to rotate it about its axes, rather than pushing or pulling through the central moment. To remedy this, it was suggested that we use a non-spherical target that will rotate with the Spaceball. The presence of this feedback should provide users with a clear understanding of how to use the device.

More seriously, pressing the buttons was found to be difficult. The users suggested several changes to the device, including mounting the buttons on the ball itself. We will investigate the possibility of modifying the ball, but it appears unlikely that we can implement this solution ourselves.

Perhaps the most important point is that the Spaceball does not allow users to take advantage of rapid ballistic movements. If a normal person wishes to move their hand a long distance, they make a rapid, approximate, motion, followed by a more precise correction. This is known as Fitts' Law (Fitts, 1954). The isometric nature of the Spaceball precludes this natural tendency.

5.2 The Wii Balance Board

Users enjoyed using the balance board to navigate and found that it was a useful addition to the experience. They found that it was easy to learn and easy to use. They reported that movement with the feet was natural, and that little thought was needed.

The exception was in the case of rotation, which most users felt was unnecessarily difficult. They found that the need to coordinate two feet was more difficult to do and harder to learn. We received suggestions for implementing a single foot rotation, or for rotating by twisting the feet. Either is possible, and we will explore this in future prototypes.

Users also requested the ability to rest their feet on the board without it responding to accidental shifts of weight. While this had been considered earlier, it requires calibration to the individual user and so was not tested here. We are, however, convinced that such a feature is necessary.

Lastly, the users found it difficult to keep the Spaceball on the desk. The light weight and the vigorous nature of the interaction meant that users regularly lifted the Spaceball off the surface of the table.

5.3 **The Pinch and Pull concept**

Users uniformly felt that the pinch and pull concept was a useful idea. They did not believe that it would be difficult to learn or to use. There were, however, concerns about the effects of occlusion and technical limitations on accuracy.

The occlusion problem is found because the hand will block parts of the screen, particularly the area that the user is trying to select. To remedy this occlusion problem, it was suggested that we could track hand movement in a separate area (much like a mouse is separate from the screen upon which it acts) and to render a virtual hand on the screen. Occlusion may still be a problem, but it could be dealt with by making the hand semi-transparent.

The need for clear feedback was also raised. Users suggested tactile feedback, such as mild vibration, or visual feedback could be provided. One particularly novel suggestion was to have the selected object squeeze slightly, as a cue that the user was holding it. Another suggestion was to

5.4 **Desktop VR**

The user thought that the desktop VR prototype provided an interesting, intuitive and compelling 3D experience. We did not find that the desktop VR and stereopsis were sufficient for this purpose, but rather that numerous 3D cues, including texture, shadows are necessary for perception. Further, the lines, while computationally efficient, are not large enough to see clearly and therefore fail to provide an informative visualisation.

While users valued the ability to look around when they needed a different perspective, they did not want to be forced to use the facility in order to perceive the display accurately.

Lastly, the background grid caused users difficulty with fusing the stereo images, which strongly suggests that – at least for anaglyph stereo – the background colour and display will need to be carefully tuned to provide a useable display. It may even be necessary to make the colour adjustable in order to cater to individual differences.

With regard to anaglyph stereo, users experienced some discomfort, and significant individual differences in their perception of the stereoscopic effect. They also felt that the glasses were distracting. There are other, more costly, interfaces that do not require the use of anaglyph stereo, and we will be examining these in the near future.

It was also clear that the size of the “cursor” makes selecting points difficult. Users requested clear feedback about when selection is possible, and when selection has been completed.

5.5 **Potential Areas for Development**

While improving the Spaceball is difficult since it is a commercial product, we can provide users with sensitivity gradients that may change some aspects of the experience. If possible we should:

- Try to support ballistic and precise motions
- Investigate different button configurations to aid users in pressing buttons easily.
- Provide a tutorial in which the Spaceball implements all six degrees of freedom. This will greatly improve the rate at which users learn to use the device.
- Provide an easy method of mounting the Spaceball on a desk to prevent it shifting during use.

The balance board concept could be improved by:

- Changing the rotation command so that foot movement is more coordinated – a single foot motion, or both feet making the same motion
- Providing calibration to allow a viable dead zone. This would give users the ability to rest their feet on the device without making accidental inputs.

Users thought that the pinch and pull concept was interesting, and that it would be an easy and natural system of interaction. To this end, future development should work towards this goal, with special notice paid to the provision of feedback.

For future implementations of the visualisation prototype, it is suggested that:

- Clear depth cues such as size, shadows and texture should be provided
- The background grid should be carefully tuned to improve stereo fusion
- The user should receive clear feedback when a selection is possible and when a selection is made

5.6 **Final conclusion**

Users found the experience enjoyable and interesting. The display is certainly able to provide an immersive 3D view, and the users were able to operate the interaction devices. With the improvements suggested by this experiment we have saved considerable time and effort in that we are more likely to develop the prototypes correctly on the first attempt, rather than repeatedly trying to find a solution that works at a later point in time.

6. REFERENCES

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