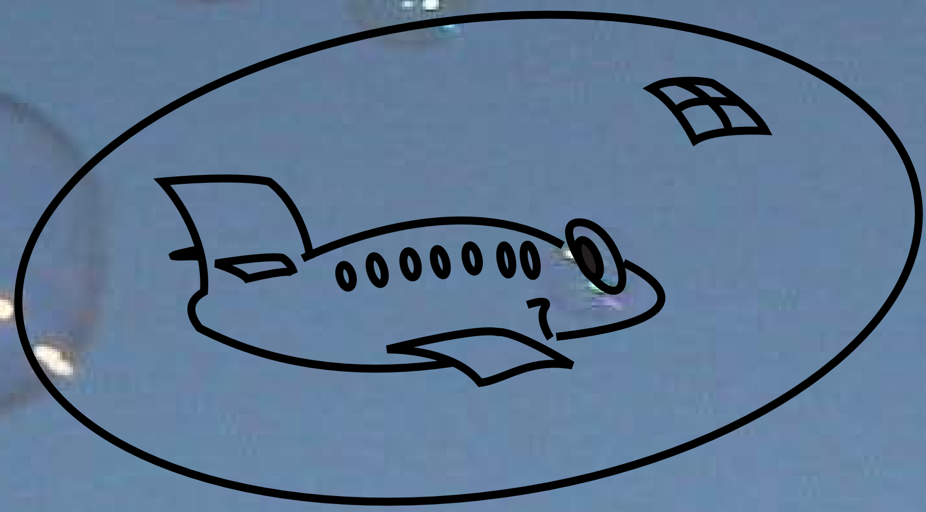
BUBBLES IN THE SKY



THE VISUALIZATION OF TEMPORAL INFORMATION IN TUNNEL IN THE SKY DISPLAYS

Masters Thesis
April, 2001

Jacco Otten
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Mentors:
Dr. C.J. Overbeeke (Industrial Design, Chairman)
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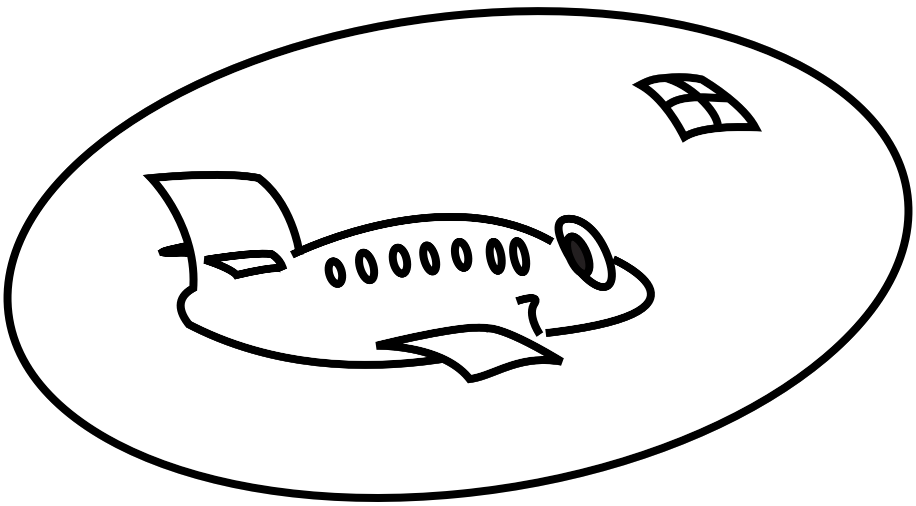

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ABSTRACT

Because of the large growth in the aviation industry, the sky is getting crowded. This growth is still continuing, It is estimated that in 2015 air traffic is doubled, or even tripled. This will lead to congestion on the airways, causing delays.
A way to reduce these delays is tot use the available airspace more flexible. This more flexible approach demands the ability to accurately fly (complex) trajectories. This asks for a change in the current flight instrumentation.
Flying is predominantly a perceptual task. The current displays do not reflect this perceptual task in a way humans perceive and act.
Technology has evolved and the aviation industry has entered 'the world of digital information displays. These displays offer the possibility to make precision navigation possible.
A prominent new display is the Tunnel in the Sky display. This display presents flight information in a way that is better suited to the way humans perceive and act.
However, when the airspace is used in a more flexible, dynamic way, temporal information is essential, to avoid collisions with other airtraffic. This information is still not integrated in to the Tunnel in the Sky displays.
Although some research is done to provide temporal information, none of the presented solutions do really integrate temporal information into the tunnel.
Integrating longitudinal information can be done by visualizing a front and rear boundary. In this way a Bubble in the Sky is created.
The Bubble in the Sky can be seen as a 'safe field of travel'. This safe field should reflect the task constraints as determined by the constraints, imposed by the Air Traffic Control and by constraints imposed by the aircraft dynamics.
In visualizing the Bubble in the Sky we can distinct four sub problems:

- How can the pilot distinct the bubble from the tunnel?
- How does the pilot know where he is in the bubble?
- How does the pilot know if he goes too fast or too slow?
- How can the pilot see beyond the limited field of view in general, and more specific how can the pilot see the rear boundary?

A number of (partial) concepts have been developed to solve the above mentioned problems. A number of (partial) solutions are integrated into three different concepts. These three different visualizations were tested in an experiment.
In this experiment, 6 subjects had to fly a complex approach-to-land trajectory.
The experiment had a preliminary character. Because not much research has been done in this field it is essential to explore the field before more specific tests can be performed. Although we now know a little bit more, lots of research needs to be done to come to a final product. Fields for further research are, among other things, the interaction between the Bubble and the aircraft to reflect the constraints better and the visual clutter in the display caused by the tunnel.
The graduation project was an interdisciplinary project in which Wright State University (WSU), department of Psychology and Delft University of Technology, faculty of Aerospace Engineering and School of Industrial Design Engineering were involved.

CHAPTER 1

INTRODUCTION

To get a better idea of the context in which the project took place we start with the problem definition. After introducing the reasons behind this project, the different parties that were involved and the roll they played will be described.

PROBLEM DEFINITION

The present day air structure, with its airways, dates from the 1950s and is based on the limited air traffic and the technology of that day, e.g. electromechanical cockpit displays.

Nowadays the sky is getting crowded. It has been estimated that till the year 2015 air-traffic will expand with 200 or even 300 percent. This will lead to congestion on the airways, causing delays. This trend is already felt today. Changing the concept of airways can solve this problem. These airways need to be more flexible. Airplanes should be given more autonomy in finding the best trajectory. This concept is known as 'Free Flight'. Although the details of 'Free Flight' are not clear, it is clear that a key to this concept is the ability to accurately fly (complex) trajectories.

Because of environmental and safety issues, present day society asks for changes in the 'air structure' as well. A perfect example of this is the growth of Schiphol and the problems this causes.

Technology has evolved and the aviation industry has entered 'the world of digital information displays. These displays offer the possibility to radically alter the way information is presented to pilots. By, among other things, making precision navigation possible, these displays offer the opportunity to help solve the aforementioned problems.

One of the most prominent of these display types is the Tunnel-in-the-Sky (TIS) display. The TIS display is used to indicate safe or preferred paths of travel for a pilot. Currently these displays only specify the trajectory. They provide spatio-temporal information about where a pilot is flying relative to the tunnel 'walls'. However TIS displays do not give spatio-temporal information in relation to the longitudinal axis of the tunnel. Here the temporal information is still separated from the spatial information. The TIS display does not provide feedback where in the tunnel the pilot is supposed to be at what time. Because these tunnels depend on dynamic conditions, such as the flight behavior of other traffic, such timing information is essential.

The aim of this project is to integrate the spatial- and temporal information by visualizing the interaction between time, distance and speed. The spatial- and temporal information will be integrated in an ecological way, to make the task of flying an aircraft better suited to the human perceptual motor skills.

COLLABORATING PARTIES

The in this thesis described project was an interdisciplinary project in which Wright State University (WSU), department of Psychology and Delft University of Technology, faculty of Aerospace Engineering and School of Industrial Design Engineering were involved.

The WSU, located in Dayton, Ohio is named for Dayton's aviation pioneers, Orville and Wilbur Wright. The university is dedicated to teaching, research and service and serves nearly 16,000 students. The Department of Psychology deals, among other things, with human-machine interactions. It focuses on improving system performance and developing effective interfaces using knowledge regarding the operator's perceptual and cognitive processes. The functional aspects of a situation are emphasized in improving performance.

Aerospace-related applications are common at Wright State University because it cooperates with the adjacent Wright-Patterson Air Force Base, a major center of Human Factors research and development.

The WSU has got the knowledge about perceptual theories, especially Gibson's ecological psychology of perception and has got the facilities to create simulations and conduct experiments.

Research and education at the faculty of Aerospace Engineering, disciplinary group Control & Simulation covers subjects like flight simulation, design and analysis of man-machine interfaces and air traffic management. This group has therefore the knowledge about- and experience with cockpit displays, especially with Tunnel-in-the-Sky (TIS) displays.

At the school of Industrial Design Engineering, the Studiolab focuses on product design that is user- and interaction centered. Knowledge about display visualizations has been gained through, among other things, Virtual Reality research. The broad and multidisciplinary character of the faculty makes it appropriate to act as a mediator. The function of mediator consists of bringing many different aspects from the different disciplines together, in order to create an integral concept.

SECTION 1

ANALYSIS

CHAPTER 2

THE VISUAL NATURE OF FLYING

To better understand the background of the project, it is best to start of with the current way the pilots get information to accomplish their task. In this chapter we see that the flying task has a visual character. The current flight instruments do not support this character. We will look at the main flight displays and try to give reasons why the visual character is not supported by the currently used displays.
In this way we want to show the reasons behind the change from the current flight displays to the Tunnel in the Sky display. This is done to appreciate and understand the principles applied to the Tunnel in the Sky displays. These principles will later be applied to integrate temporal information in the Tunnel in the Sky displays.

THE DISCREPANCY BETWEEN FLYING VISUAL AND FLYING ON INSTRUMENTS

In order to obtain a save airspace, the International Civil Aviation Organization (ICAO) has divided air traffic into two categories; air traffic that uses 'Visual Flight Rules' (VFR) and air traffic that uses 'Instrument Flight Rules' (IFR).
In VFR the pilot self is responsible for keeping separation with other airplanes on his route. Therefore the pilot relies on his view through the windshield. VFR flights are therefore limited to daytime and good visual meteorological conditions. So VFR-flights cannot always be performed.
Because it is not possible for civil aviation to only fly at daytime in good weather, all commercial flights are conducted in IFR. In IFR the pilot flies on his instruments and is accompanied by air traffic control on the ground to maintain separation with other aircraft. Only during the last part of the landing the view through the windshield is important. In this phase the pilot(s) must see the (illuminated) runway.
Flying only on instruments gives the flying task a different character, as Mulder (1999) describes:
"Guiding an aircraft along a trajectory near the earth's surface is a task that is similar to everyday locomotion as walking or driving a car. With respect to walking the aerial locomotion is guided by manipulating a machine instead of our own limbs; the vehicle acts as some interim between the bodily motion and the locomotion itself. With respect to car driving it are the restricted car kinematics and the less complex car dynamics that are different.
Despite these differences the task of manual aircraft control is of similar difficulty, at least when visual contact with the environment is continuously available, i.e. in VFR flight (Naish, 1971; Wilckens, 1971). In IFR flight, when visual contact with the environment is not available, the pilot relies on the cockpit displays. In this case the control task rapidly becomes more difficult, while all other characteristics remain the same. Apparently, whereas the out-of-the-windshield visual information of the 3D environment leads to an immediate awareness of the flight situation, the current displays do not (Wilckens, 1971)".
To understand why flying on instruments is more difficult it is necessary to see what the current displays look like.

ELECTRONIC FLIGHT INSTRUMENT SYSTEM

Currently, the main flight and navigation information is presented on two color displays. These displays are placed in the cockpit panel direct in front of the pilot and are therefore called Heads Down Displays (HDD's); the Primary Flight Display (PFD) and the Navigation Display (ND). These displays are orthogonal and have typically a viewable area of 6,7 x 6,7 inch (17 x 17 cm).

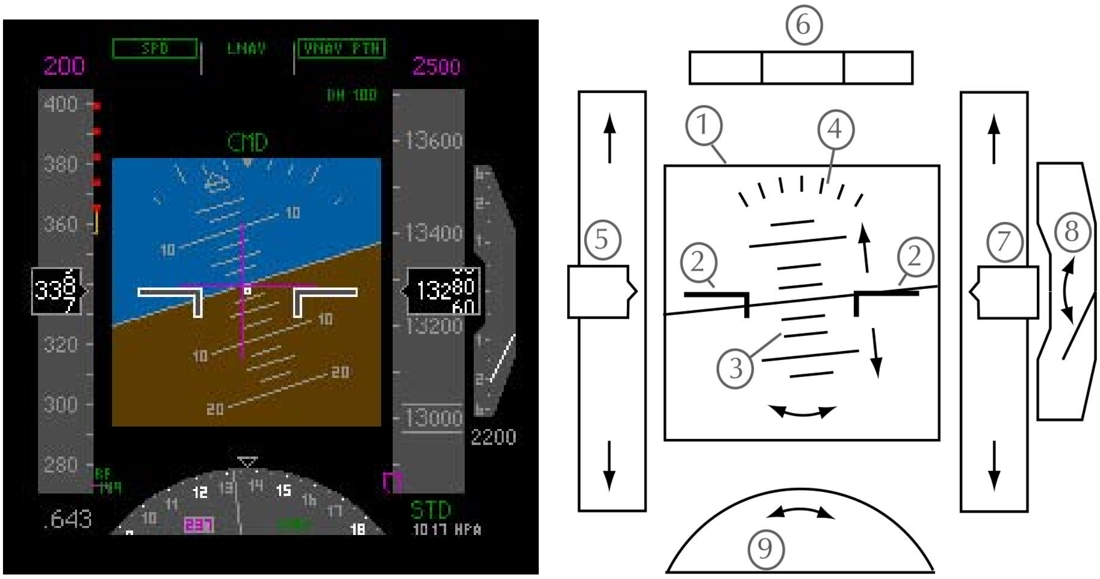


Fig 2.1. A typical PFD. The arrows in the 'wire frame' model depict the indicator movements.

The Primary Flight Display (PFD) (figure 2.1) contains five basic display formats and presents primarily aircraft guidance information. In the center of the PFD we find the artificial horizon that shows the aircraft attitude (1). The artificial horizon is dominated by the aircraft symbol (2), the pitch ladder (3) and the roll scale (4). The artificial horizon works according to the inside-out principle. The representation resembles the view of the outside world from the inside of the aircraft, i.e. the horizon moves and the aircraft symbol is fixed (In figure 2 the aircraft is in a right hand turn).
The linear tape on the left of the artificial horizon (5) depicts the airspeed. A digital readout of the airspeed is visible in the window. Across the top in the three windows, the active modes of the automatic pilot are shown (6), e.g. 'spd' means that the autopilot maintains the commanded speed. To the right of the attitude indicator, the altitude tape is visible. A digital readout of the altitude is visible in the window inside the altitude tape (7). To the right of the altitude display we find an instantaneous vertical speed indicator (8). When the pointer in this indicator points down, the aircraft is descending (and vice versa). At the bottom of the display, a segment of a compass rose, showing the current magnetic heading is visible (9). When the Flight Director (FD) is engaged, the horizontal and vertical FD command bars (magenta cross in middle of the artificial horizon) appear on the display.

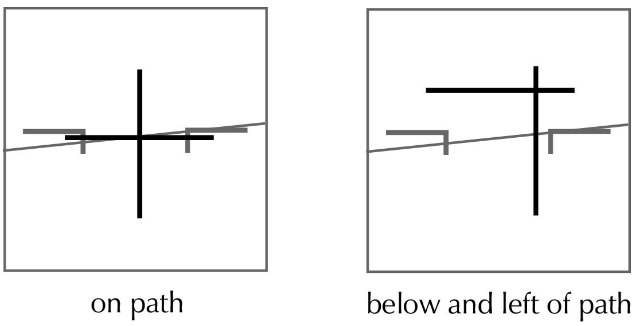


Fig 2.2. The Flight Director command bars

The above-mentioned Flight Director is an instrument used to fly a pre-determined course. The pilot's task in following this course is keeping the horizontal and vertical FD-bars in the center of the artificial horizon (figure 2.2). In case of the right picture in this figure the pilot must climb and make a right hand turn in order to stay on course.

Fig 2.3. A typical Navigation Display in Map Mode

The Navigation Display (ND) presents navigation information in 2 ways: In Compass mode and in Map mode. The normally used Map mode will be described here.

The ND in Map Mode (ND-MM) depicts the aircraft position on a moving map in relation to airports, en-route fixes or waypoints and the intended course or track. The information is presented in a top down, two-dimensional view (figure 2.3). The compass arc dominates the ND across the top. Also near the top, in the right corner, the arrival time and distance to the next active waypoint (magenta) are visible. In this case the next waypoint is BNN. If the aircraft maintains its course, this waypoint will be crossed at 15:17 (Zulu time, i.e. the time expressed in the Universal Time Code (UTC)). In the left upper corner the speed of the aircraft relative to the earth (GS; Ground Speed) and relative to the air (TAS; True Air Speed) is displayed. Below this the wind direction and speed is displayed. The white triangle near the bottom represents the own ship. The magenta line depicts the route the aircraft has to fly.

TOWARDS THE TUNNEL IN THE SKY DISPLAY

As said in the first section of this chapter, flying on instruments is more difficult than flying on visual contact with the environment. A reason for this is, that the current EFIS displays, the PFD and ND, are planar representations of the aircraft's spatio-temporal situation. Two 2D displays represent the three-dimensional situation in a way that is incompatible with the way humans perceive their 3D environment (Haskell & Wickens, 1993). "To become aware of the current flight situation, by mentally recreating a 3D picture, the pilot must integrate a considerable amount of information from a set of integrated or individual displays from several spatial locations on the instrument panel. The difficulty of pilots in mentally reconstructing the flight situation from the two planar EFIS displays, especially in high workload situations, is certainly one of the main causes of the occasional lack of situation awareness" (Mulder, 1999).

When we look at the task of navigating an aircraft along a trajectory, we can see that this task can be divided into two elements: Local guidance and global awareness.

Local guidance involves staying on the desired navigational path, through 3D space. For this task route knowledge is necessary; the navigator needs to know the deviation (error) from the ideal trajectory.

Global awareness requires knowing where things are in space. The information necessary for global awareness is different from the information necessary for the guidance task. Global awareness must support rapid and accurate responses to events that are unexpected and possible departures from the planned (ideal) course. The information is world referenced. Therefore a 2D

top view is better suited than an egocentric point of view (Prevett & Wickens, 1994). For the task of global awareness in flying, the ND-MM is very suited.
Although the Navigation Display in Map Mode supports global awareness, the PFD is not well suited for the local guidance task. Apparently the deviation from the ideal trajectory cannot properly be derived from the display. Mulder (1999) confirms this:
"Also the pilot is unable to achieve the necessary trajectory following performance with the EFIS displays. When precise flight maneuvering is required, pilots are forced to either engage and use the flight director steering command system, or engage the autopilot. In the first case the pilot still has some direct control over the aircraft. He only acts as a mere stick actuator, by doing what the FD computer tells him to do. In the second case the pilot has no direct control over the aircraft, he acts as a system supervisor. However, in both situations the information-processing task is performed by the computer, not by the pilot".

So what information should be presented to support the task of local guidance? Prevett & Wickens (1994) have got an answer to this question:
"To provide local guidance information, a key feature would be to present this information in an ego referenced frame in which the language of the displays should match the language of control. E.g. the display should rotate accordingly to the momentarily attitude of the navigator. The 'local guidance' display should also present a forward 'cone' of visual space (the most likely place where the vehicle will be in the future), 'zoom in' (representing near space more precisely than far space) and representing the world in a 3D perspective."
What should be captured in the display are the constraints in navigating an aircraft along a trajectory. This means not only the visual constraints, but also the invisible constraints, e.g. the constraints in the aircraft dynamics. These constraints then need to be made visible to communicate this information to the pilot.

From the paragraph above we can conclude that the current PFD is not good enough. But does this mean a complete new display needs to be developed? Can't the PFD display be modified to allow for precision navigation? According to Mulder (1999) this is possible, but the display would still be far from optimal:
"Although the current systems can, in principle, be enhanced for precise navigation, which will be necessary in the future, there still is a growing concern about the suitability of these systems from a pilot's perspective. For instance, the Flight Director does not present any information about the current nor the future aircraft motion status in relation to the trajectory. So the pilot is not able to judge the importance of the actual path deviation from the FD command bars.
Clearly, for the future ATM (Air Traffic Management) environment where an aircraft probably receives clearance for only a certain volume of airspace, moving along the negotiated trajectory, other forms of presenting 3D/4D guidance information should be developed. To do so the flexibility of the programmable electronic displays must be exploited. This could mean a great change towards the design of displays that take the advantage of humans' unique strengths in visual processing".
"…consensus in the aviation community is growing that the Primary Flight Display of the future should present the aircraft spatio-temporal navigation guidance situation in a manner that is intuitively understandable, that enhances the pilot's situation awareness during al phases of flight and that is compatible with and among the various pilot's control and monitoring tasks to be performed" (Mulder, 1999).
A good candidate to become the future PFD is the Tunnel in the Sky display. This display will be explained in the next chapter.

CHAPTER 3

TUNNELS IN THE SKY

In previous chapter we have seen the current flight displays. We have seen that the PFD is not well suited for its job. A perspective flight path display, like the Tunnel in the Sky display, would be better. This display will be described in this chapter. Although the Tunnel in the Sky display is a promising candidate for the future PFD, the temporal information (like speed) is still not integrated in the display. An already existing concept that integrates temporal information will be discussed.

3D TUNNEL IN THE SKY

A suitable candidate that could satisfy the current and future air navigation demands is a perspective flight-path display such as the 'Tunnel in the Sky' (TIS) display (see figure 3.1).

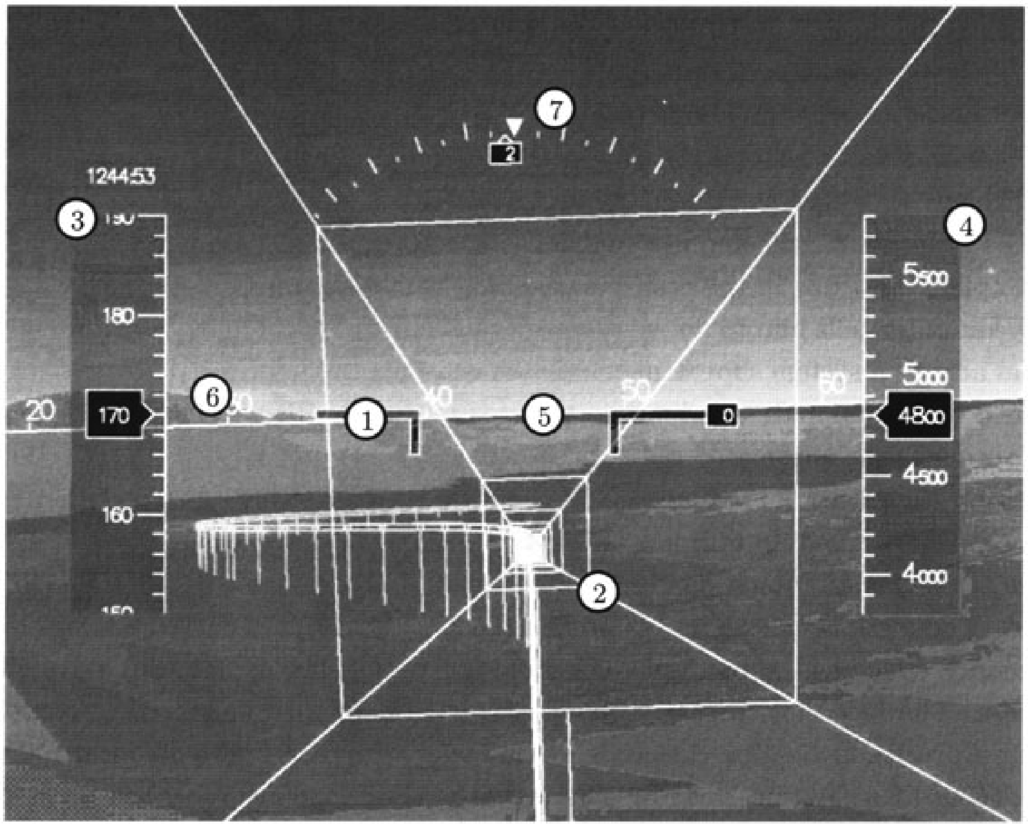


Fig 3.1. 'Tunnel in the Sky' display. In this figure are visible; the aircraft symbol (1), the tunnel geometry (2), the aircraft velocity tape indicator (3), the aircraft altitude (4), the horizon (5) with the heading angle indicator (compass) (6) and the bank angle indicator (7).

"The perspective flight display is a simplified computer generated perspective image of the visual field as a tunnel in the sky. It presents the aircraft 3D guidance situation with respect to the trajectory to be followed in an integrated fashion through a spatial 3D representation of that situation. The tunnel display provides, in addition to the control error, a direct spatial orientation of the aircraft's position, attitude and motion relative to a fixed landmark (the tunnel geometry) in the environment. In this way the spatio-temporal flight situation with respect to the environment is presented in a way that is compatible with the way humans perceive their environment, allowing pilots to use their perceptual system in an ecological fashion. The display allows and supports pilots to rely on the same perception and action cycles they use in everyday life. It frees pilots from mentally reconstructing the flight situation from an array of planar, quasi-spatial displays and allows them to literally perceive the flight situation in a glance. The tunnel display maps the task-related variables onto a visual pattern that directly represents the variables of the task domain. Because of this, the task domain variables can be defined and, most importantly,

controlled in terms of the properties of the visual pattern itself, not requiring any transformation between task and information domains at all" (Mulder, 1999).
"The perspective tunnel display mimics the outside world in a stylized manner, which has the advantage that the display is in correspondence with the natural way of visual perception, while the pilot only gets the essential info. This helps prevent the display from being cluttered (Below & von Viebahn, 1995). Because the provided picture is totally synthetic, the visual information can be enhanced with elements that are not available in the outside world; a computer generated display allows the designer to emphasize or augment those display elements that convey clear and unambiguous guidance information, like the flight path predictor symbol" (Mulder 1999).
The above mentioned flight path predictor, is a symbol that shows the position of the aircraft in the near future. The predictor helps in estimating the vehicle path and can in this way help dampen vehicle movement (figure 3.2).

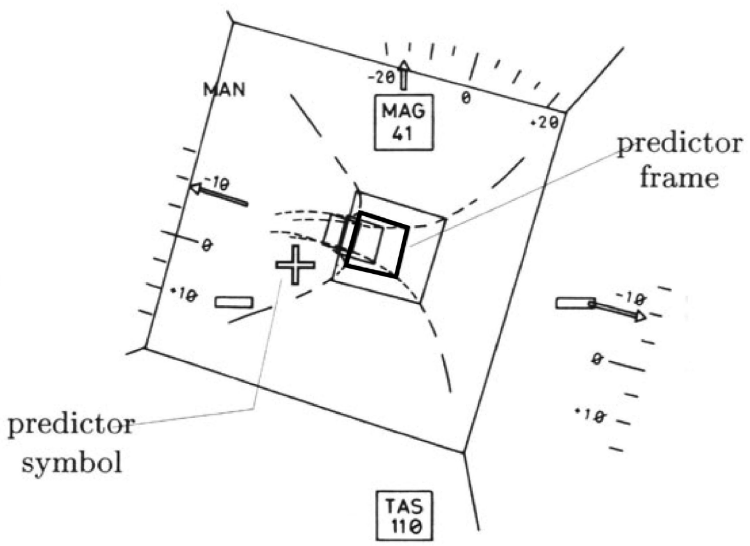


Fig 3.2. Tunnel-and-predictor. The predictor symbol lies in the same plane as the predictor frame and provides information of where the aircraft will be in 5-7 seconds if the pilot does not change the control input.

4D Tunnel in the Sky

A perspective flight path display is not a new concept. The idea originates from before the Second World War.
"The promising contact analog display concepts that have been propagated since the 1950's, however, could not be implemented effectively with the contemporary technology. This changed with the advent of analog- and digital computers in the late 1960's, resulting in several successful demonstrations of various forms of pictorial, perspective cockpit displays. Recently research in perspective flight path displays is booming. All this research points out that it is a very promising candidate to become the primary flight display of future aircraft cockpits" (Mulder, 1999).
However, currently these displays only specify the trajectory, they provide spatio-temporal information about where a pilot is flying relative to the tunnel 'walls'. TIS displays do not give spatio-temporal information in relation to the longitudinal axis of the tunnel. Here the temporal information is still separated from the spatial information. The TIS display does not provide feedback where in the tunnel the pilot is supposed to be at what time. Also no information is available how fast the pilot is supposed to fly. Because the tunnel trajectories depend on dynamic conditions, such as the flight behavior of other traffic, such timing information is essential.

Since 1977 research on integrating temporal information into the Tunnel in the Sky display has been done. Till now basically three different solutions are known.

- The spatial lead plane (Walter and Mulley, 1977; Filarski and Hoover, 1983; Snow, 1999)
- Flight path triangles (Below and von Viebahn, 1995)
- Reference square with tickmarks (Grunwald, 1980 and 1984)

The solution Grunwald presents is the closest to the original tunnel visualization and is therefore the best integration with the 3D tunnel. The other solutions give the information by adding other visual information, like a virtual airplane. Because of this Grundwald's solution will be further discussed here. The other two solutions are described in Appendix B.

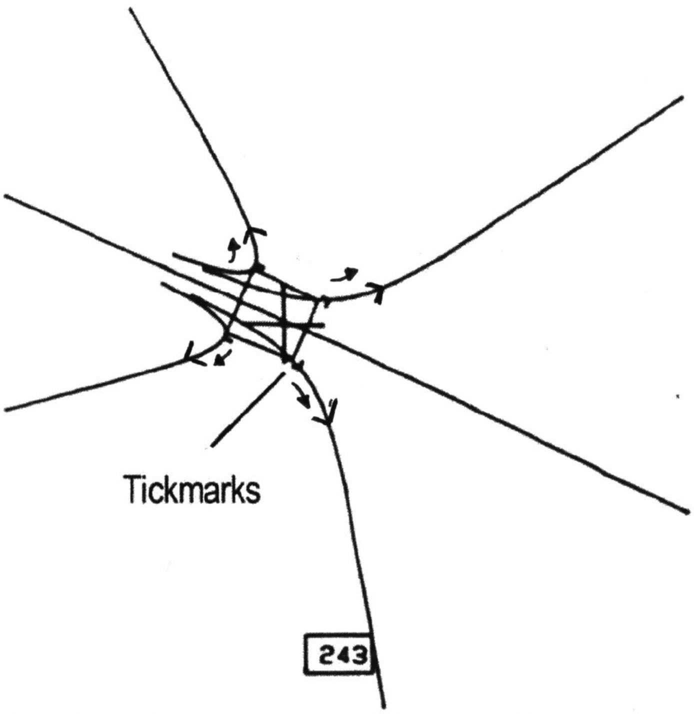


Fig 3.3. The 4D solution Grunwald presents.

In Grunwalds' research the Tunnel in the Sky concept is extended to allow for accurate control of the aircraft forward velocity in a 4D guidance task. This is accomplished by presenting a predictor symbol related to actual forward speed as well as a reference frame in the tunnel, ahead of the own plane, related to the desired speed (figure 3.3).

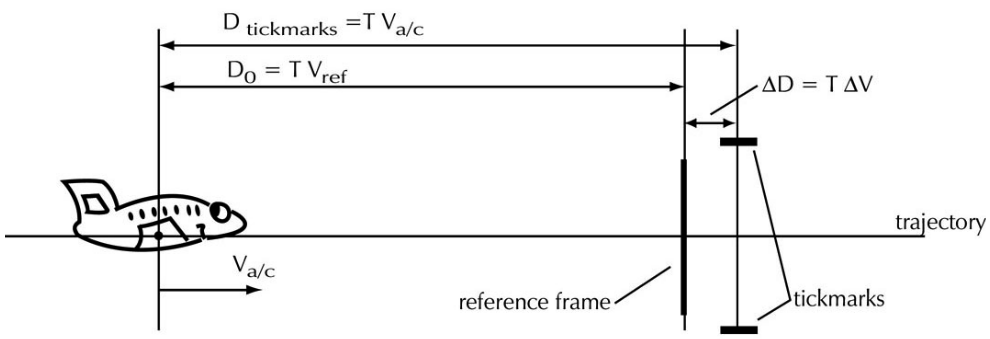


Fig 3.4. Kinematics of Grunwalds' 4D Tunnel solution.

With the predictor symbol four tickmarks, presenting a cross section of the tunnel, move along ahead of the vehicle at a distance D. In the tunnel image Grunwald uses, all squares have been removed, except one; this solid square, the reference frame, represents the desired velocity (V_0). This frame is placed at a distance $D_0 = T\ V_{ref}$ ahead of the aircraft. The tickmarks represent the actual speed of the aircraft ($V_{a/c}$). The tickmarks are placed at a distance $D_{tickmarks} = T\ V_{a/c}$ ahead of the aircraft. In both above-mentioned formulas T is a time-constant of 5-7 seconds (Grunwald, 1980). So, when the aircraft flies too fast, the tickmarks move forward (and vice versa). In order to fly at the optimal speed ($V_{a/c} = V_{ref}$), the pilot must match the tickmarks with the reference frame

(in the longitudinal direction) ($D_{tickmarks} = D_0$; $\Delta D=0$). So basically, in order to visualize the speed, this quantity is translated into distance (figure 3.4).
In this way all information for accurate 4D path following is presented centrally in the display through the use of a single symbol.
In addition to the above mentioned speed cue, speed is also displayed in a digital manner at the bottom-center of the display. In this way the precise speed can also be derived from the display, so that the pilot knows the speed relative to the optimal speed as well as the speed in an absolute sense.
Experiments showed that accurate velocity control was achieved with moderate throttle activity and without affecting the path following performance. This contrary to the comparison-experiment in which the speed was digitally represented. In this experiment the tunnel following performance deteriorated, because the velocity-controlling task took too much attention. (Grunwald, 1984). It is essential that the velocity-controlling task won't lead to poor path following performance.

Comments on Grunwalds' 4D Tunnel in the Sky solution

In Grunwalds' solution a significant part of the cues that reflect forward speed are lost: By removing all the rectangles from the tunnel image, the cue of optical flow that could be derived from them is lost. This optical flow can be very useful in integrating the speed information in the display.
The information that is provided in Grunwalds' solution could be confusing: When the pilot flies to slow the tick marks move towards the aircraft (figure 3.3). From this movement of the tick marks the pilot can conclude that the forward longitudinal boundary of the separation margin is coming towards him, i.e. that he is flying to fast. Therefore he will slow down, while he should speed up. The tickmarks will move even further towards the pilot, and so forth. In this way the speed error will only become larger, instead of smaller. When we take this unstable situation to the extreme, the aircraft can eventually stall.

Grunwalds' 4D solution, i.e. keeping the tickmarks on the solid square, is a task very similar to that of following the Flight Director command bars. In this task the pilot acts as a 'throttle actuator' by keeping the speed error as small as possible. In this solution no information is available about the speed margins, so the pilot has no information about the current- nor the future longitudinal separation with aircraft in front and behind the own aircraft. I.e., the pilot won't be able to see if he's still within the 'safe field of travel'.
This safe field of travel will be further elaborated in the next chapter.

CHAPTER 4

THE SAFE FIELD OF TRAVEL

The term 'safe field of travel' originates from Gibson and Crooks (1938). They wrote a paper that was called 'A theoretical field-analysis of automobile-driving' to create a systematic description of what goes on when man drives an automobile. The description needed to have a practical as well as psychological validity in an ecological context.
Because the task of automobile driving is mainly a perceptual task, the analysis was carried out on a perceptual level. In their paper Gibson and Crooks state:
"Locomotion is guided chiefly by vision and this guidance is given in terms of a 'path' within the visual field of the individual as such that obstacles are avoided and the destination ultimately reached. The concepts of terrain, destination and path should be applicable to any type of locomotion."
As said in chapter 2, flying is like automobile driving predominantly a perceptual task. Although the dynamics in flying an aircraft are more complicated and controlling an aircraft involves an extra dimension, it is perceptually similar to driving a car or to walking. In flying, like in automobile driving, man uses a tool to make locomotion more effective. Excerpts from this paper that are relevant can be found in Appendix C.

THE SAFE FIELD OF TRAVEL APPLIED TO FLYING

When we apply Gibson and Crooks' article to aviation we notice that although flying is perceptually very similar to driving, the boundaries that form the field of safe travel are different. To start with, aircraft cannot simply stop like a car can. We can not really speak of a minimum stopping-zone like Gibson and Crooks do. An aircraft can decelerate to its minimum speed (i.e. the stall speed) or it can alter its course to evade objects. So it is better to talk about a minimum speed zone, or better an evasion- or avoidance zone.
In the air are fewer objects than on the ground. Objects that are in the air, almost all have a high negative valence. The ground is a special object in that it can have a high negative valence as well as a high positive valence. This is especially true when landing, when the goal is to touch the ground. When this is not done properly, the ground can be a threat.
Because of the high speeds aircraft fly with, the field is stretched out far forward. The human vision is not sufficient to overlook the safe field. Therefore, and because vision can be hindered by clouds or darkness, pilots need to be aided to maintain a safe field of travel. The safe field should be made visible.
The aid to maintain this safe field is provided by the Air Traffic Control (ATC). ATC imposes legal boundaries on aircraft. By means of these legal boundaries an airway (with a certain width and height) is formed on which one can fly with a certain speed (to maintain separation with aircraft in front of the ownship). In this way objects with a negative valence are avoided.

The above mentioned 'safe field of travel' then can be seen as an airspace section in which the aircraft is allowed to be in at a certain time. This space is reserved for only that aircraft. The reserved airspace is laterally and vertically bound by the tunnel walls and longitudinally by the separation between aircraft. It can be seen as a 'Bubble in the Sky'. This bubble moves along the aircraft's trajectory at a certain speed.
This speed is subject to a number of constraints that can be divided into hard- and soft constraints. The hard constraints are determined by the aircraft dynamics and constitute basically of the stall speed (V_{stall}), which is the minimum speed of the aircraft. This speed can be considered as the rear boundary of the 'safe field of travel', and the maximum speed (V_{ne}) of the aircraft. The soft constraints are determined by the optimal speeds for the aircraft, like the 'economy cruising speed' of the aircraft to save fuel and engine life. The soft constraints can also be determined by Air Traffic Control (ATC), who can designate a certain speed to the aircraft, so as to maintain separation with other aircraft. Also ATC can tell a pilot to cross certain waypoints only before or after a certain time.

The ‘safe field’ has a gradual character in that the safest possible place is the center. When moving to the boundaries the tunnel will ‘gradually become ‘less safe’. This because the error margin between the aircraft and the closest tunnel wall becomes smaller and thus the chance of moving outside of the ‘safe field of travel’ becomes greater.
From Godthelp (1984) we can conclude that the visualization of the safe field of travel as a Bubble in the Sky fits the way a vehicle is controlled. In automobile driving research Godthelp pointed out that, because of the boundary control nature of a driver’s task, drivers do not need to minimize the guidance errors per se. Rather, these errors can be neglected up to the moment the driver decides to act on them again, yielding a control strategy referred to as error-neglecting control. Godthelp showed that drivers make an estimation of a temporal, rather than a spatial range with respect to the road boundaries. This temporal range is called the Time-to-Line Crossing (TLC) variable. In error-neglecting control, drivers can neglect the path errors up to the moment the temporal range, the TLC, drops below a certain threshold. In this way the driver maintains a temporal region of safety.
Analogous to TLC, which is more relevant to lateral and vertical boundaries, is Time to Contact (TTC) which is relevant to the longitudinal boundaries. Time to Contact is further elaborated in Appendix D.
In the task of keeping the aircraft within the ‘safe field of travel’, error neglecting control is relevant. The pilot should get more information about the ‘safe field of travel’ rather than only the discrete information of the optimal or desired speed.
The pilot’s task is not as much that of ‘keeping the optimal speed’, but that of ‘keeping the speed of the aircraft between certain limits so as to keep the aircraft within the ‘safe field of travel’. The pilot should be presented with information about the ‘safe field of travel’ rather than with the optimal or desired speed to fly with.

Aircraft dynamics

What also should be presented in the flight display is the task domain, i.e. controlling an aircraft. The paragraph describes what variables come into play and which ones should be represented in the display.

Figure 4.1 is a simplified representation of the way an aircraft is controlled. In the figure we can see the four control inputs the pilot has (i.e. stick fore-aft, throttle, stick left-right and pedals). We can also see through what variables the four inputs come to the goal state, i.e. the pursuit of the bubble during an approach. The lines depict the causal relation between the variables.

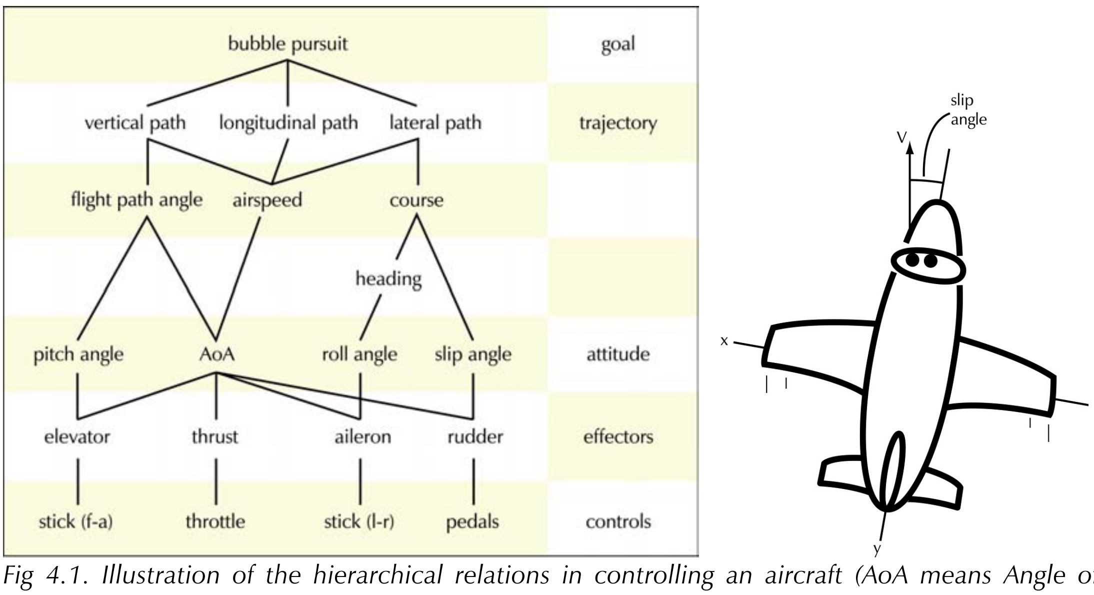


Fig 4.1. Illustration of the hierarchical relations in controlling an aircraft (AoA means Angle of Attack). The slip angle is depicted in the right picture.

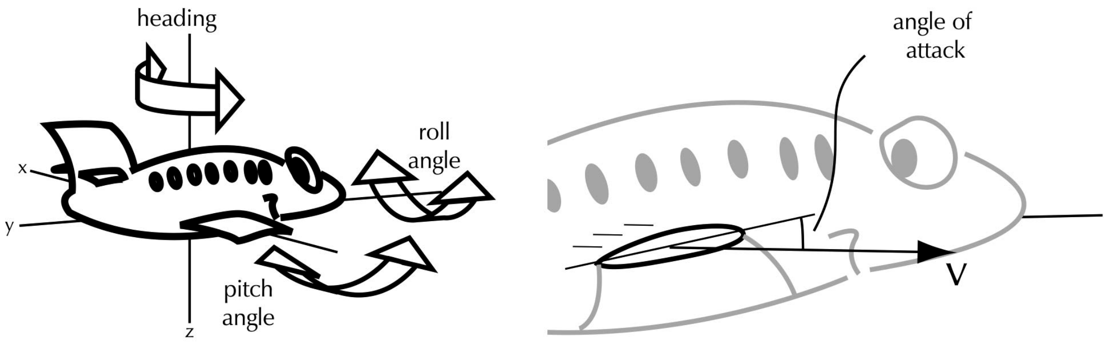


Fig 4.2. Left: The depiction of the heading, roll angle, pitch angle. Right: depiction of the Angle of Attack, the angle at which the air, which is the opposite to the direction of the speed, meets the wing.

Figure 4.1 emphasizes the hierarchical relations among the performance variables. What can be noticed is that the four control paths are not separated, all paths are in some way coupled.
These couplings have important implications for the control task: Every control-input affects some combination of output variables. So when a pilot wants to reduce an error on one variable, he can introduce a new error on another variable. On the other side, the couplings often give the opportunity to come to multiple solutions to a control problem.
These interactions between various variables make flying less intuitive. A clear example of the less intuitive nature of flying can be seen in the interactions between the stick (f-a) path and the throttle path (figure 4.3). The interactions between the two paths will be further elaborated below.

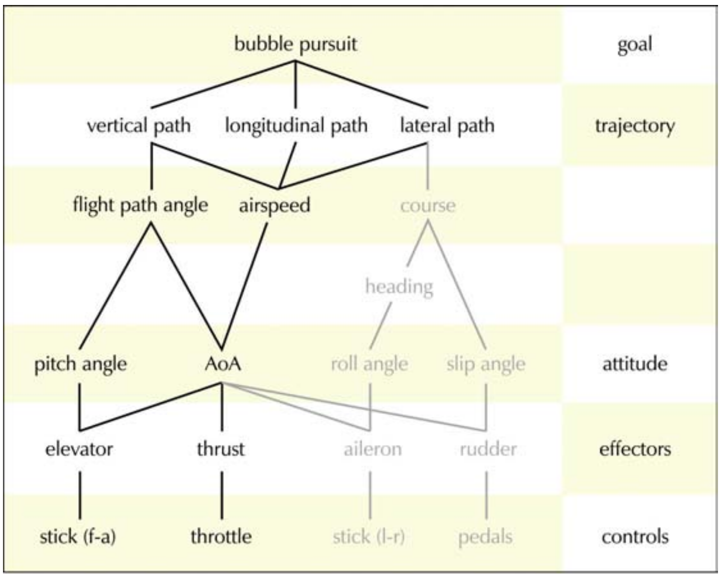


Fig 4.3. The control diagram for pitch and speed control.

An aircraft has the tendency to follow a certain speed it is set to. Although it would be obvious (if we compare aircraft to ground vehicles, like cars) that this speed is set by the throttle, this is not completely true. Because of the aerodynamic nature of an aircraft, speed is set by the elevator (stick fore –aft). The aircraft will always try to pursue the speed that is set by the elevator.
When the pilot opens up the throttle, the aircraft wants to maintain its speed. So instead of accelerating, the aircraft will use the extra thrust to climb. What makes the story even more difficult is that, when the pilot pulls the stick back to slow down, the aircraft will instantaneous climb as well, before setting into a new equilibrium. This effect depends on how fast, how far and how long the pilot pulls the stick back and also on the speed of the aircraft. Because the

interaction depends on so many variables there is as multitude of possible inputs to come to a control solution.
The couplings among the variables are in reality far more complex than described here. The essence of the story nevertheless doesn't change. What it comes down to is that, in order to control an aircraft, the flight display should represent all possible variables as seen in figure 4.1, from attitude up.
The current Tunnel in the Sky display provides almost all altitude and higher order variables in a pictorial form. As said before, the variable 'airspeed' is still not integrated in the display.
The Bubble in the Sky display needs to capture all constraints in an ecological manner. It should allow for direct perception and action, independent of how the control dynamics interfere with each other.

SECTION 2

CONCEPTUALIZATION

C HAPTER 5

TOWARDS A NEW DISPLAY

In order to integrate temporal information in the new display, we took off from the existing Tunnel in the Sky display, e.g. the visualization of the lateral and vertical boundaries in the path that the pilot is supposed to follow. Adding a front and rear boundary inside the tunnel extends the visualization of the mentioned boundaries in the Bubble in the Sky display. The front and rear boundary as well as the lateral and vertical boundaries then form the 'bubble', which visualizes the safe field of travel.

Before we go to a number of concept sketches we will first look at the kinematics of the Bubble in the Sky. Through the kinematics we come to a number of sub-problems in visualizing this bubble. The concept sketches try to solve the recognized sub-problems.

To create an overview of the presented solutions, the sketch-section ends with a summary of the sketches.

KINEMATICS OF THE BUBBLE OF THE SKY

When we look at the 'safe field of travel' in the longitudinal direction, we see that this 'bubble' is traveling along the aircraft's trajectory at the desired, optimal speed (V_{ref}). The pilot's task is to keep the aircraft in this bubble, e.g. by matching the aircraft speed ($V_{a/c}$) with the desired speed (V_{ref})(, which is the speed of the bubble (figure 5.1).

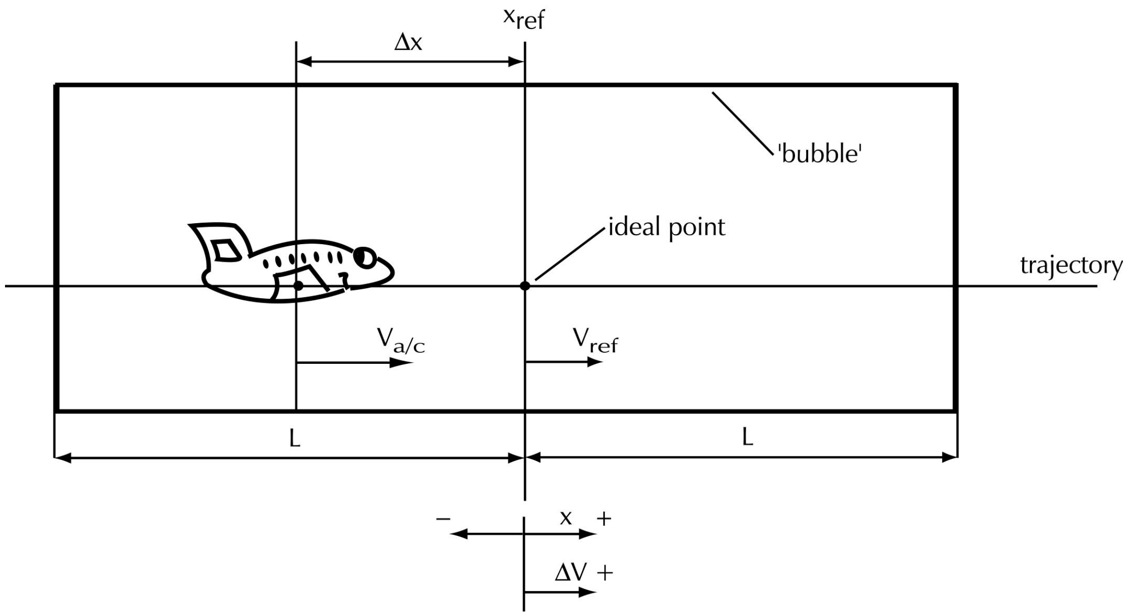


Fig 5.1. Kinematics of the Bubble in the Sky, in the longitudinal direction. The sign convention is visible below the bubble.

When the relative speed is reduced to zero, the aircraft stands still relative to the bubble. The distance to the bubble will be constant, but it is not clear what the position of the aircraft is relative to the bubble (Δx). The 'safest' possible place of the aircraft in the 'safe field of travel' is in the middle of this field, the ideal point, where the distance to the tunnel walls is as large as possible. So not only must the speed error (ΔV) be as small as possible, the distance error (Δx) must be minimized as well. In this subtask the pilot has a margin of $-L < \Delta x < L$ (error neglecting control) (figure 5.2).

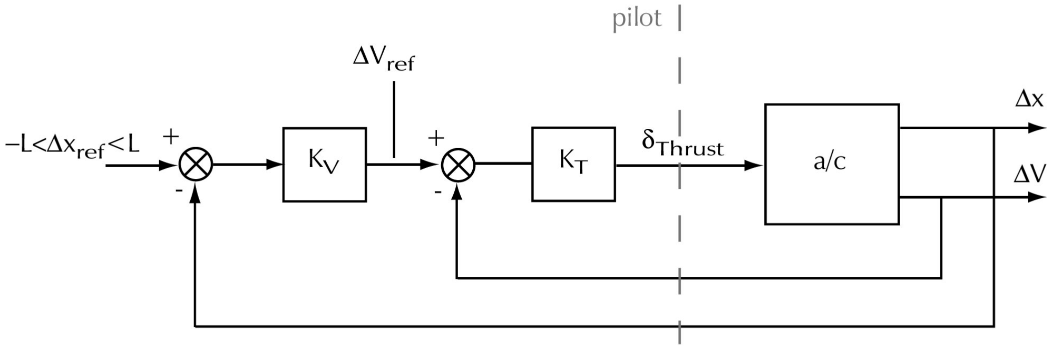


Fig 5.2. Pilot model of the task of staying in the 'bubble'.

So for the task of keeping the aircraft in the safe field of travel, information about the speed and the distance relative to the bubble, as well as information about the ideal point must be provided. Also it might not be sufficient to only provide information about the 'bubble' (distance information). It can be difficult to derive the relative speed (ΔV) from the distance information only. Visualizing a higher order variable, like the relative speed, can help solve this.

Sub-problems in visualizing the Bubble in the Sky

In visualizing the bubble, we can see a number of problems emerging:

- How can the pilot distinguish the bubble from the tunnel?
- How does the pilot know where he is in the bubble (ΔX)?
- How does the pilot know if he goes too fast or too slow (ΔV)?
- How can the pilot see beyond the limited field of view the display has in general? And more specifically: How can the rear boundary be perceived?

Below these problems will be further elaborated. A number of sketches will be shown that present suggestions toward a solution.

TUNNEL-BUBBLE DISTINCTION

In order to see where the boundaries of the bubble are, the bubble and the tunnel need to be differentiated. This can be done by using thicker lines or different colors, or by removing or altering parts of the tunnel geometry.

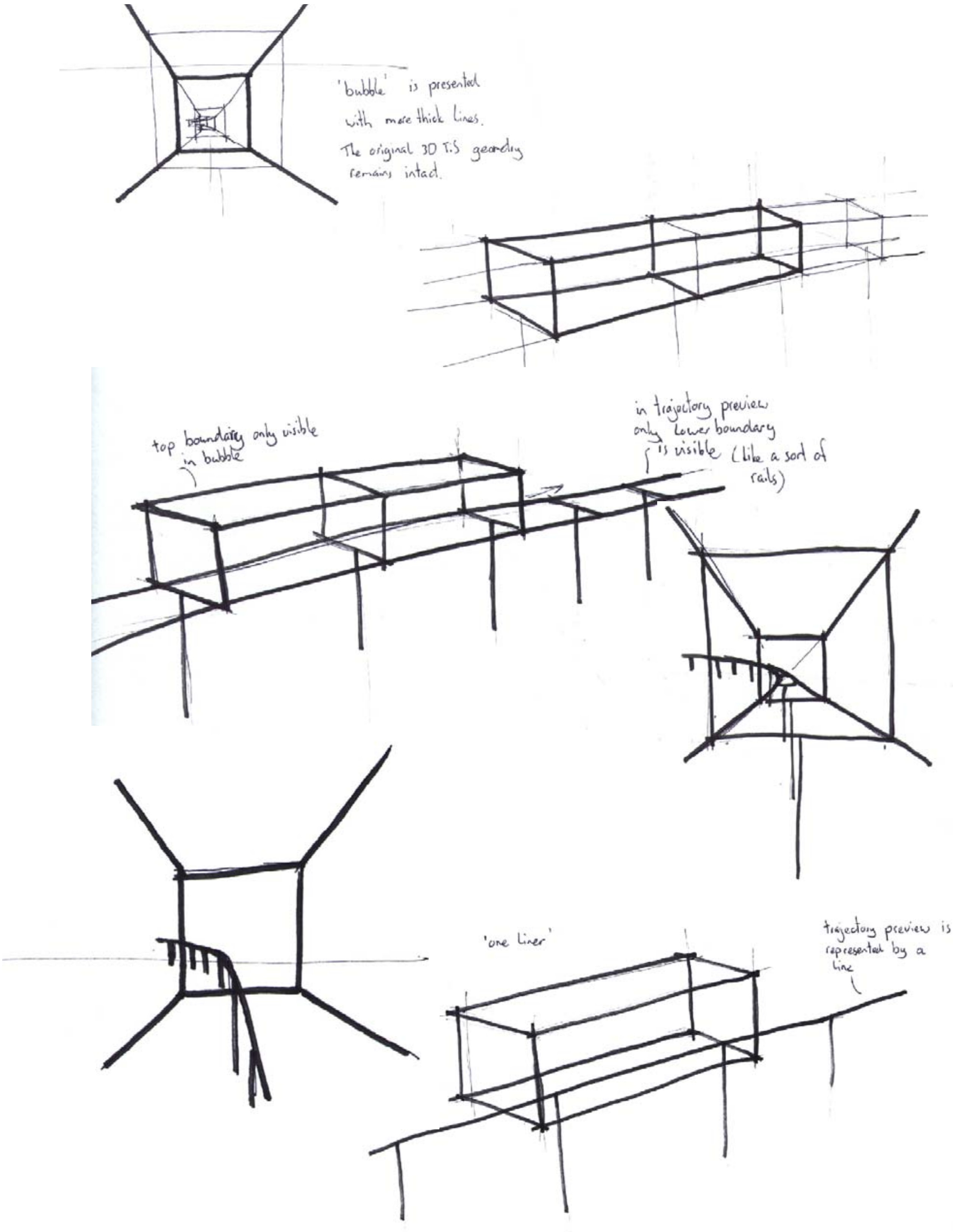


Fig 5.3. The pilot- and external view of three possible solutions to distinct the bubble from the tunnel.

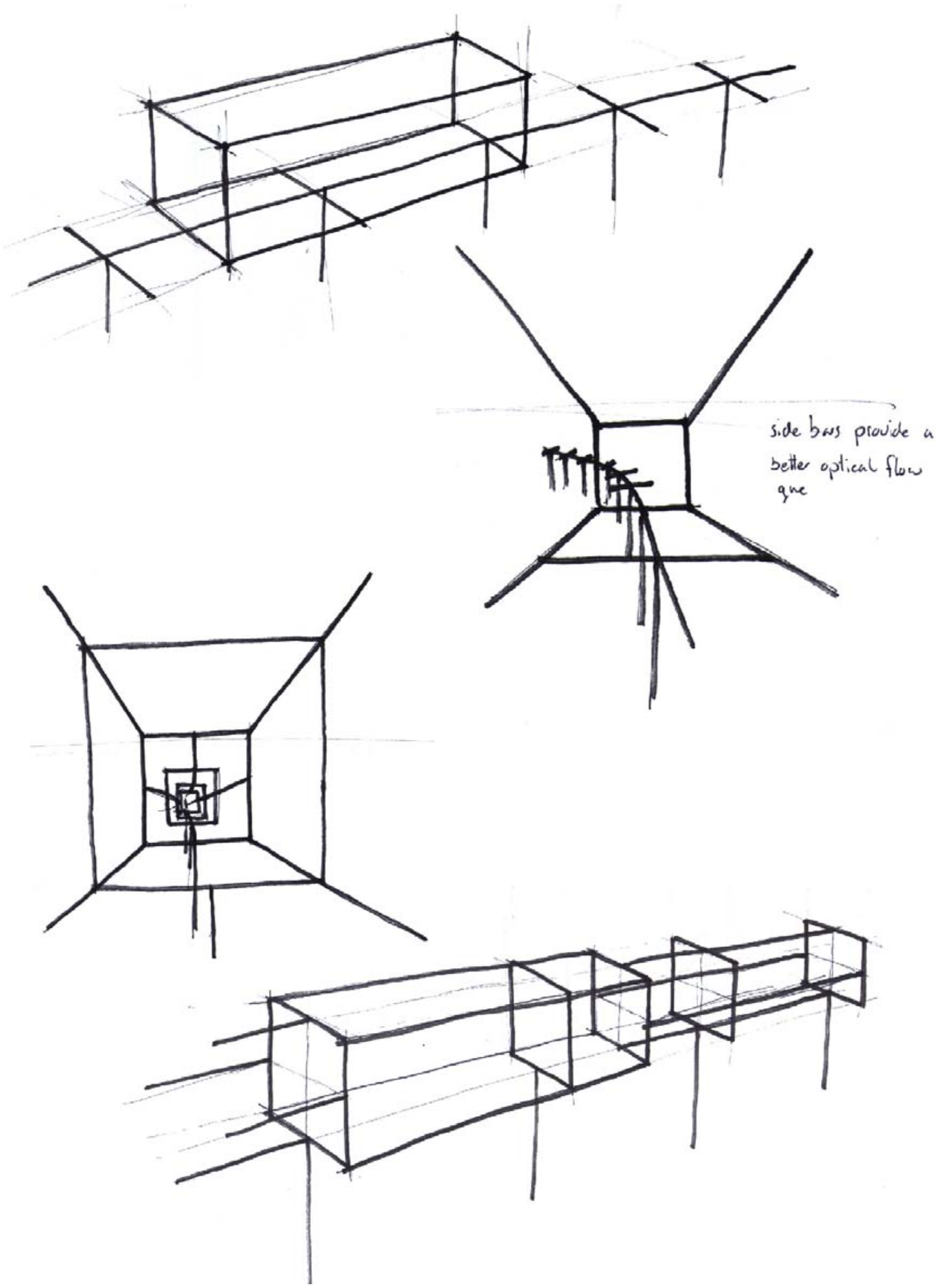


Fig 5.4. The pilot- and external view of two possible solutions to distinct the bubble from the tunnel.

POSITION IN THE BUBBLE / LIMITED FIELD OF VIEW

Because the pilot flies inside the bubble he needs to know where he is inside this bubble. How far to the front or the back is he or she? Although time-to-contact in itself appears to be a useful cue, it might be necessary to visually stress the approach to the front or rear boundary to enhance the awareness of the pilot.

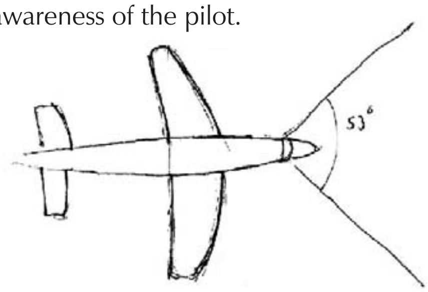


Fig 5.5. The limited field of view in the display.

Very closely related to the position problem is the problem with the limited field of view. The field of view in the display is 53°. This means the pilot is never able to see the rear boundary while he is inside the bubble. This boundary is important though; the pilot needs to know when he is about to cross the rear boundary.

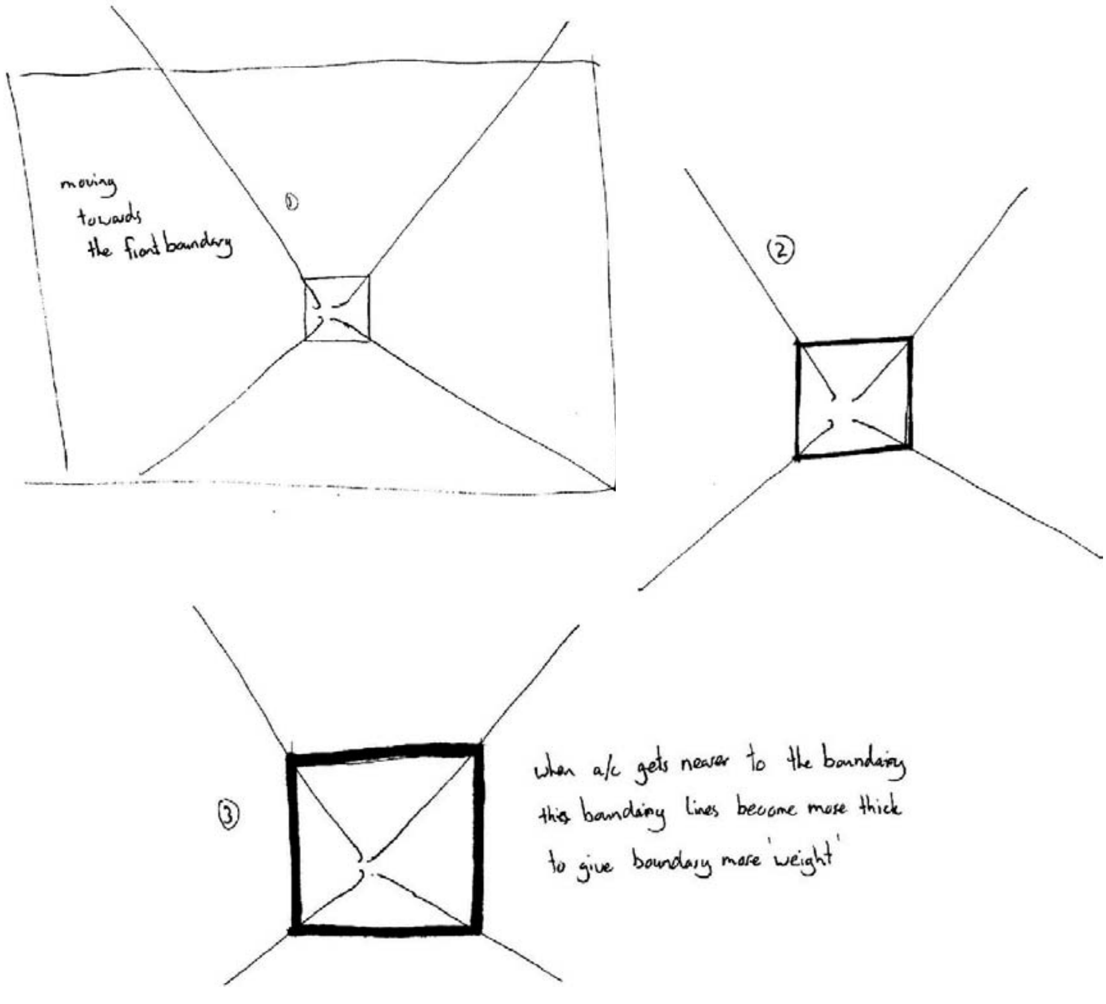


Fig 5.6. A solution to visually stress the approach to the front boundary.

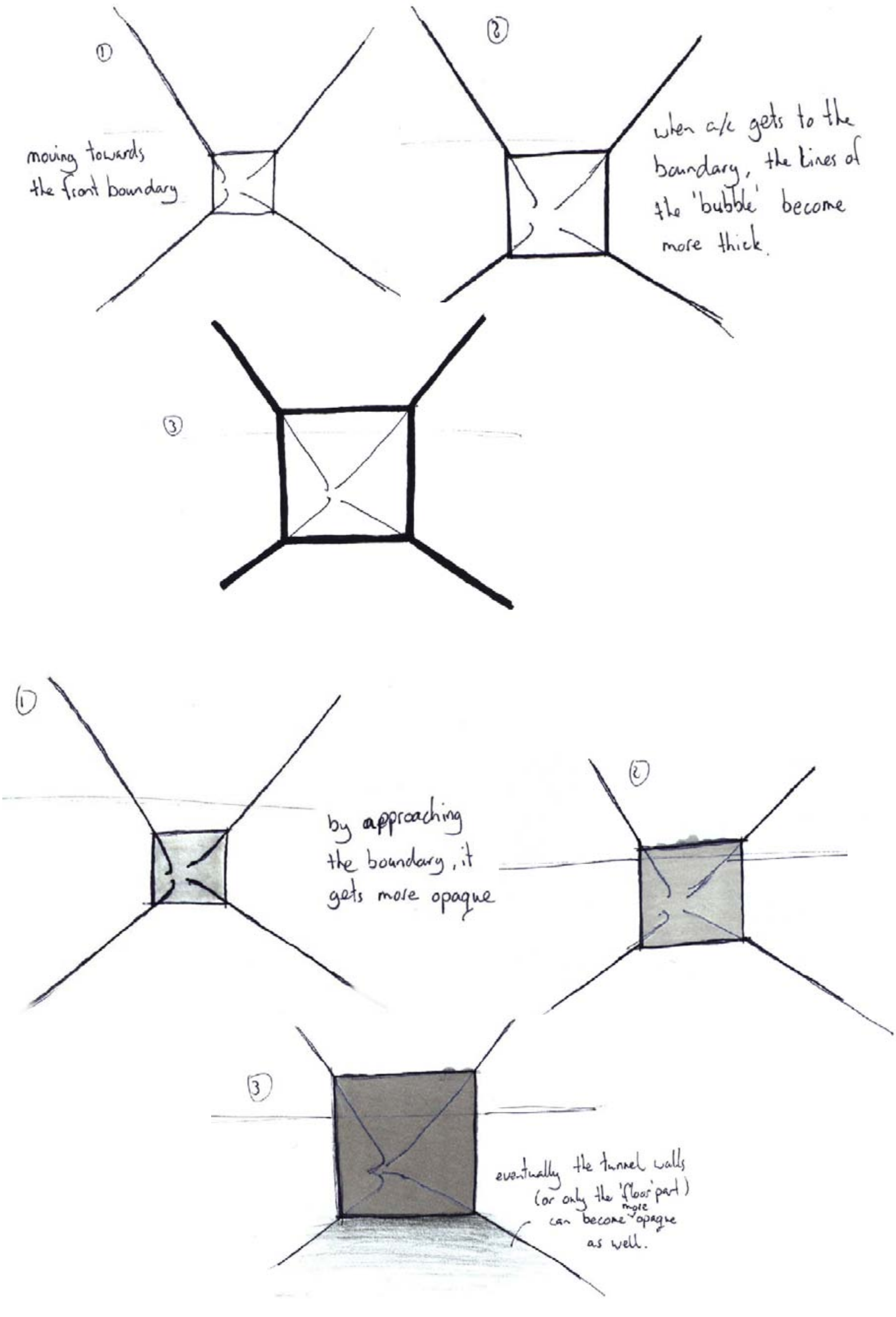


Fig 5.7. Two solutions to visually stress the approach to the front boundary.

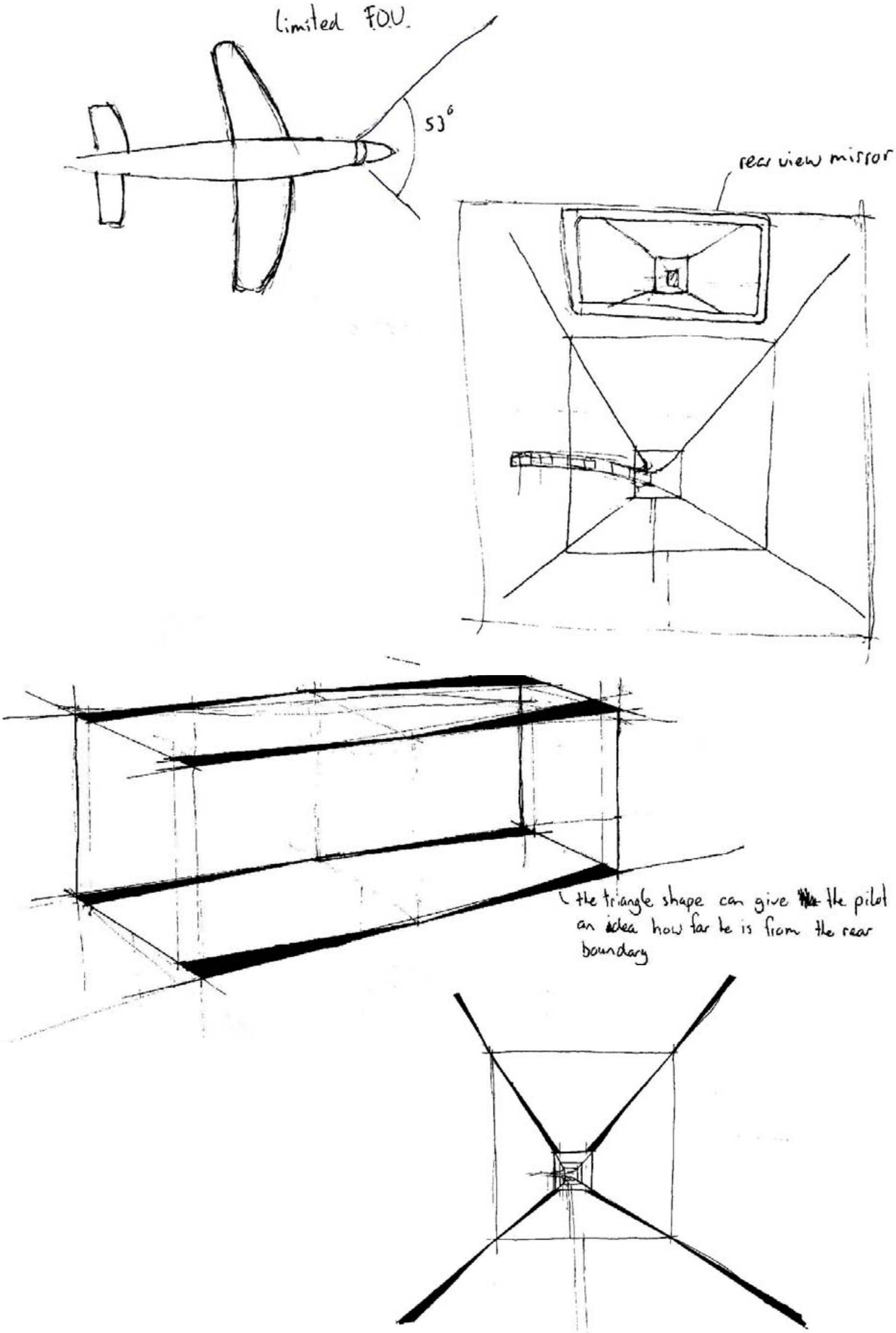


Fig 5.8. Solutions for the limited field of view; A 'rearview mirror' in the display and symmetrical triangle shapes inside the bubble.

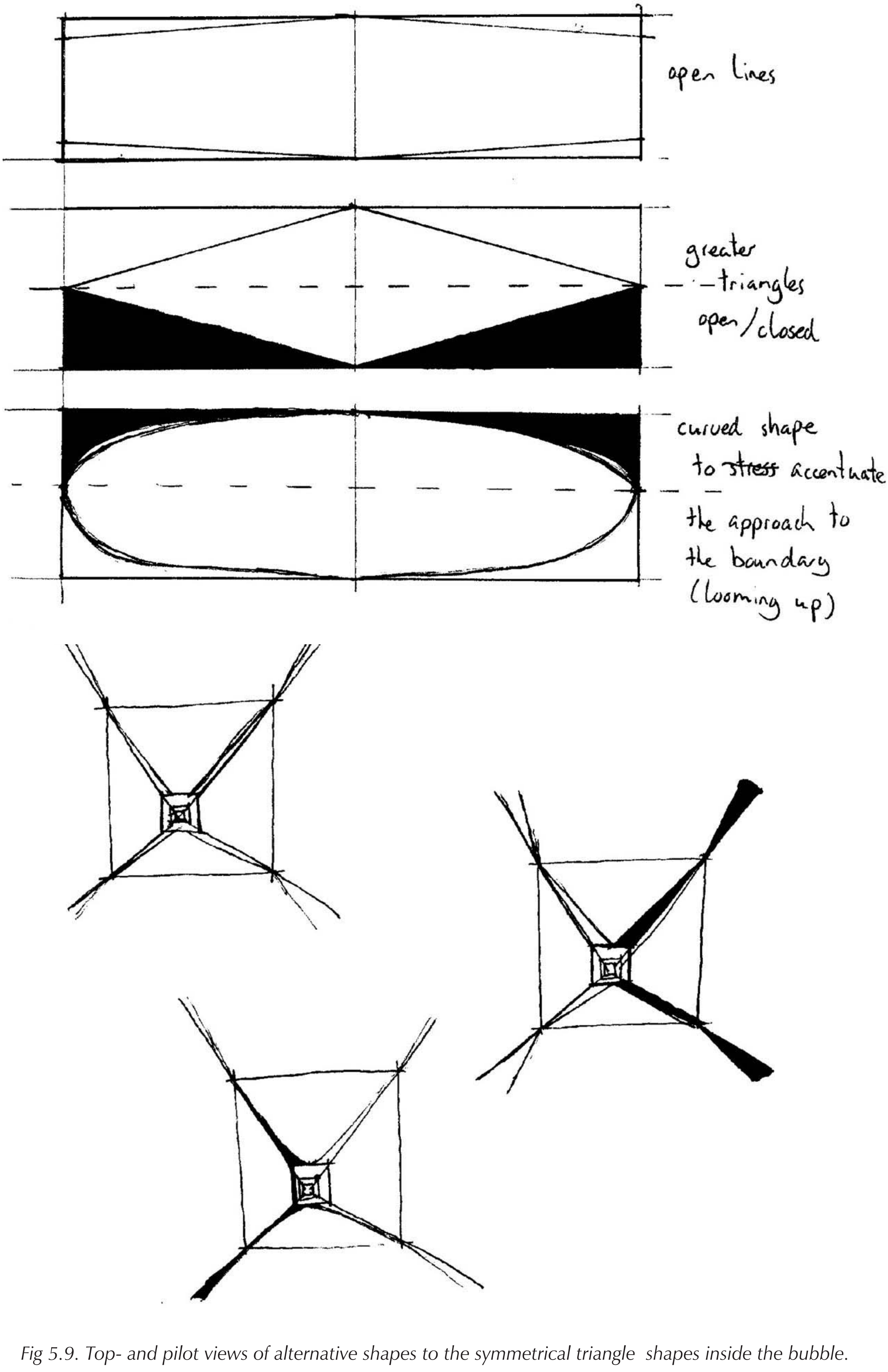


Fig 5.9. Top- and pilot views of alternative shapes to the symmetrical triangle shapes inside the bubble.

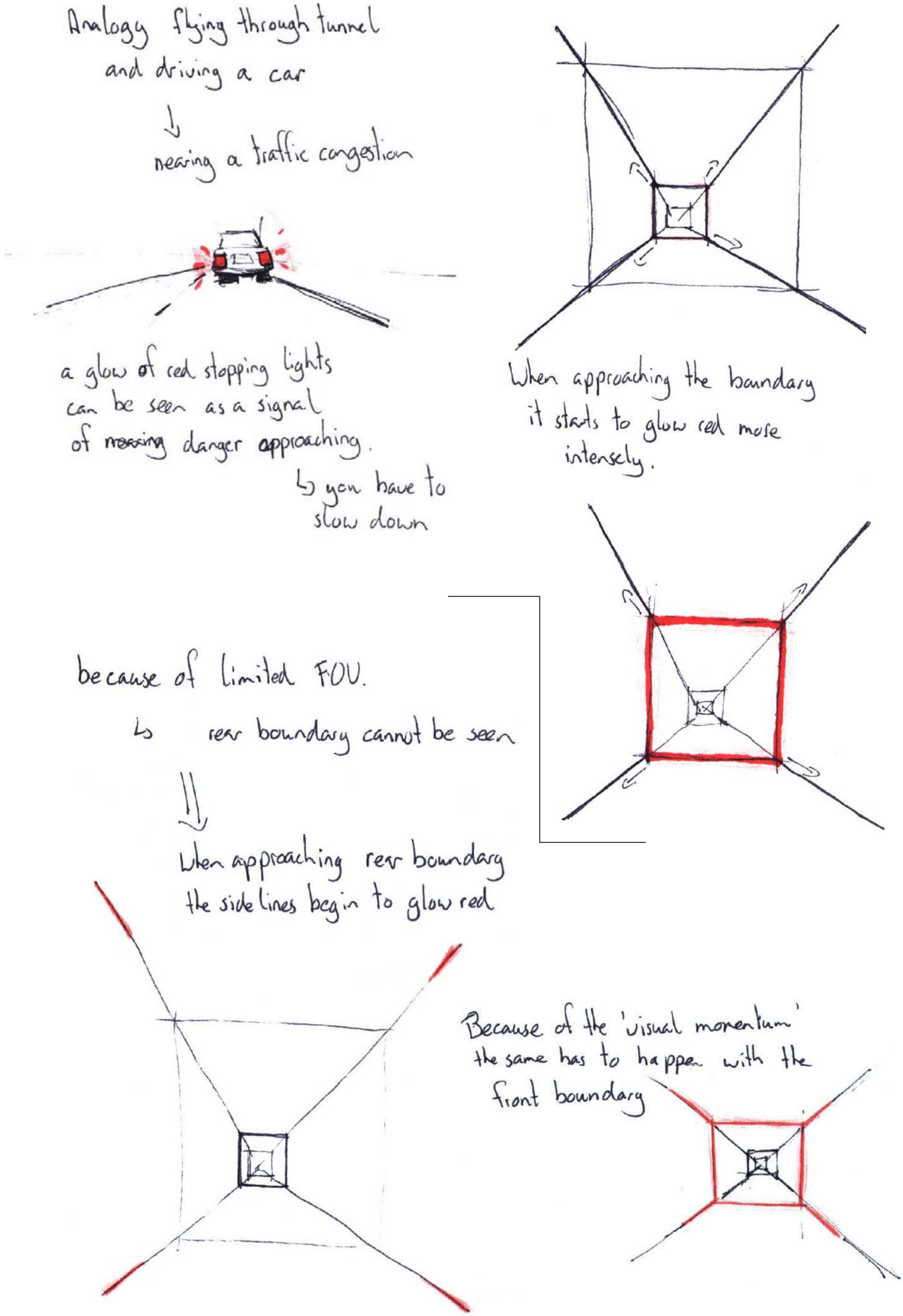


Fig 5.10. A solution to pronounce the approach to the front and rear boundary.

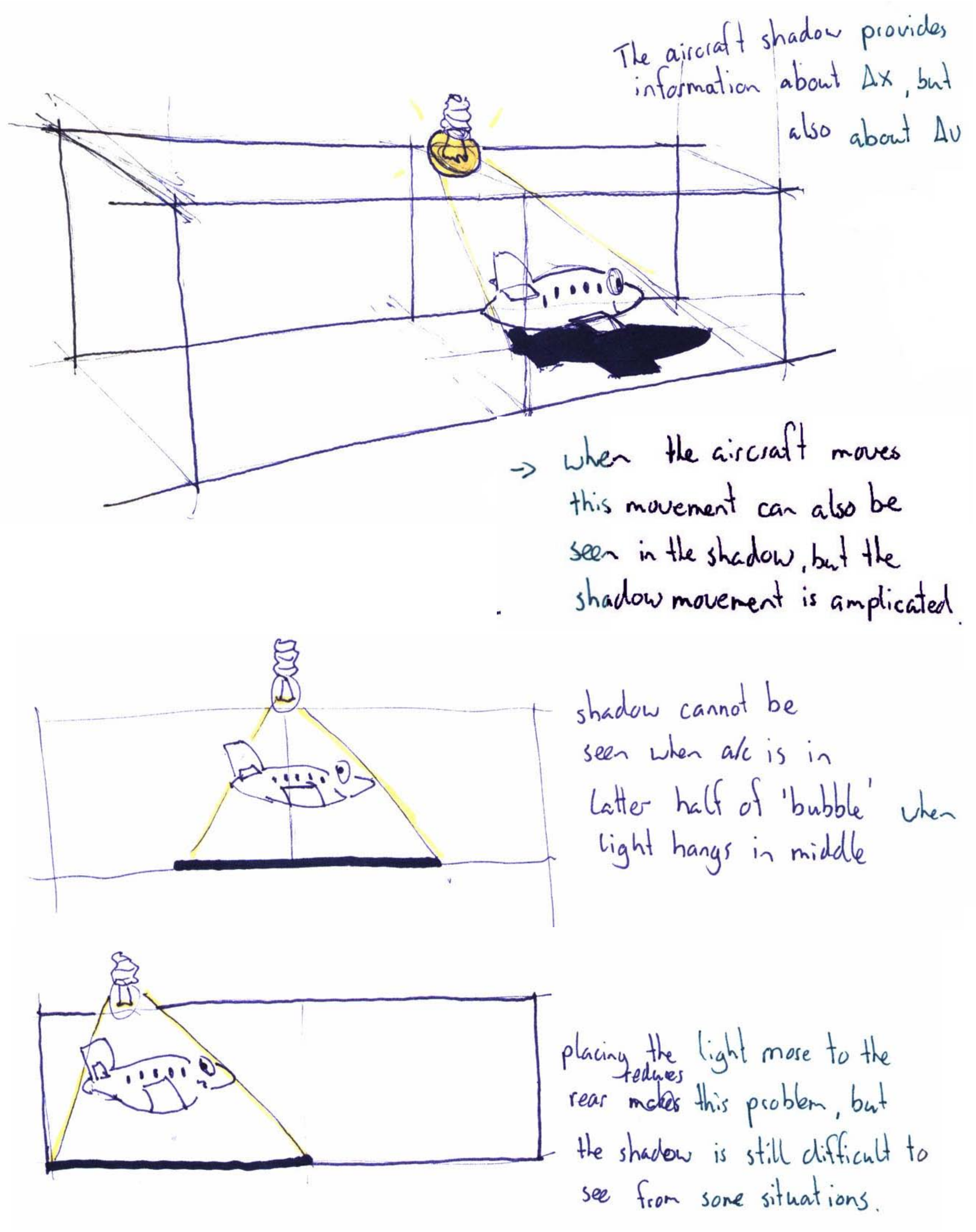


Fig 5.11. A combined solution to the limited field of view and the position problem by means of a shadow.

TOO FAST / TOO SLOW

To stay inside the bubble the pilot needs to fly with roughly the same speed as the bubble does. Although the aircraft will move with respect to the bubble, this movement might be difficult to be observed by the pilot. In this section a number of solutions will be presented that can make the relative speed difference more clear.

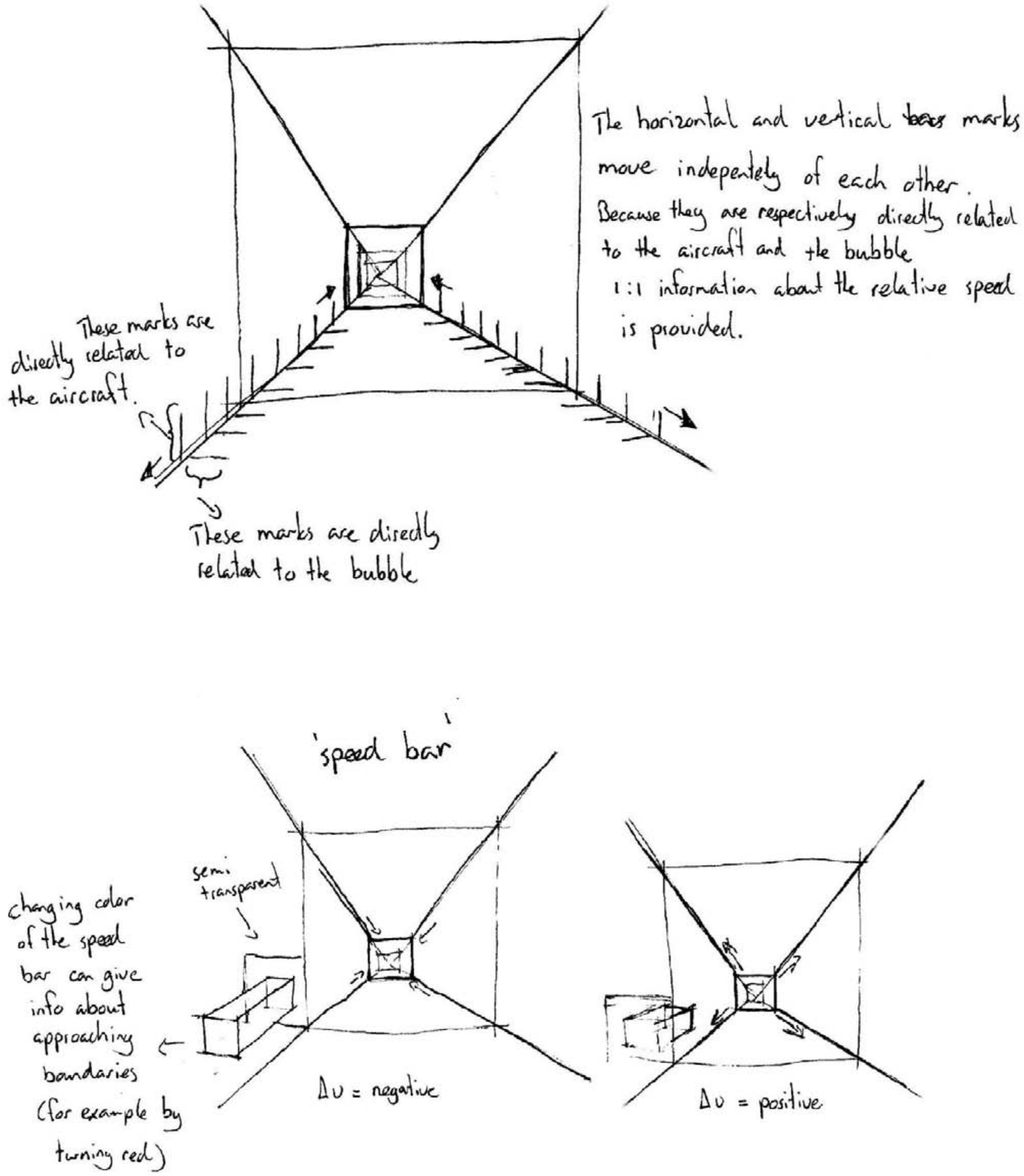


Fig 5.12. Two solutions to indicate the relative speed between the bubble and the aircraft.

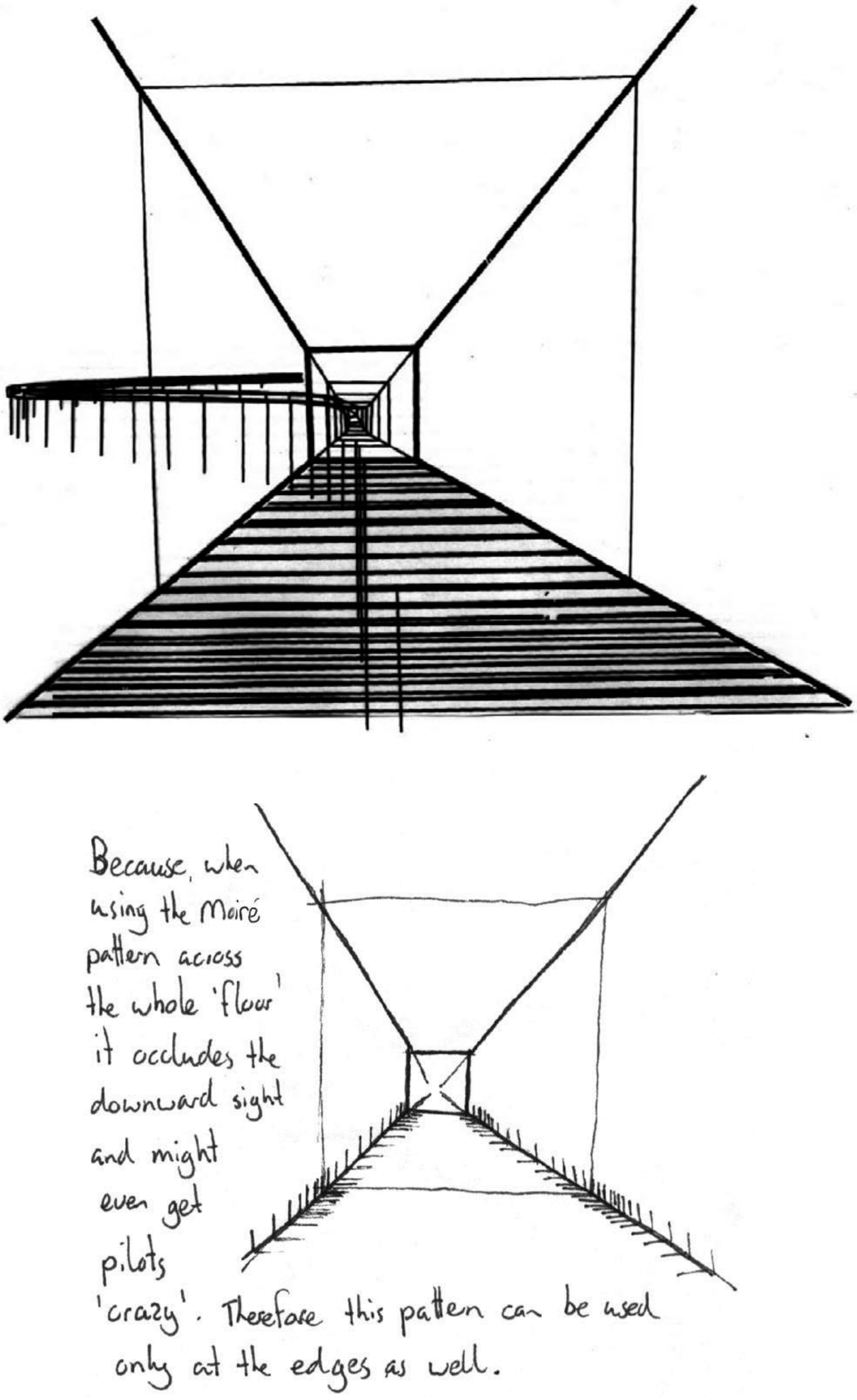
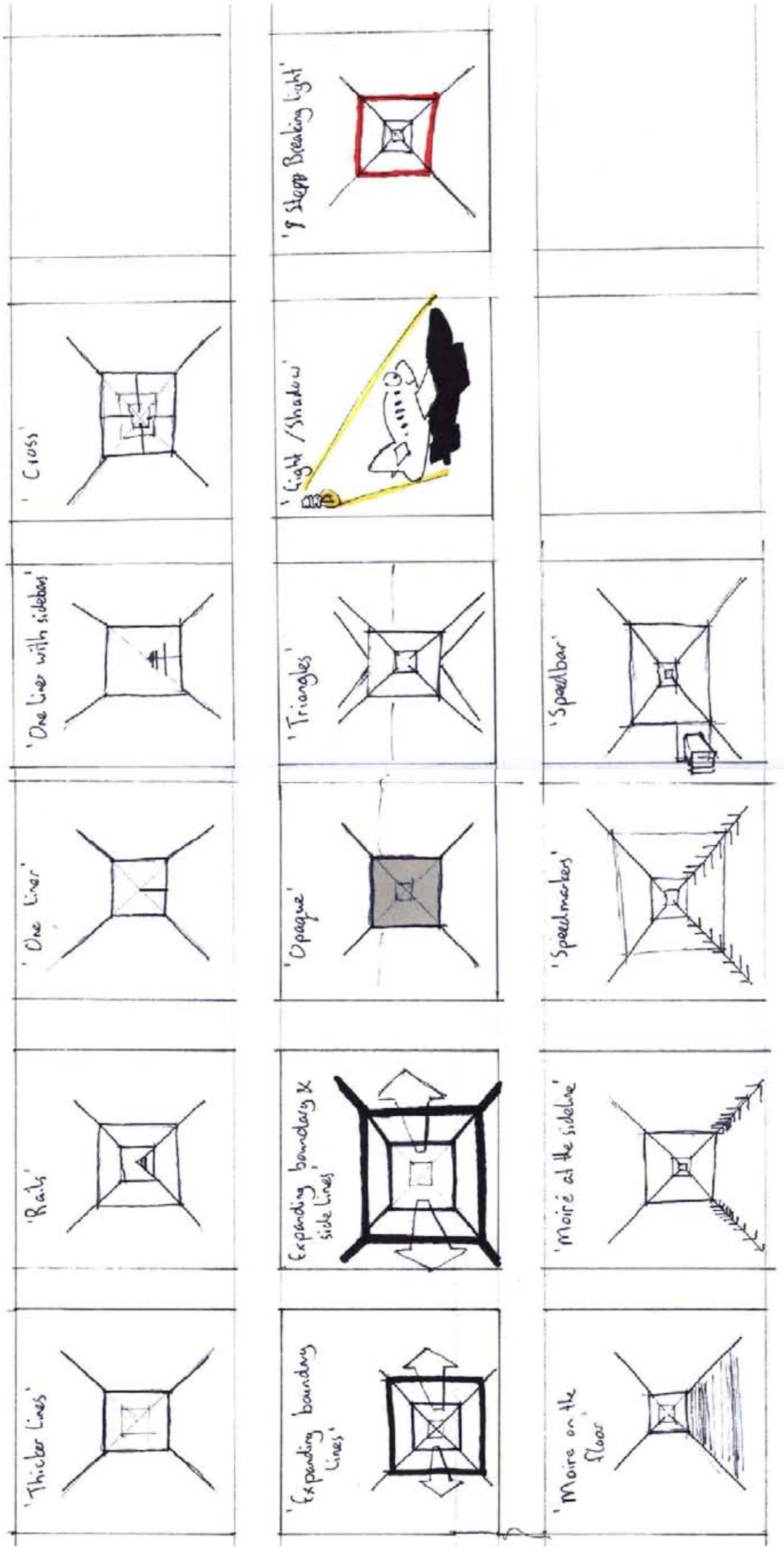


Fig 5.13. Two solutions to indicate the relative speed between the bubble and the aircraft. Both consist of a patern that moves forward when the aircraft flies to slow, and moves backward when the aircraft flies too fast. The patterns are based on the moire effect.



Tunnel-bubble distinction | Position in bubble/ limited view | Too fast / slow

Fig 5.14. Overview of all solution sketches.

CHAPTER 6

ANIMATED CONCEPTS

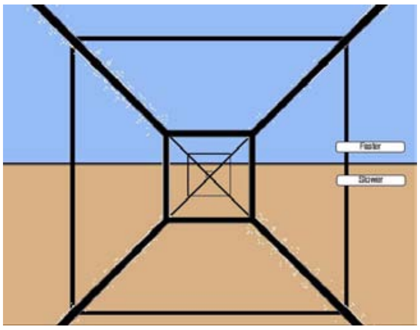
Since most solutions that were presented in the previous chapter are dynamic, it is difficult to comprehend how the solutions work out. To see how the solutions work out dynamically, a number of concept-ideas are animated. The animated concepts, which can be found on the accompanying CD-ROM (Appendix J), are described briefly below. After the description, remarks about the good and/or bad points of the concepts are given in Italics.

GENERAL

In each animated concept one can see the display, as it would be presented to the pilot. In the display the tunnel is represented from the pilots' point of view. The background of the display is divided into two halves separated by the horizon. The upper part of the background is light blue, the lower part has got a brown color. The two background halves respectively depict the air and the ground. The trajectory that can be seen in the display has got a small downslope. The horizon is therefore placed higher in the display. The moving rectangular tunnel segments suggest movement through the tunnel.
One can move inside the bubble by flying faster or slower.

TUNNEL-BUBBLE DISTINCTION

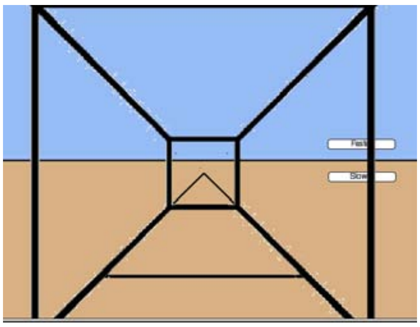
Thicker lines



Making the bubble lines thicker than the tunnel lines represents the distinction between the bubble and the tunnel. The bubble is made out of three rectangles, one in the front, one at the back and one rectangle in the middle of the bubble. The middle rectangle can help determine where the aircraft is in the bubble.

The concept is easy to interpret, the differences between the tunnel and bubble are easy to interpret.

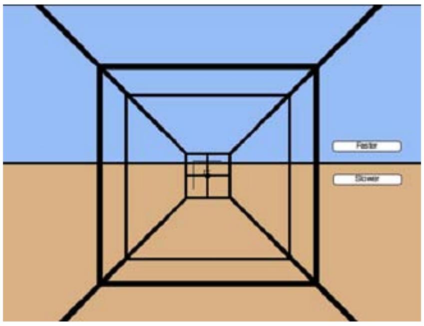
Rails



In the Rails solution, removing the upper lines of the tunnel creates the distinction between the bubble and the tunnel.

Because the upper tunnel segments are missing, the display has got less clutter. When the aircraft will fly low in the tunnel, the tunnel preview will be difficult to see.

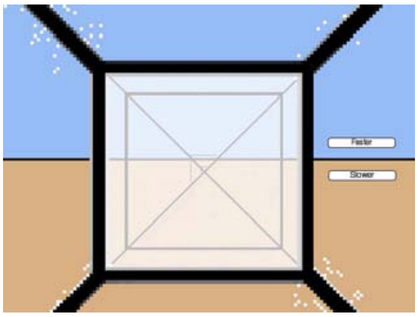
Cross



In the Cross solution the bubble is distinguished from the tunnel by moving the lines, which connect the tunnel-frames to each other, from the corners to the center of the rectangles.

The transition between the tunnel and bubble is quite a large discontinuity.
The information the tunnel gives is very different from the original tunnel information. The tunnel has got a different 'meaning'.

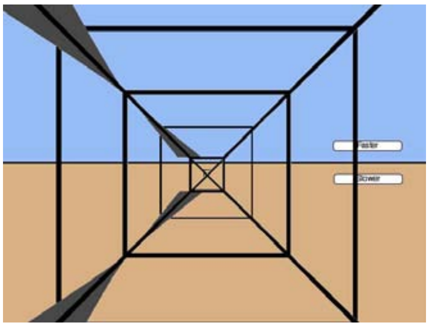
Transparent



In the Transparent concept the front boundary becomes less transparent when the aircraft approaches the front- or the rear boundary.

In the concept it is clear that approaching the boundary isn't desired. The disadvantage of making the boundary less transparent is that the tunnel preview becomes almost unavailable at a critical moment.

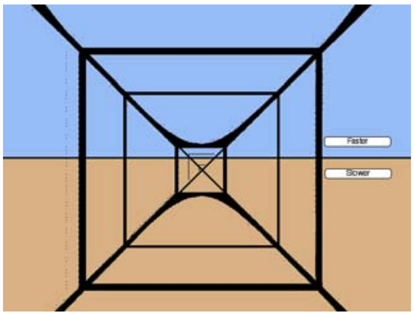
Triangles



In this concept two triangles are placed in the upper- and lower plane of the bubble. The triangles are the exact mirror images of each other, with the middle rectangle of the bubble as mirror plane. In this way the pilot can, by looking forward, see if he approaches the rear boundary.

The triangles really help in 'seeing' the rear boundary. The triangles are aesthetically not well integrated in the bubble.
The line in the triangles inside the bubble has got a discontinuity in the middle of the bubble. This makes it more difficult to extrapolate this line to the rear boundary.

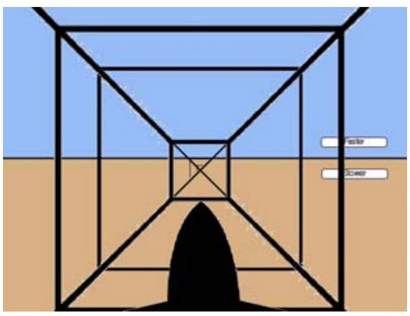
Curves



As an alternative shape to the Triangles shape, curves are used in this concept. The Curves shape reflects the gradual character of the bubble (see chapter 3) better in that the sidelines increasingly become thicker nearer to the front- and rear boundary. This thickness then, more or less, reflects the risk of crossing the boundary. Also the curved line is a continuous line that goes from the front to the rear part of the bubble.

As with the Triangles concept, the curves help in 'seeing' the rear boundary. Compared to the Triangles concept, the curve lines are better integrated in the bubble, the lines are better to extrapolate and the curves are also more 'proportional' to the task of keeping the aircraft inside the bubble.

Light/shadow



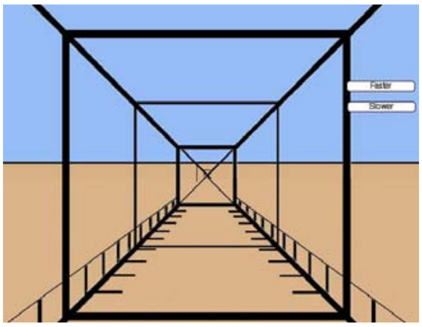
In this concept the pilot can see the shadow of the aircraft in front of him, projected on the lower plane of the bubble. When the aircraft is too far to the front, the shadow will cross the front boundary. When the aircraft flies too far to the back, the pilot gets 'blinded' by the light source that 'created' the shadow

The Shadow concept integrates the position-, limited field of view- and relative speed problems nicely. The pilots might not give much meaning to a shadow that crosses a boundary.

The 'blinding', i.e. the lighting up of the display, when the aircraft gets too far to the back can look like the display has got a malfunction.

Too fast / too slow

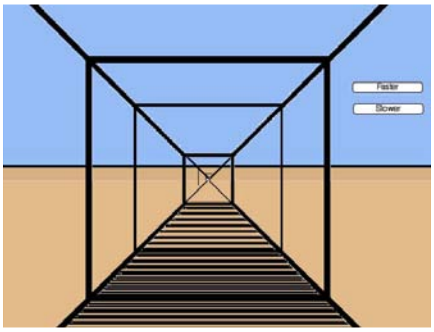
Speedmarks



The Speedmarks concept has got a number of horizontal lines on the floor and vertical lines on the sides of the bubble. The lines are only visible in the lower corners of the bubble.
The vertical lines are coupled to the aircraft and appear stationary to the pilot. The horizontal lines are coupled to the bubble. When there's a speed difference between the bubble and the aircraft the horizontal lines will move with the bubble. The vertical lines will help in perceiving this motion.

The movement as a result of the speed difference can be seen clearly. It might be a problem to 'remember' which lines are coupled to what. This can lead to confusion whether the aircraft is flying too fast or too slow.

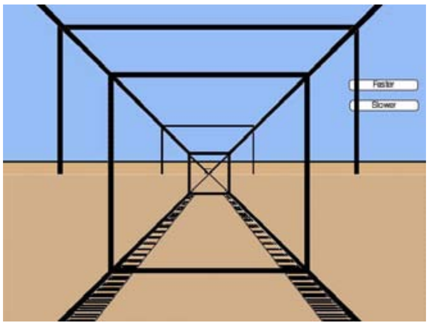
Moiré on the floor



Here, a pattern is placed on the lower plane of the bubble. To create an optical flow effect, the pattern moves forward when the aircraft flies too slow, and moves backward when the aircraft flies too fast. This moving pattern is based on the Moiré effect.

The pattern that moves faster than the bubble does, makes speed differences better to distinct than the 1:1 movement of the Speedmarks concept. But at higher differential speeds the pattern movement becomes more difficult to see.

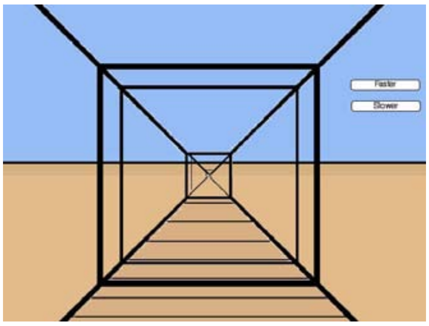
Moiré on the sides



This concept is the same as the Moiré on the floor concept. The difference is that the pattern is reduced. The pattern is only visible at the sides of the bubble so as to create less occlusion.

The display is cleaner, with less clutter, but the pattern movement is more difficult to see than that of the Moiré on the floor concept. Sometimes the movement of the pattern appears to invert.

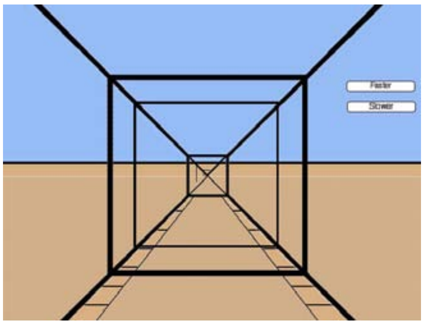
Moving ground



The Moiré effect used in the two above-mentioned concepts appears to be difficult to see. The effect depends on the grid spacing, the speed difference and the display refreshing-rate. Because of this, the pattern can sometimes appear to be moving in the opposite direction.
The effect of a moving pattern on the display can be made without the Moiré effect. This is done in the Moving ground concept. Here a simple grid is used instead of the more complex Moiré grid. The simple grid moves with a speed that is higher than the speed difference between the bubble and the aircraft. The grid moves faster to augment the optical flow effect.

The moving pattern of lines is better to see than the Moiré effect variant. Also the display looks clearer, calmer.

Moving sides



In this concept the moving grid, as described above is only visible at the sides of the bubble.

The Moving sides concept is as good as the Moving ground concept with less clutter. The display is even more calm, but the optical flow from the moving lines are still very good visible.

The choice, which concepts will be used for further analysis will be explained in the next chapter.

CHAPTER 7

TOWARDS AN EXPERIMENT

The choices for the visualizations were made with an eye towards an experiment. The main question for this experiment was: "How much information should be presented in what way to be optimal for the pilot?" In order to try to answer the question it is necessary to know whether the basic bubble contains enough information in itself, or if more information is necessary. This extra information can be about the position inside the bubble and/or about the relative speed between the bubble and the aircraft.
To get more insight in the question, we chose to test three different visualizations. These three visualizations will be described here.

CHOSEN VISUALIZATIONS

Boxcar

The Boxcar visualization is essentially a tunnel segment with a front and a rear boundary that creates the basic bubble-shape. To indicate the middle of the bubble, a rectangle is placed here (figure 7.1).

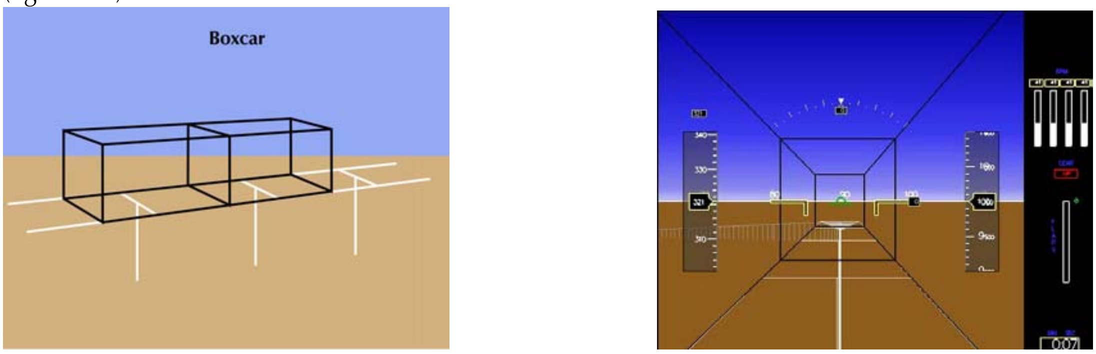


Fig. 7.1 External- and pilots view of the Boxcar visualization.

Using different colors creates the distinction between the tunnel and bubble; the tunnel is white, while the bubble is black. The bubble-lines are also thicker than the tunnel lines. The line-thickness is respectively two and one points. To pronounce the tunnel-bubble distinction, the tunnel is represented as rails; the upper lines of the tunnel are not shown.
The Boxcar has got no other extra information added. All information about the position of the aircraft in the bubble, the rear boundary and information about the speed relative to the bubble, have to be derived from the basic bubble shape only.

Moving sides

This visualization consists of a basic bubble, like the Boxcar, inside a complete tunnel (figure 7.2).

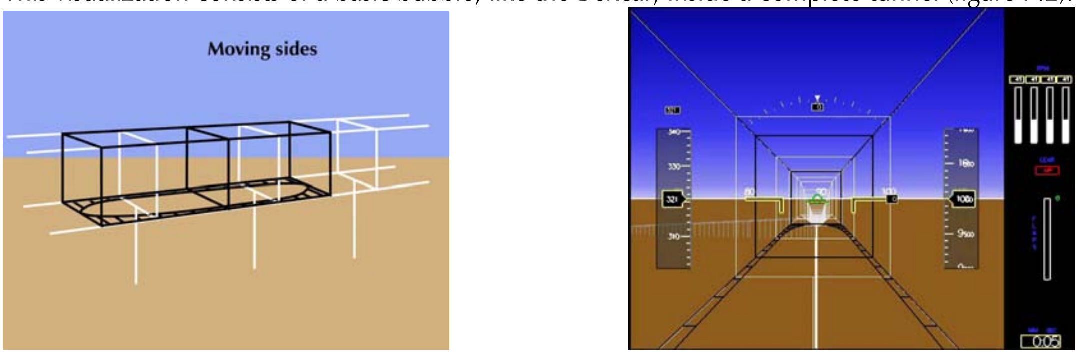


Fig. 7.2 External- and pilots view of the Moving sides visualization

Except that the tunnel is completely visible now, the tunnel-bubble distinction is identical to that of the Boxcar. Information about the position of the aircraft is given by using the Curves concept; the bottom plane of the bubble has got an oval shape to better see the position in the bubble, especially when approaching the rear boundary.

Speed information is represented by means of the Moving sides concept. This concept consists of cross-lines on the bottom plane of the bubble. When the aircraft flies too fast the cross lines will move from the front to the back. This movement reverses as the aircraft flies slower than the bubble. The two concepts are integrated by varying the moving lines in length so as to form an oval shape. This visualization is called ‘Moving sides’.

Shadows

The Shadows visualization is a basic bubble inside a complete tunnel, like the Moving sides visualization (figure 7.3).

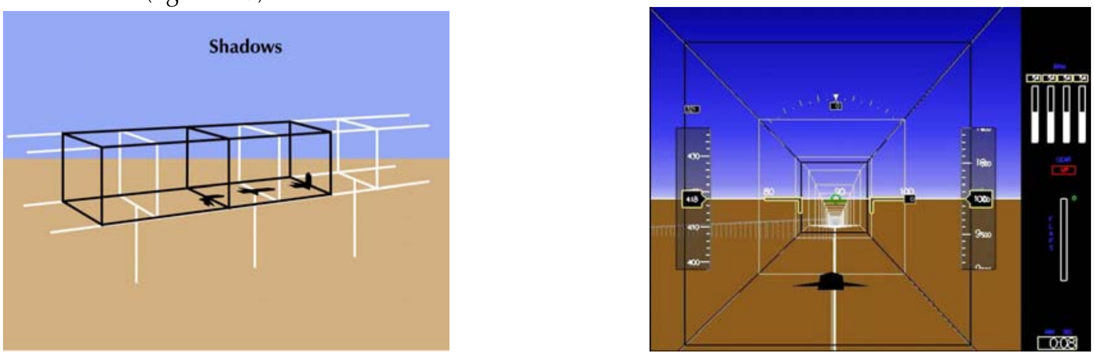


Fig. 7.3 External- and pilots view of the Shadows visualization.

In the third visualization, position- and relative speed information is presented in an integrated fashion by means of the Shadows concept. To add more meaning to the shadow when it crosses the front boundary, the shadow climbs up the wall instead of crossing this boundary. The blinding effect to depict the rear boundary is replaced by the shadow falling of the lower plane of the bubble.

TUNNEL DISPLAY GEOMETRY

Apart from the bubble visualizations, more information is presented to the pilot. This information consists of navigation as well as aircraft information (figure 7.4). Below, this will be explained.

The tunnel used in the experiments consisted of square frames positioned on altitude poles that were connected with longitudinal lines. The distance between two successive tunnel frames was 450 meter. This distance is based on earlier research, done by Mulder (1999). As said before, in the experiment the tunnel-lines were white, the bubble lines were black.

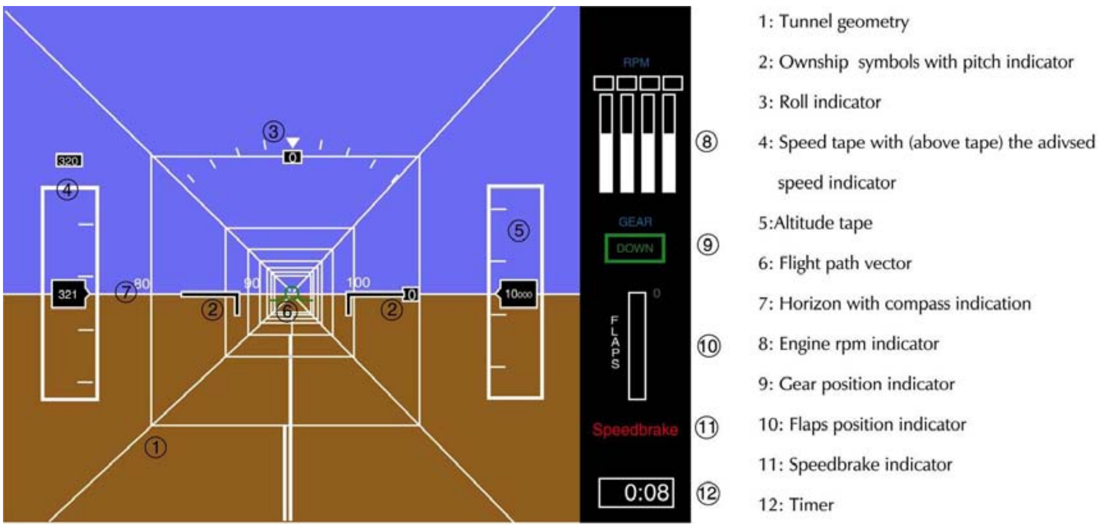


Fig 7.4. Basic display features of the visualizations, used in the experiment.

The size of the bubble depends lateral- and vertical-wise on the tunnel cross-section and longitudinal-wise on the speed of the bubble.
The size of the tunnel cross-section is based on earlier research, done by Mulder (1999). The size is variable and depends on the speed the bubble has at a given place. The approach-to-land the subjects had to fly, started out with a speed of 320 kts (knots) in a tunnel cross-section of 135 x 135-meter. During the approach the subjects had to slow down to a speed of 180 kts, the accompanying tunnel cross-section was 45 x 45-meter.
The distance between the front- and rear boundary of the bubble depended on the bubble speed. The separation between the boundaries is 10 seconds and was based on an estimation of the separation-margin that ATC allows. So at the start of the approach (v= 320 KTS or 165 m/s) the bubble length is 1650 meter. At the end of the approach the speed is 180 KTS or 93 m/s so the corresponding bubble length there is 930 meter.
Both the tunnel cross-section and the bubble length are directly correlated to the bubble speed.

Information about the aircraft that was necessary to perform the experiment was placed to the right side of the Bubble display (figure 7.4). The four bars in this panel give information about the number of revolutions, the 4 engines make (8). The gear position indicator tells whether the landing gear is in up, down or in transition. It does this by means of changing color, respectively red, green and white. The information is also given in alphanumerical format (9). Below the gear position indicator we find the flaps position indicator. The flap position is indicated by means of a bar and alphanumerical information that shows the selected flaps position (10)
When the speedbrake is selected a red rectangle labeled Speedbrakes. flashes (11). The timer in the right lower corner indicated the elapsed time of the test run. This timer was not used during the experiment.

THE MOST RELEVANT TRAJECTORY

To perform the test, a trajectory needs to be flown. The best-suited trajectory is the approach-to-land. During the approach/landing phase of the flight, navigating through space-time is the most critical. Because of the high aircraft density in the vicinity of airports, it is essential that in this part of the flight the aircraft stays on its trajectory and maintains separation. In this phase the 'safe field of travel' comes of interest.
When approaching an airport following a Standard Terminal Arrival Route (STAR), usually a strict velocity constraint holds (figure 7.5). In the future it can be expected that further strict time constraints hold for the aircraft approach routes.
Although the 'safe field of travel' is relevant to the cruise flight phase as well, during this flight phase, flying is mostly done by the autopilot. Also the margins are usually greater. Therefore it is more interesting to use the approach phase for the experiment.

	A	B	C	D
S-ILS 01R*	189/730m		200 (200-800m)	
S-LOC 01R**	440/730m 451(500-800m)		440/1220m 451(500-1200m)	440/1520m 451(500-1600m)
CIRCLING***	620-1600m 631 (700-1600m)		760-3600m 771(800-3600m)	880-4800m 891(900-4800m)
S-ASR 01R**	580-2000m 591 (600-2000m)			

*When ALS inop, increase vis 400m.
**When ALS inop, increase vis 800m.
***Circling Rwy 19L: ceiling 1200, vis 5000m.

OM to MAP 3.8 NM					
Knots	60	90	120	150	180
Min:Sec	3:48	2:32	1:54	1:31	1:16

Fig 7.5. A typical STAR for Schiphol. Notice the remark in the red circle (Cross the circle at a distance of 15 miles from beacon SPL at a speed of 220 knots, unless otherwise instructed).

SECTION 3

EXPERIMENT

CHAPTER 8

EXPERIMENT METHOD

The experiment described in this report is a preliminary experiment, that investigates the effects of three different Bubble in the Sky visualizations against the Tunnel in the Sky display as a baseline. The experiment has a preliminary character in that it is a starting point for further research on the Bubbles in the Sky visualizations.

SUBJECTS

The task the subjects had to perform was quite difficult. The subjects had to fly a complex approach, within a broad speed range and with various aircraft configurations, i.e. multiple flap settings. Because we did not have enough time to train subjects, subjects who already had pilot experience were required (table 8.1).

Table 8.1. Subject flying experience.

Subject	Experience		
1	60+ hrs	(VFR only)	The author, glider pilot experience
2	25 hrs		Simulator experience in flying ILS approaches
3	2000 hrs	(VFR / IFR)	Military jets, pilot experience gained as a backseater
4	280 hrs	(VFR / IFR)	Light aircraft experience
5	3200 hrs	(VFR / IFR)	Medium sized commuter aircraft experience
6	6800 hrs	(VFR / IFR)	Military and civil experience on heavy aircraft

Six subjects, among which the author, participated in the experiment. Five of the subjects were pilots with varying experience. Of the 6 subjects, 2 subjects (subject 2 and 4) made too large deviations from the desired trajectory to give proper data readout. Because of this, the results from these two subjects were not used for the analysis.

APPARATUS

The experiment was held in a CAVE virtual environment. The CAVE is a room of 3.1 x 3.1 x 3.1-meter. The sides are made up of four rear-projected walls and a down projected floor. The images are generated on an SGI Onyx computer with InfiniteReality graphics and displayed by five CRT projectors (Electrohome M 8500).

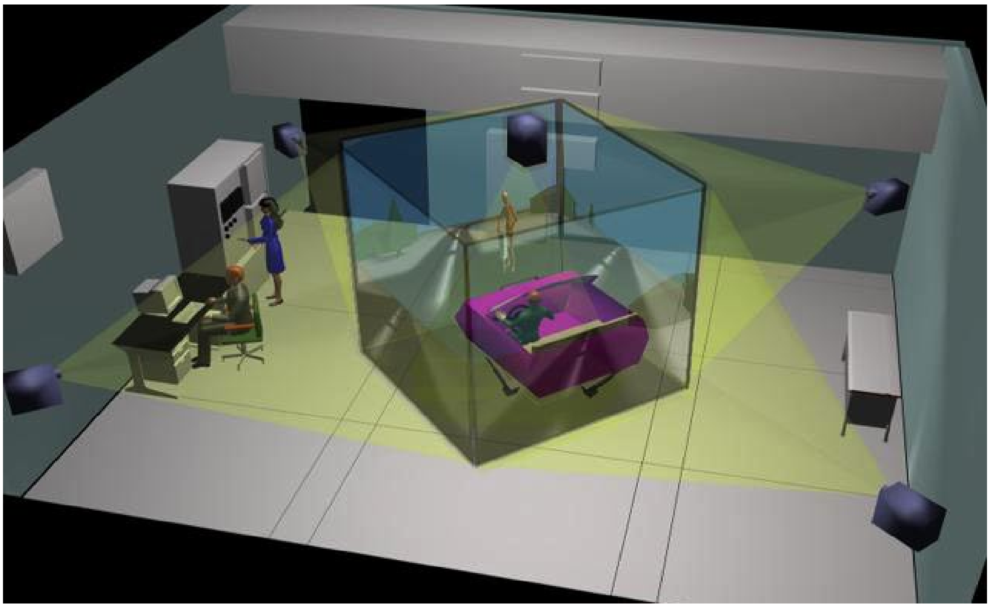


Fig 8.1. An example of a CAVE setup. Note the 4 wall projectors (blue boxes in each corner) and the floor projector. In this CAVE setup we can see a person driving in a mock-up car through a virtual environment (a person standing on a road).

Inside the CAVE an external computer (SGI O2) was placed. This computer was coupled to the CAVE computer through an Ethernet connection and drove an SGI LCD display (37.2 x 23.4-cm). On this LCD screen the display visualizations were displayed.
For the experiment only the front-, side- and floor projectors of the CAVE visual system were used to create an out-of-the-windshield view. The projection system was not used in stereo (binocular) mode, because the stereo-goggles interfered with the LCD screen (polarity). Also according to Koenderink (1986) the binocular effect can be neglected when the depth of 3D objects or scenery is less than five percent of its distance to the viewer. In the used scenery, most large scenery objects, like mountains, can be found in the background. So we can neglect the binocular effect in the projected scenery.

The subjects were seated in front of the display. The chair on which they were seated had a throttle (Thrustmaster F16 TQS) assembled at the end of the left armrest. On the right armrest a flightstick (Immersion Corporation) was assembled. The throttle had a number of buttons on it, which were used to select flap-positions, speed brakes and landing gear.

The aircraft simulation model used for flying the approach was that of a Boeing 747 –200 (FLSIM, Virtual Prototypes). Because of the deceleration from 320 to 180 KTS, selecting flaps was essential to keep the aircraft flying. Because the flying task itself already was difficult enough, we simplified the flaps positions so that only three positions were available (0, 20 and 30 degrees).

Independent variables

The independent variable that was varied in the experiment is the display visualization.
The three different Bubble visualizations are explained in chapter 7. The baseline, as used in the experiment, will be described here.

Tunnel

The basic Tunnel in the Sky display was used as baseline for the experiment (figure 8.2). The used display is similar to the Tunnel in the Sky display as described in chapter 3.

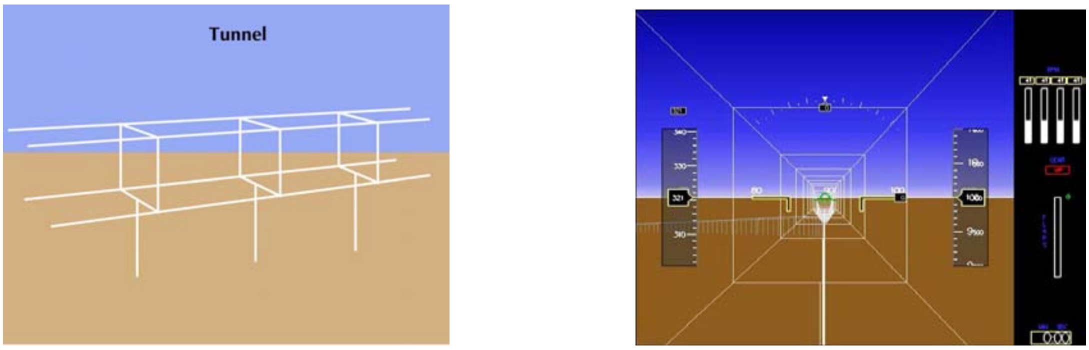


Fig 8.2. External- and pilot view of the Tunnel visualization. For a complete description of the display elements in the pilot view see figure XX.

To present some form of temporal information in the display, a small window was added above the speed tape to indicate the advised speed. This speed is similar to speed the (not visible) bubble currently has. This speed indicator doesn't take in account whether the aircraft has got a large deviation from the position it should have, i.e. the speed indicator doesn't provide the speed needed to come back to the preferred position, it only gives the speed the bubble has.

EXPERIMENTAL DESIGN

The experiment consisted of 20 runs (20 times flying a specific approach-to-land); five repetitions of four visualizations. In order to counteract gained experience throughout the test trials, i.e. maturing, the visualizations were randomized over the experiment.

The experiment was divided into two blocks, which were held on separate days. Both blocks consisted of a familiarization or a refresh run and respectively 8 and 12 runs for data collection.

Three approaches-to-land that varied in difficulty level were available. However only the first approach-to-land was used because the other approaches-to-land were too difficult to perform.

DEPENDENT VARIABLES

To measure the tracking performance we measured the error in X-, Y- and Z directions. The X error and the Z error are respectively the lateral- and vertical deviation from the ideal path. The Y error is the error along the track, measured from the middle point of the bubble to a plane perpendicular to the path that goes through the center of the aircraft (figure 8.3).

For all three directions we measured the RMS, variance and mean error from the path per approach segment.

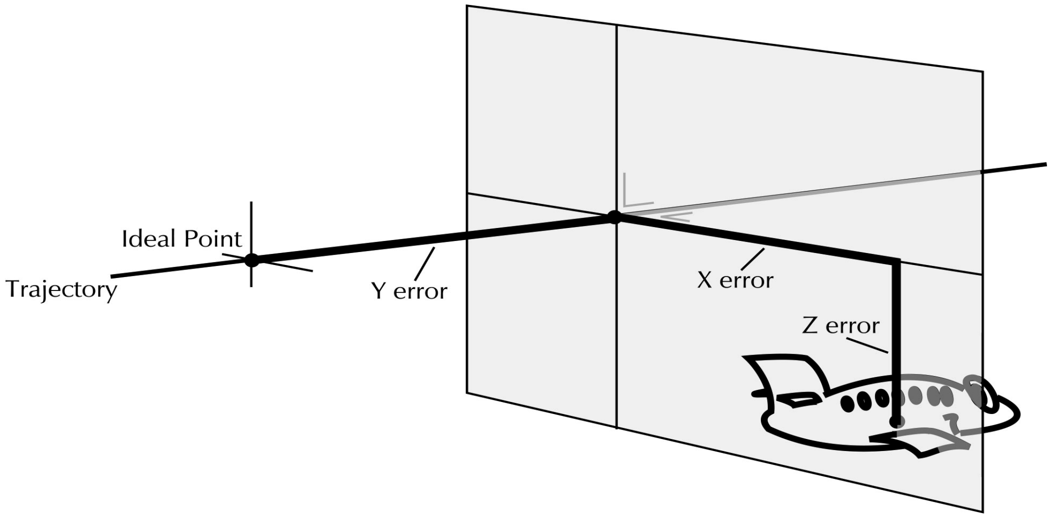


Fig 8.3. The X, Y and Z error measures.

We used RMS (root mean squared error) to indicate the error level per segment, because RMS is a common used measures for tracking performance. RMS essentially consists of two other measures; the mean error and the variance (Mean squared error = Mean error^2 + Variance). In RMS, a large deviation from the ideal path will count more than small deviations from the path. This makes measuring RMS well suited for tracking tasks.

To obtain a better understanding of the errors, we also looked at the components of the RMS measures, i.e. variance and mean error.

To acquire a more task-relative measure, we also measured the Times out of Bubble, Times out of Tunnel and Times out of Bubble longitudinally (figure 8.4). These measures are more task-relative in that the task is to stay inside the bubble. Besides this, the measures also take in account the decreasing bubble size. The measured times are a percentage of the time the aircraft needs to fly the segment

CHAPTER 9

RESULTS AND DISCUSSION

In this chapter the results and observations will be shown and discussed. Because of the preliminary character of the experiment and the complex interactions in the experiment, conclusions need to be considered against this preliminary background.

ANALYSIS

The analysis is divided into to the pilot performance related measures, the pilot activity measures, and the questionnaire.

For the performance-related measures we did an Analysis of Variance (ANOVA). For each measure we will first look at the performance per segment placed in the chronological order from segments 1 to 12 of Approach 1. This approach-to-land can be found in Appendix I, which can be folded out to use as a legend or guide for the presented graphs.

After this we will look at the performance differences throughout the four visualizations per segment type.

Each segment can be categorized as a certain segment type. In Approach 1 we can distinct six different types of segments (see figure 9.1, the referred approach segments are placed next to the segment type).

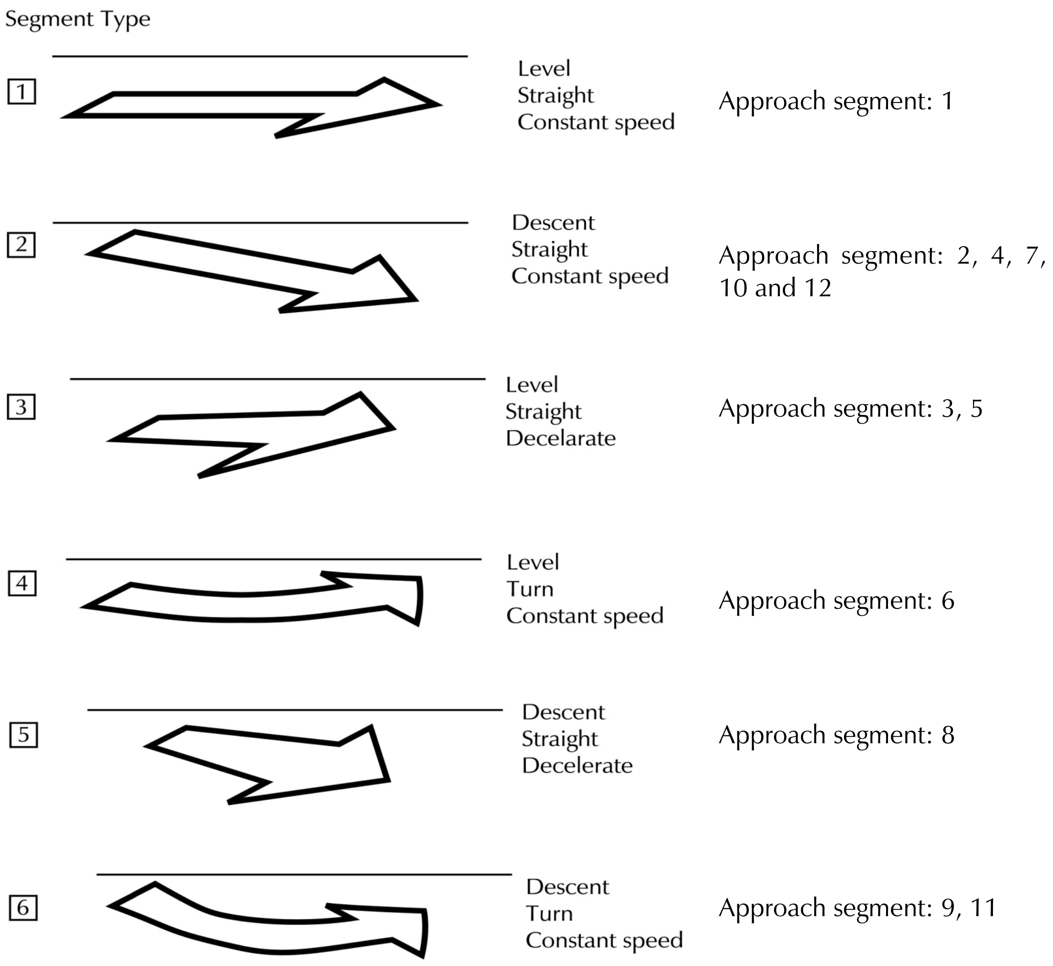


Fig 9.1. The different types of segments in Approach 1.

X error

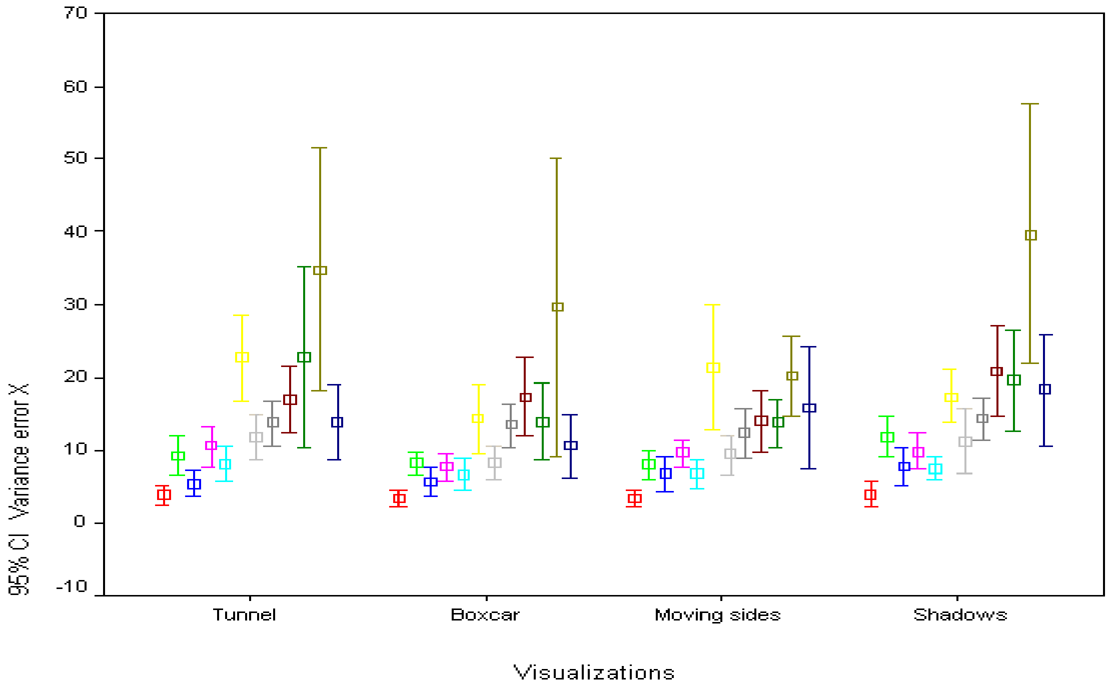


Fig 9.2. Variance of the X error.

In figure 9.2 we can see that, although the tunnel size decreases, the lateral variance error increases throughout the trajectory

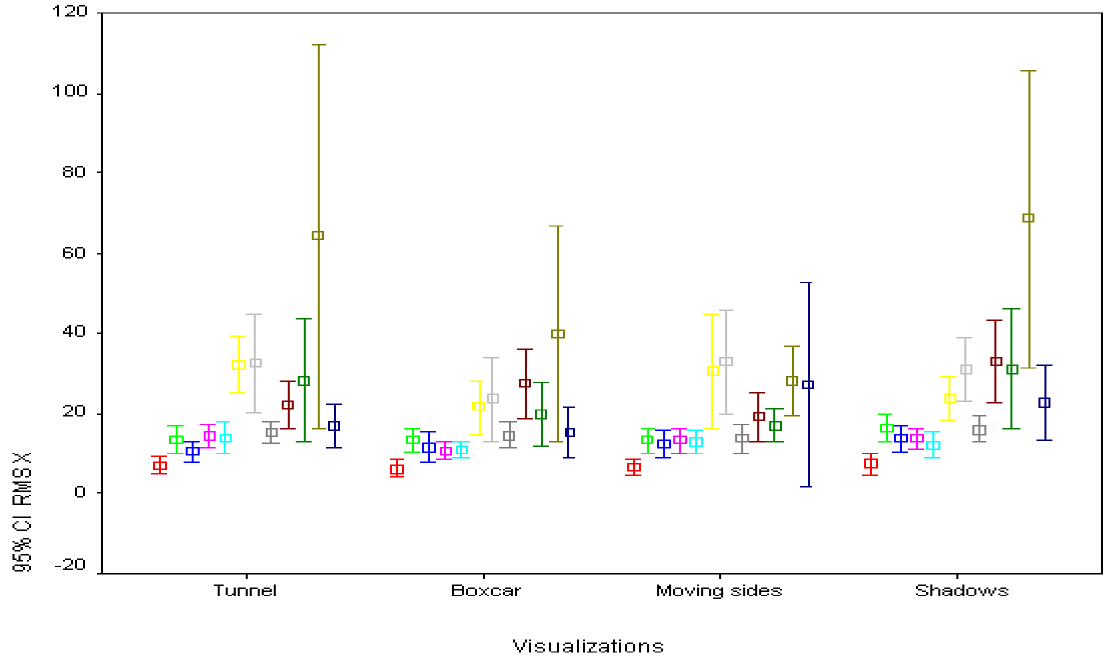


Fig 9.3. RMS of the X error.

What could already be seen in figure 9.3 can be better seen in figure 9.4. When one has to fly through a curve, the RMS error becomes and remains high.
What can be seen in both figures as well is that in both the Moving sides and the Boxcar have less extreme values in the last segments.

Z error

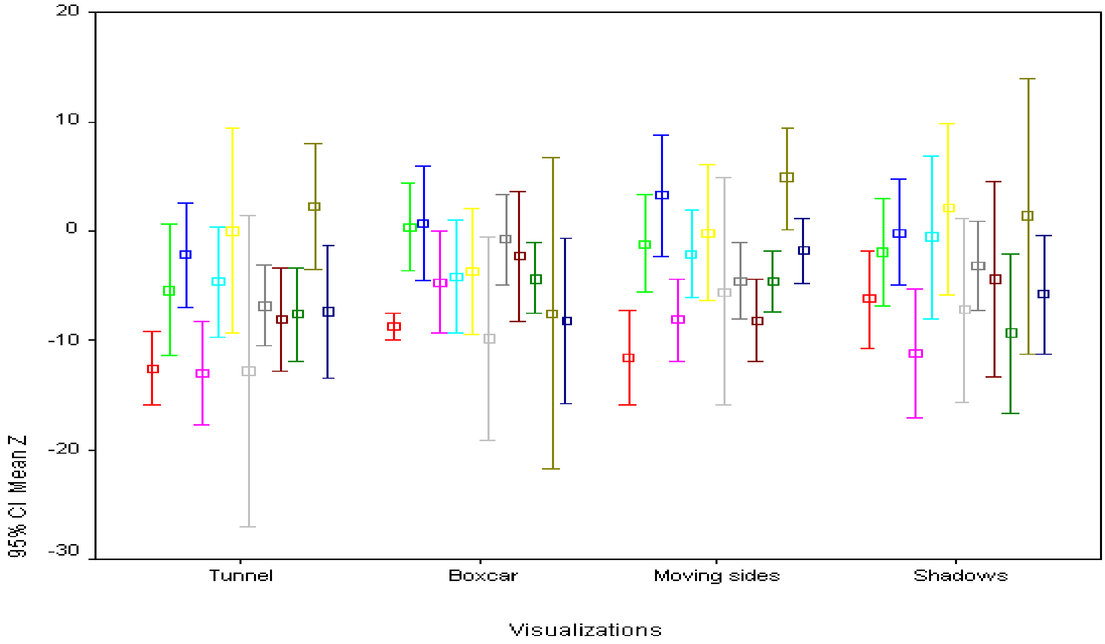


Fig 9.4. Mean of the Z error.

When we look at the average deviation in figure 9.4, we can see that the subjects had a tendency to fly more in the lower half of the bubble.

Y error

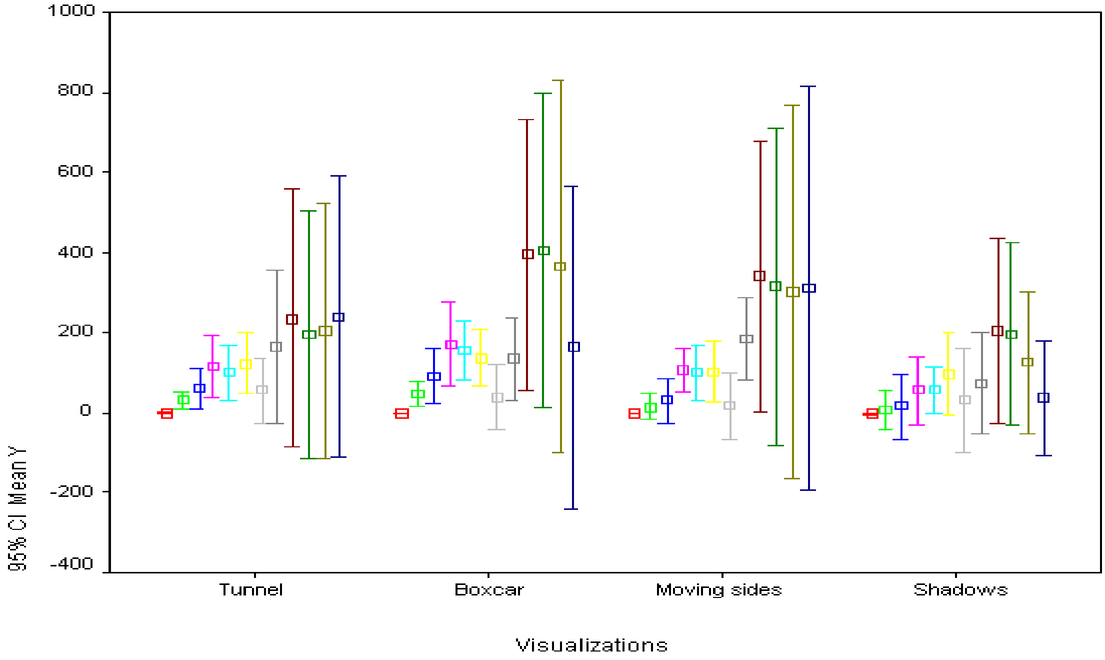


Fig 9.5. The mean of the Y error.

In figure 9.5 we can see that there's a trend that the subjects stay more in the forward half of the bubble than in the rearward part.
What also can be noticed is that during or after segment 8 the mean error in longitudinal direction gets bigger but the errors in segments 8 and further are less in the Shadows visualization.

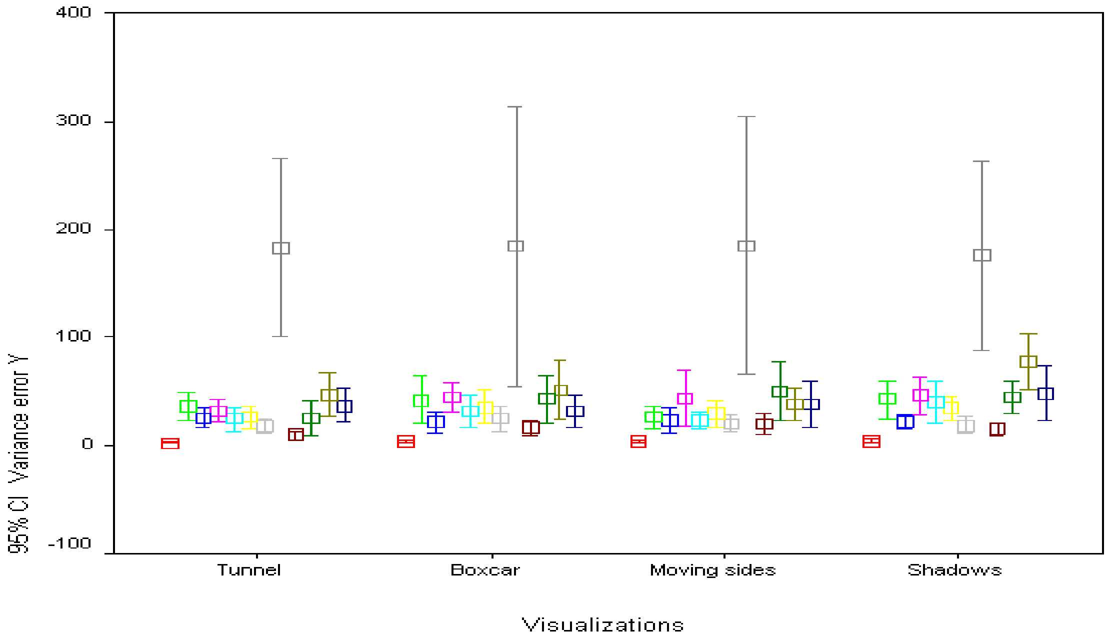


Fig 9.6. The variance of the Y error.

When we look at figure 9.6 we can see that all subjects stay in fairly the same place in the Y direction of the bubble, except for segment 8, which is a streched out deceleration. Possibly because of this slow deceleration it is difficult to maintain a constant position inside the bubble. In such a situation the bubble probably doesn't provide enough information. What also worked against the subjects was that just before this segment the subjects had to fly through a curve. This took quite some attention, so the subjects didn't watch their speed very carefully, what often resulted in overshooting the bubble in segment 8.

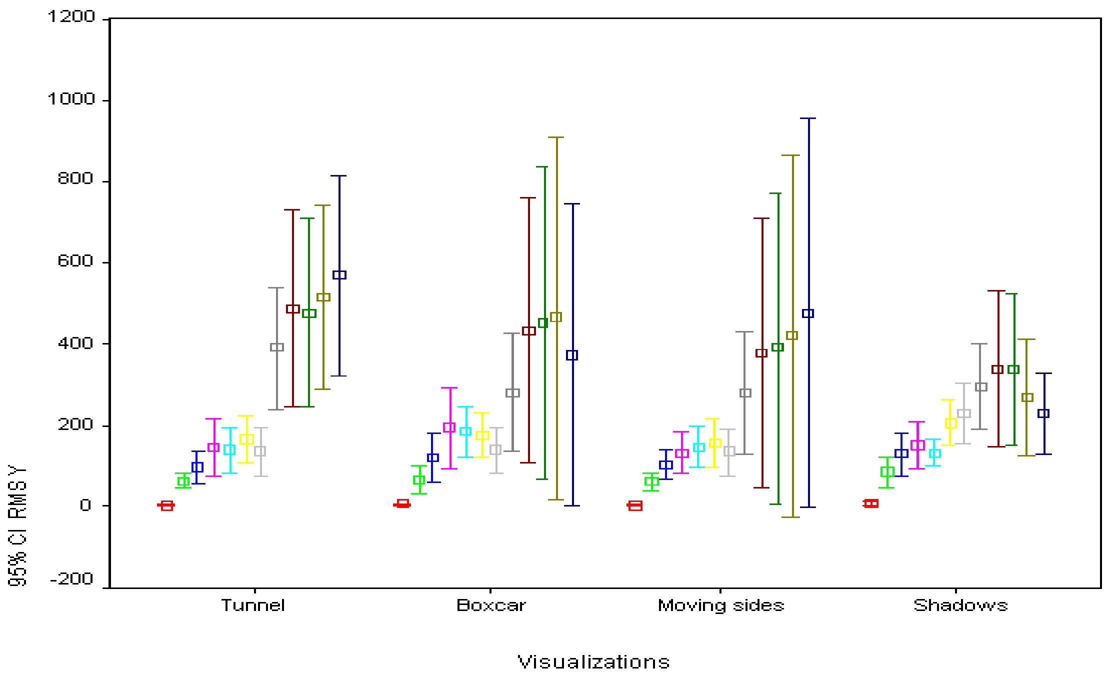


Fig 9.7. The RMS of the Y error.

In figure 9.7 we can get a clearer picture of the remarks on the Y errors placed before. Interesting is the down-going line in the last four segments of the Shadows visualization, while the other visualizations show a raising line.

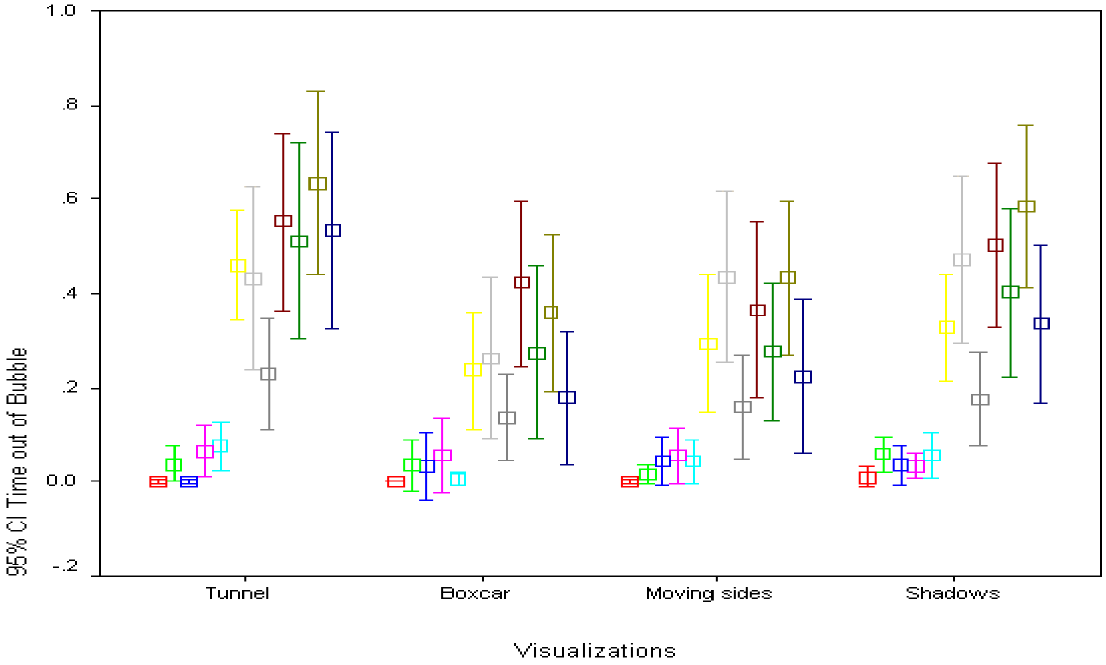


Fig 9.8. Time out of Bubble.

In figure 9.8 we can see that in correspondence with the RMS X, after segment 5 it is far more difficult to stay inside the bubble.

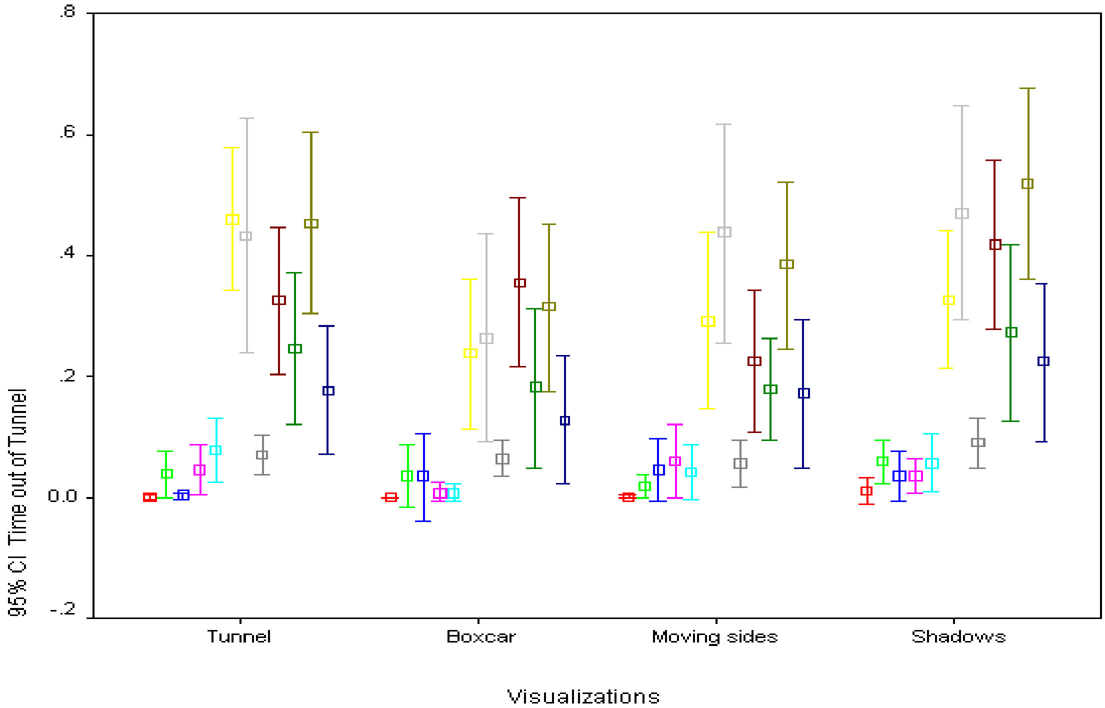


Fig 9.9. Time out of Tunnel.

The Time out of Tunnel graph (figure 9.9) shows the same trends as the Time out of Bubble graph (figure 9.8).

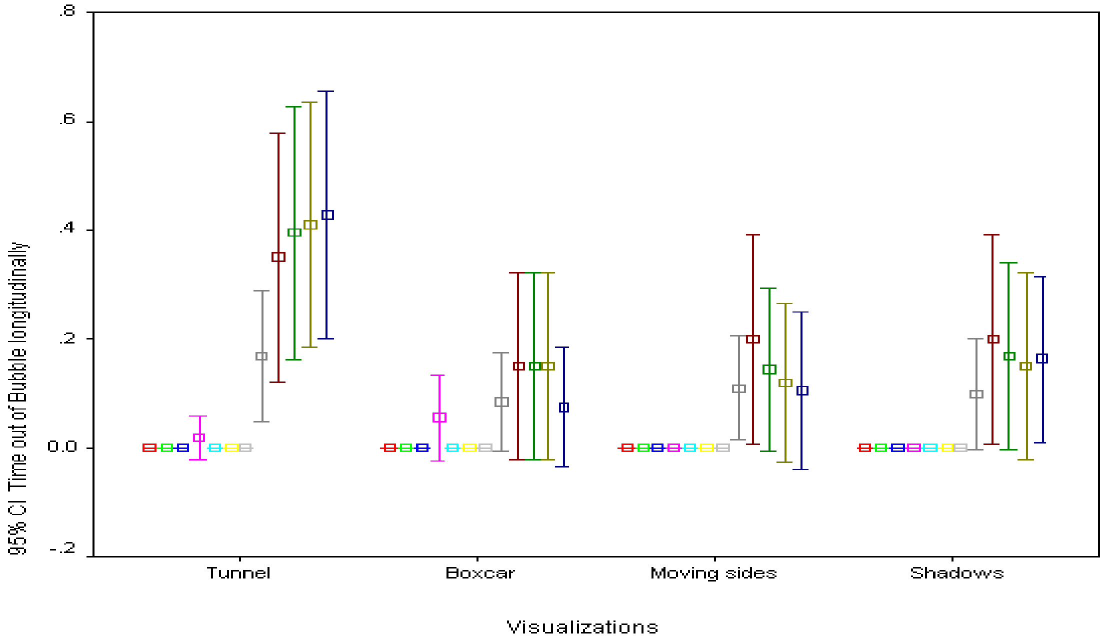


Fig 9.10. Time out of Bubble longitudinally.

In longitudinal sense we can see in figure 9.10 (time that the aircraft is ahead or behind the bubble) that during and after the stretched out deceleration of segment 8 the task of staying inside the bubble becomes more difficult. The rising trend in the Tunnel visualization can be because this visualization lacks visual feedback of where one should be. Instead errors keep accumulating. Interesting to notice are the errors in segment 4 (pink) for the Tunnel and Boxcar visualizations. Both can only be seen in the visualizations without extra ΔX and ΔV information and occur in a descent just after a deceleration. Not everybody was able to slow down in time before the descent. This resulted in an overspeed, while one had to descent as well. Because of the descent it was difficult to get rid of the excess speed.

PILOT ACTIVITY MEASURES

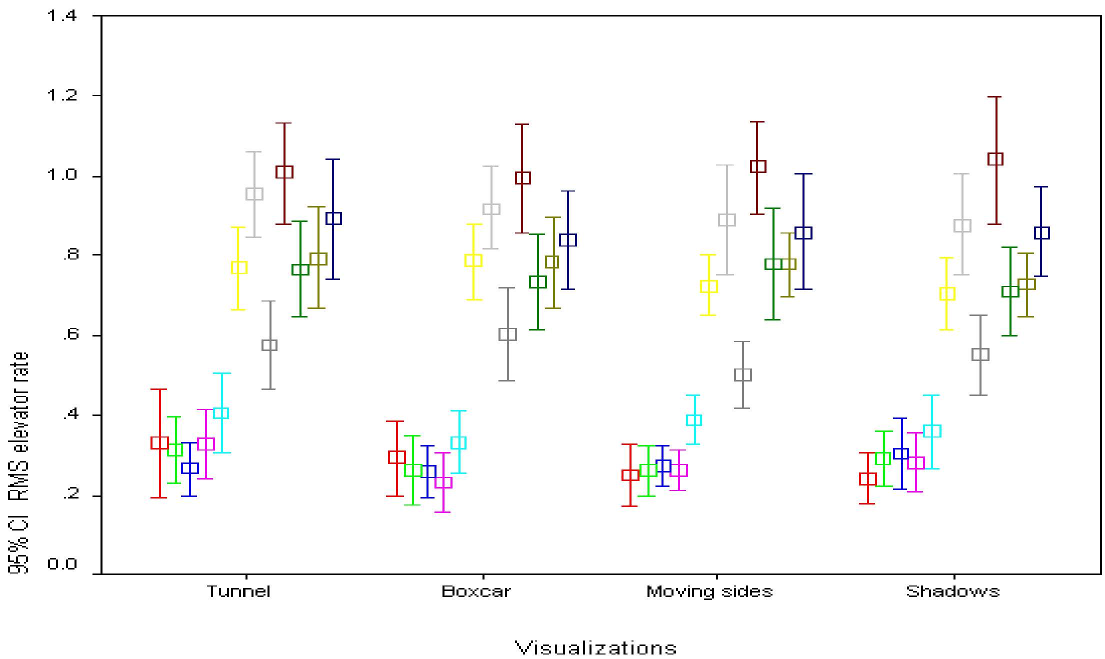


Fig 9.11. The RMS of the elevator rate.

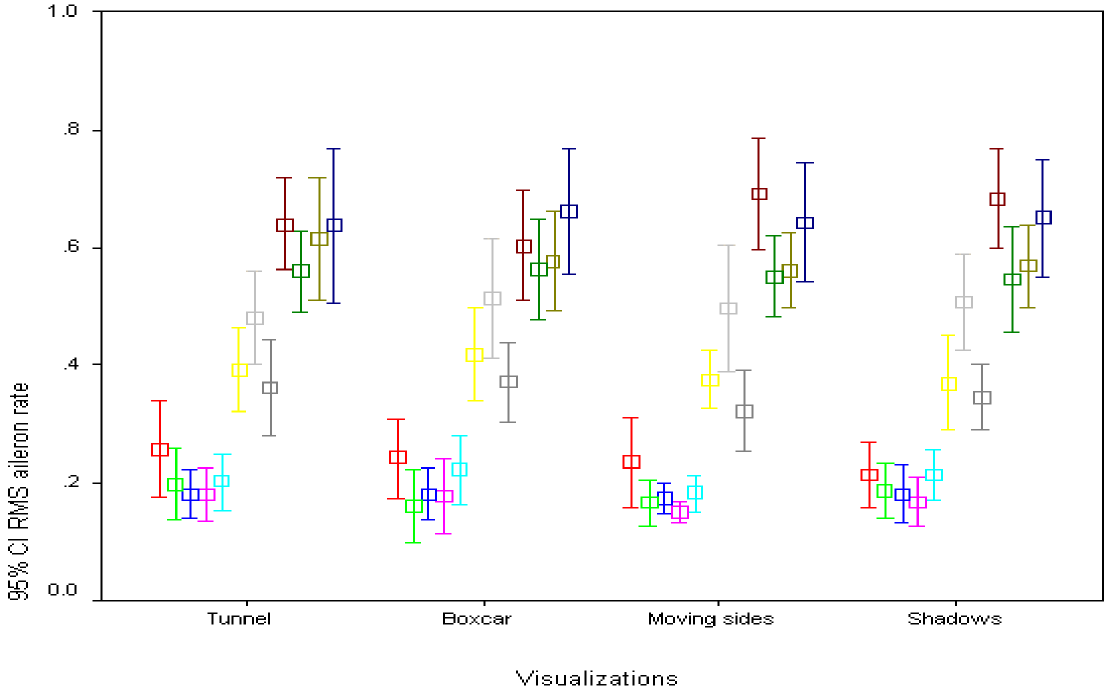


Fig 9.12. The RMS of the aileron rate.

In both RMS elevator rate and –aileron rate (figures 9.11 and 9.12) we can see that after segment 5 the pilot control activity increases.

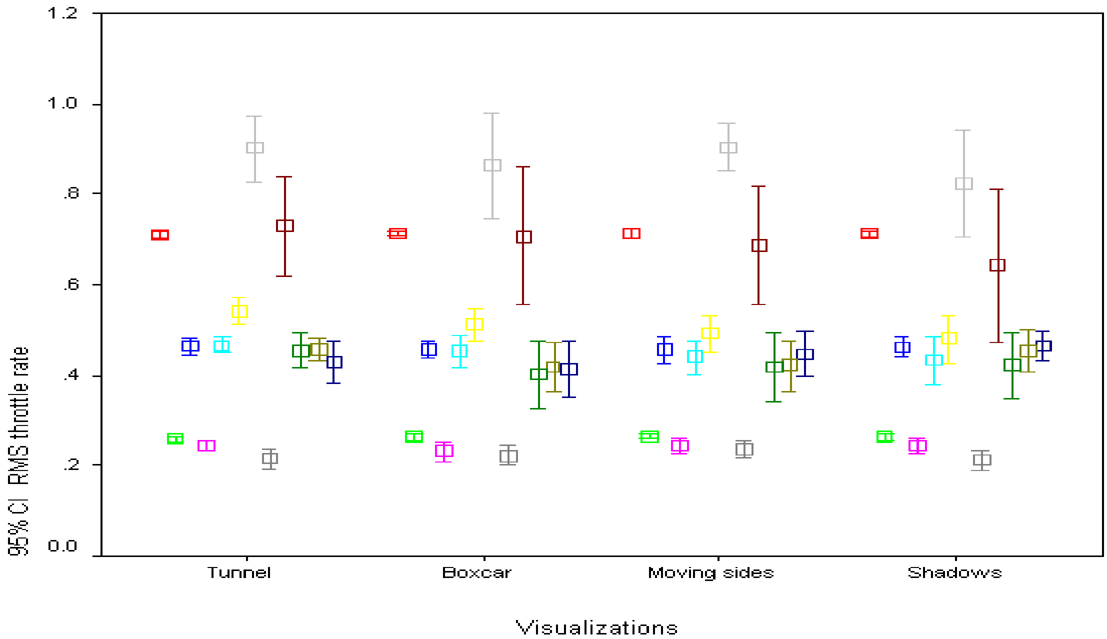


Fig. 9.13 The RMS of the throttle rate.

In figure 9.13 we can see that there is not much variance across the segments, like there's quite a fixed way to change the throttle, independent of the visualizations.
What also can be noticed is that during the slow deceleration in segment 8, there's almost no throttle activity. Instead in the segments just before and after this segment have got a high throttle activity. The low throttle activity in segment 8 can be the result of the situation where the subjects tend to overshoot the bubble (see figure 9.6, Variance error Y). As a result they will put the throttle in idle to decelerate as fast as possible.

ANALYSIS OF VARIANCE

To create an overview of the results, gathered with the ANOVA, these results were put in a matrix. In this matrix we can see the results for each measure per segment type. A one way ANOVA was used in the analysis per segment type. In the analysis with all segment types a two way ANOVA was used.
The four lines that can be found in a number of matrix positions, depict the performance level of respectively the Tunnel, Boxcar, Moving sides and the Shadows visualization.
Only when significant differences ($p \leq 0.1$) were observed, the results were put in the matrix.

For all results were $p \leq 0.1$ the Student-Newman-Keuls post hoc test was performed. The results from these tests as well as the full size graphs can be viewed in Appendix H.

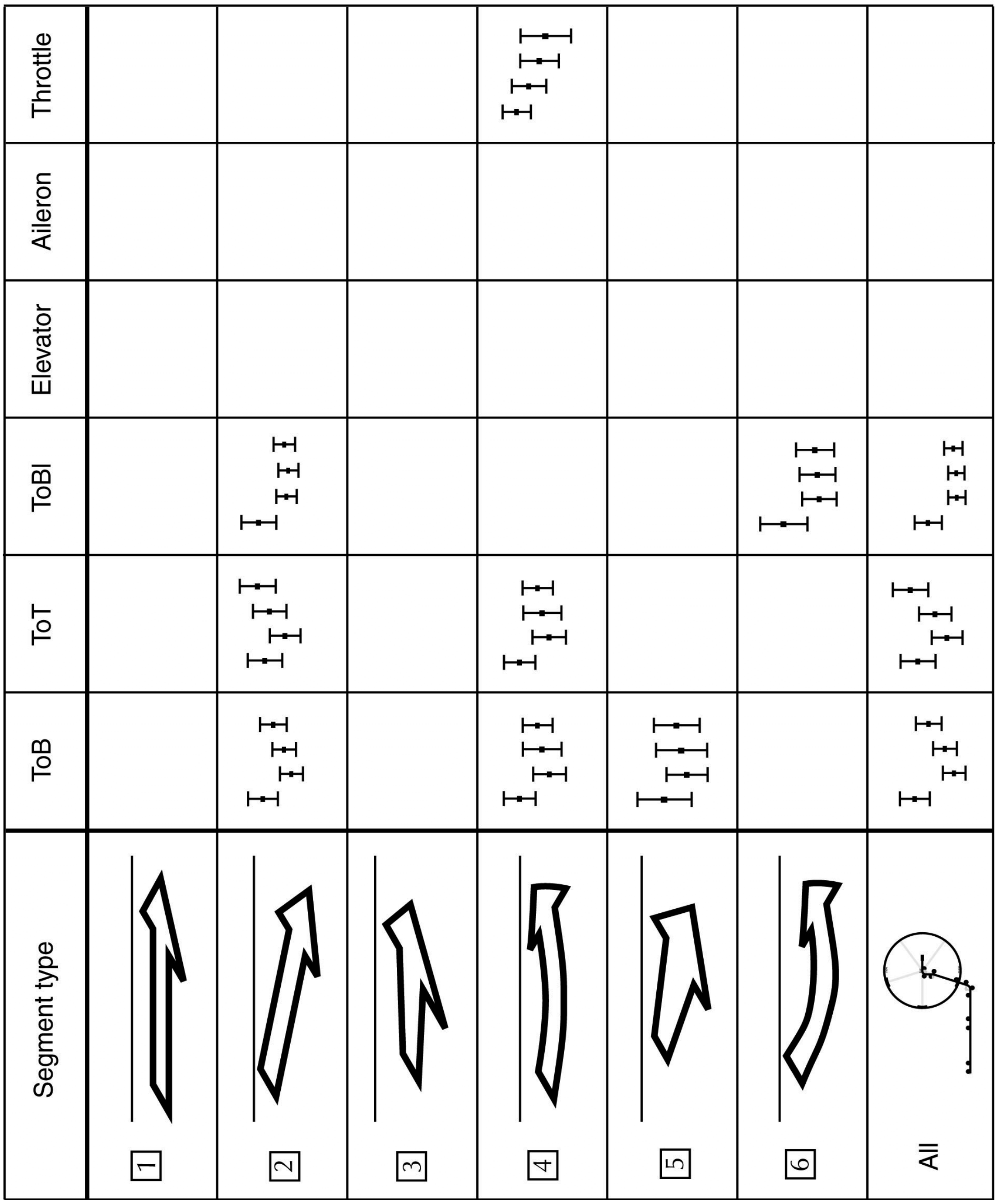


Fig 9.14 The ANOVA result matrix, first part.

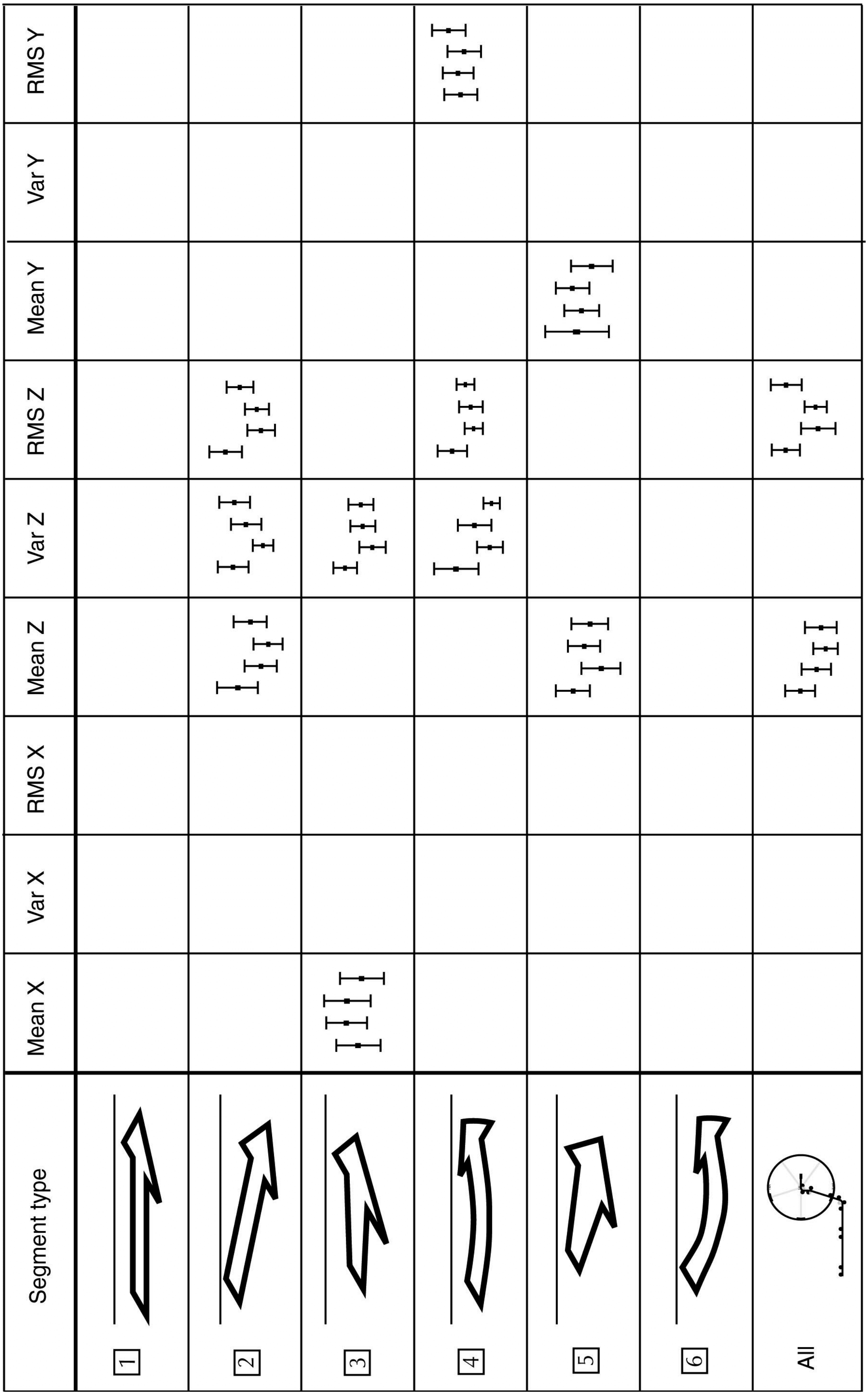


Fig. 9.15 *The ANOVA result matrix, second part.*

What can be observed in figures 9.14 and 9.15 is that in the most cases the performance with the Tunnel visualizations is the least, while the other visualizations are better. In most cases the performance with the Boxcar is the best. Although we can see differences across the various visualizations, these differences are small.
What is striking, is that the most significant errors can be found in the Z error, not in the Y error. Pitch and speed are clearly coupled. The task of keeping the aircraft inside the bubble is manifested in the Z direction.

Why the Boxcar visualization appears to be better is difficult to explain. It is quite a complex matter. One can think that it has got something to do with the absence of the upper tunnel lines, which creates a far less cluttered, calmer display. It can also be because the pilot has good information of where he should be in time, without the extra distracting information the Moving sides – and Shadows visualizations have.

QUESTIONNAIRE

NASA Task Load Index per run
The TLX after each run didn't give any significant difference between the four visualizations. This situation is analogous to the subjective task load measures (Elevator-, aileron- and throttle rate).

Questionnaire
After each block we gave the subjects a questionnaire in which they were asked to give an overall TLX rating for each question. Also we asked the subjects an open question about their comments on the visualizations, why they rated the visualization like they did.
To get a picture of the subjects' attitude towards the visualization the subjects were asked if they would like to use the visualization in a future situation on which they could response with 'Yes, always', 'Maybe, sometimes' and 'No, never'.
Finally the subjects had to put the visualizations in a ranking order (1 = best; 4 = least).
Also additional comments could be entered.

Because the TLX rating sheets in the questionnaire were filled in two to three hours after the experiment it was not clear how reliable these ratings were. Because of this, we didn't analyze the overall TLX ratings.

Observations: Overall
The observations made below are quotes of remarks the subjects made during the experiment.

Because the bubble is more or less a steady factor in the display it is good help for making turns, because it provides aiming points to put the flight path vector on.
Because the approach made use of rate one turns (180 degrees per minute) the aircraft had to fly the curves with a too high angle of bank (more than 35 degrees), which made the approach very difficult to fly, it made task less realistic. The bank angle on an approach should be no more than 30 degrees and when on final approach no more than 15 degrees.
A number of subjects had visual disorientation: They didn't know whether one was inside or outside the tunnel. Also subjects felt more like they were more 'flying the tunnel' than flying the airplane.
Because bubble has no interactivity, sometimes safety had to be sacrificed to stay inside the bubble. The bubble didn't respond to a potential hazardous situation (e.g., stalling the aircraft while slowing down to get inside the bubble again), even could make it worse.
Observations: Tunnel
The tunnel doesn't provide feedback, which is missed. The complete tunnel makes the subjects focus too much on the inside of the tunnel, because of this, important information at the sides of the display, like airspeed could be missed. It creates more or less 'tunnel vision'.
The tunnel can be distracting and disorienting.

Observations: Boxcar
Less clutter is very pleasant because the top part of the tunnel is not visible one does not create 'tunnel vision'. It allows the pilot to focus on other areas in the cockpit, without sacrificing the control of the aircraft.
The feedback the bubble provides makes the task less concentration/attention heavy. The bubble visualization is easy to perceive, the bubble is visible yet not distracting. It gives the pilot room to make and recover from his mistakes.

Observations: Moving sides
The moving lines help for controlling airspeed, but there's still a need for alphanumerical depiction of the (relative) speed to accurately follow the bubble speed. It is easy to recognize where you are in 'time'.
Sometimes the moving sides are not noticed. The oval shape is seen as something to fit the nose of the aircraft in, which also gives the visualization a 'forcing' character. One tends to 'chase' the bubble (at any cost).
The moving lines can provide too much information, can be too distracting, even disoriented making.

Observations: Shadows
When one flies forward in bubble (especially when one is further in the trajectory, when the bubble is smaller) the shadow can really block your view at critical moments.
Shadow not as good for small speed differences, it helps better in the more extreme cases
The visualization is seen as the hardest representation to recognize where you are in 'time', even making it harder to fly the airplane. It does not allow the pilot to recover from his mistakes, it only causes more mistakes.

Attitude
The attitude the subjects had towards the display has more variance between the subjects than within the subjects. It therefore doesn't appear to be very informing.

Ranking order
When we look at the total ranking order we can see that the Boxcar is rated as best, followed closely by the Moving sides visualization. Both the Tunnel and the Shadows visualizations get low ratings.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

As a conclusion to this report and as a startingpoint for further, more detailed, research on Bubble in the Sky displays, this chapter gives a number of conclusions and recommendations.

GENERAL

The integration of spatial- and temporal information in Tunnel in the Sky displays is not an easy subject. The interaction between time, distance and speed in flying a precision approach is complex, especially because of the non-intuitive nature of the aircraft dynamics.
I think we have started to capture and visualize the right elements, but lots of things need to be explored and fine tuned.

Although the performed experiment had a preliminary character and lots of things need to be improved, it is good starting point for further analysis.
The measures that were taken appear to be sensitive to the task constraints, because we can see in the chronological graphs that some types of segments are clearly harder than others, which leads to consistent main effects for segment types.

In the experiment we can see a small supremacy of the Boxcar visualization over the others. Like we've stated in the hypothesis, the baseline appears to be less then the other visualizations. This is quite obvious, because very little temporal information was provided in this visualization. But the baseline still is a good representation of the current status quo in the development of electronic flight instruments.
Because the performance levels are less than those of the Boxcar it appears that both the Moving sides and the Shadows visualizations appear to provide too much information that is seen as distracting.
A possible solution for the Moving sides visualization might be to not show the cross lines, unless the relative speed between the bubble and the aircraft is high enough that it needs the attention of the pilot.

Although some visualizations were not rated very positive, like the shadows visualization, we need to keep in mind that the tested visualizations still are concepts. Small and simple changes can make quite a difference.

CLUTTER CAUSED BY THE TUNNEL VISUALIZATION

An interesting field for further improvement is the clutter the tunnel creates in the display. In the experiment it appeared that the tunnel takes up too much attention and can even be disorientating.
Reasons for this effect can be the number of tunnel frames, visible in the display. The distance between the frames in the experiment was 450 meter. A solution can be to extend the distance between the tunnel frames so as to make the display less cluttered.
Another way to make the tunnel less pronounced is by changing the tunnel color. The white lines of the tunnel are very pronounced in the display. Altering the tunnel color or the tone of the tunnel lines can improve the situation.
A more rigorous approach to create less clutter is to remove the upper lines of the tunnel. Research in this field needs to come to a solution that provides a preview that is good to perceive

CONSTANT FACTORS IN A FLEXIBLE ENVIRONMENT

The reason for the Bubble in the Sky display is to support flying precision approaches. An implication of the idea behind flying precision approaches is the flexibility it offers. This flexibility implies that pilots will almost never fly the same approach. To help the pilot to learn the 'approach system', to provide a constant factor within the flexible approach system, the approaches-to-land should be made out of 'building blocks'. These blocks are standard segments, standard to a specific aircraft type. E.g. a standard deceleration element has got a certain length, so that a standard throttle setting can be used to decelerate to the specified speed. In this way the pilot knows what actions to take during the approach, by knowing the upcoming 'building blocks' of the approach.

Backside of information integration

Although integrating information in a format that supports human perception action is a good thing, it has its drawbacks. When we look at the current way information is provided to the pilot, i.e. in a one sensor- one indicator format, the pilot needs to integrate this information himself. This is quite a difficult task for the pilot to perform. However, when one of the sensors fails, the pilot is able to notice this by cross-referencing with other indicators. It is even possible to derive the failed information from the other indicators.

In the Bubble in the Sky display it will be difficult to notice whether a sensor has failed, because information is already integrated. A way to provide information when one or more sensors have failed needs to be developed to come to an operational working Bubble in the Sky display.

Interaction

The Bubble, as used in the experiment did not reflect all task constraints. Only the constraints from ATC are visualized, the constraints of the aircraft dynamics are not really visualized

The aircraft dynamics need to be captured in the interaction between the bubble and the aircraft. In the experiment the bubble only flew a predetermined course, independent of the aircraft. The bubble should help stabilize the aircraft. The opposite was more true in the experiment. In a number of situations, the pilots needed to push the aircraft to its boundaries to stay inside the bubble.

The character the bubble should have is twofold:

- Providing protection, i.e. a safe field of travel. The bubble should always surround the aircraft, stabilize the aircraft, prevent stalls, etc.
- Providing guidance, i.e. the bubble should force the aircraft in keeping the right trajectory at the right speeds.

The interactive nature of the bubble will take place in this tension field.

Two examples of this interactivity are:

- The bubble should 'push the aircraft forward' when the aircraft is about to enter a stall.
- The bubble should give protection within reasonable limits. Normally the aircraft should always be able to stay inside the bubble note: this then will be aircraft type dependent). If the pilot is not able to comply with this trajectory and really is about to go outside the bubble, e.g. with strong wind gusts, then a re-negotiation for a new trajectory needs to be made.

The exact 'bubble behavior' will be a nice follow up study. This study will be essential to make the bubble concept work. Without this interactivity the Bubble in the Sky display will not reflect all constraints that need to be reflected.

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APPENDICES

Appendix A

Project description

Afstudeeromschrijving

The visualization of temporal information in 'Tunnel in the Sky' displays

Student	Jacco Otten
Institutes	Delft University of Technology, Aerospace Engineering, disciplinary group Control & Simulation Wright State University, Department of Psychology
Mentors TUD	Dr. C.J. Overbeeke (Industrial Design, chairman) Dr. ir. M. Mulder (Aeronautics) Dr. P.J. Stappers (Industrial Design)
Mentor WSU	Prof. dr. J.M. Flach (Psychology)
Start date	March 2000
End date	December 2000

Introduction

This project will be an interdisciplinary project in which Wright State University (WSU), department of Psychology and Delft University of Technology, faculties Aerospace Engineering and Industrial Design Engineering are involved.

Research and education at the faculty of Aerospace Engineering, disciplinary group Control & Simulation covers, amongst others, flight simulation, design and analysis of man-machine interfaces and air traffic management. This group has therefore the knowledge about- and experience with cockpit displays, especially Tunnel-in-the-sky (TIS) displays.

At the faculty of Industrial Design Engineering knowledge about display visualizations has been gained through, among other things, Virtual Reality research.

The WSU, located in Dayton, Ohio is dedicated to teaching, research and service. Named for Dayton's aviation pioneers, Orville and Wilbur Wright, the university serves nearly 16,000 students with programs leading to more than 100 undergraduate and 40 Ph.D., graduate and professional degrees. The Department of Psychology deals, among other things, with human-machine or human-computer interactions. It focuses on improving system performance and developing effective interfaces through the application of knowledge regarding the operator's perceptual and cognitive processes. It emphasizes the functional aspects of a situation, looking for ways to modify the physical environment in order to improve performance. Aerospace-related applications are common at Wright State University because it is adjacent to Wright-Patterson Air Force Base, a major center of Human Factors research and development.

The WSU has got the knowledge about perceptual theories, especially Gibson's ecological psychology of perception and has got the facilities to create simulations and conduct experiments.

For an Industrial Design Engineering student this project is appropriate, because, in order to create an integral concept many different aspects from the different disciplines have to be brought together.

Problem definition

The present day air structure, with its airways, dates from the 1950s and is based on the few air traffic and the technology of that day, e.g. electromechanical cockpit displays.

Nowadays the sky is getting crowded. One has estimated that till the year 2015 air traffic will expand with 200 or even 300 percent. This leads to congestion on the airways, which causes delays. This trend is already felt today. Changing the concept of airways can only solve this problem. Airplanes should be given more autonomy in finding the best trajectory. This concept is known as 'Free Flight'.

The present day society asks for changes in the 'air structure' as well because of environmental and safety issues. A perfect example of this is the growth of Schiphol and the problems this causes.

However, technology has evolved and the aviation industry has entered 'the world of digital information displays'. These displays offer the possibility to radically alter the way information is presented to pilots. These displays offer the opportunity to help solve the aforementioned problems.

One of the most prominent of these display types is the 'Tunnel-in-the-sky' (TIS) display. The TIS display is used to indicate safe or preferred paths of travel for a pilot. Currently these displays only specify the trajectory, they provide spatio-temporal information about where a pilot is flying relative to the tunnel 'walls'. However TIS displays do not give spatio-temporal information in relation to the longitudinal axis of the tunnel. Here the temporal information is still separated from the spatial information. The TIS display does not provide feedback where in the tunnel the pilot is supposed to be at what time. Because these tunnels depend on dynamic conditions, such as the flight behavior of other traffic, such timing information is essential.

Afstudeeromschrijving

Assignment

Study the state of the art of 'Tunnel in the Sky' displays, the role of additional temporal information for the longitudinal axis of the tunnel and for which (sub)tasks this information is needed. Determine which information is necessary and how this interacts with the spatial longitudinal tunnel information as given in the current TIS-displays. Determine how the information can be visualized to indicate the 'safe field of travel'. Design and prototype a number of visualizations of temporal-tunnel displays, and test these in a simulator. Create a final prototype on the basis of these experiments.
The 'practical work' traineeship will be fulfilled during this graduation project.

Approach

Introduction (1wk) (NL)
During the introduction phase the assignment will be specified. To do so an orientation in the relevant area will take place. The introduction phase will result in an assignment and an approach/planning.

Analysis (6 wk) (NL)
In the analysis phase insight will be gained in how temporal information is provided in the current cockpit instrumentation as well as insight in the state-of-art TIS displays, properties of gradual (temporal) information and the relevant (sub)tasks.
The study of the interaction between spatial- and temporal information, Gibson's 'Ecological psychology of perception' and arcade/real time 3D computer games must lead to 'design guidelines how to indicate the 'safe field of travel'.
A global test strategy will also be created during the analysis phase.
Results will be reported in an intermediate report.

Synthesis (9 wk) (NL)
During the synthesis ideas for visualizing the 'safe field of travel' will be created. The most potential ideas will be developed to concepts. These concepts will be developed/detailed to a level ready to be implemented into a simulation program. This will result into a second intermediate report and an intermediate presentation at the TUD, faculty of Aerospace Engineering.

Transition (1 wk) (NL ➔ USA)
One week is reserved for the flight to Dayton, Ohio and getting 'settled' there.

Testing (20 wk) (USA)
During this period the concepts will be implemented into a simulation program. The design of the usability tests will be finished, test persons will be recruited and the experiments will be conducted.
These experiments will lead to conclusions for the final prototype, which will be created.
The test phase will be reported in a third intermediate report.

Final Report (4 wk) (NL)
During this phase the end report will be created and the end presentation will be prepared.

Time total
41 weeks

Planning

Introduction	8 Mar – 14 Mar
Analysis	15 Mar – 16 Apr
Synthesis	17 Apr – 18 June
Transition	28 June – 4 July
Testing	5 July – 14 Nov
Final report	15 Nov – 13 Dec

Appendix B

Other 4D Tunnel in the Sky solutions

Other 4D Tunnel in the Sky solutions

In this appendix the two other types of solutions for integrating temporal information are discussed. Each concept will be described. After the description, comments on the solution will be given. For the description of the spatial lead plane the current research of M.P. Snow et al of the Airforce Research Laboratory at Wright Patterson AFB, Ohio is used as an example.

Flight path triangles

In Below & von Viebahns' experiment the predicted flight path is presented by a set of flight path triangles. The predictor changes its length according to the speed of the aircraft, thus providing a continuous feedback. In addition to the variable length of the predictor the colors of the triangles can change; when the aircraft tends to reach an over- or under speed the triangles will turn orange or red, respectively. At first the furthest triangle changes color, when the pilot won't take action, the more close triangles change color to indicate that the over- or under speed is coming closer. In this way an early warning is created, so the pilot has time to correct his speed. Speed information is also provided in the tape scale on the left side of the display (figure B.1).

Research pointed out that the concept was well accepted by the pilots: Compared to conventional instrumentation, flight path deviations as well as pilot's control activities significantly decreased. In the report no mention is made about the path following performance in the 4th dimension (time/speed) (Below & von Viebahn, 1995).

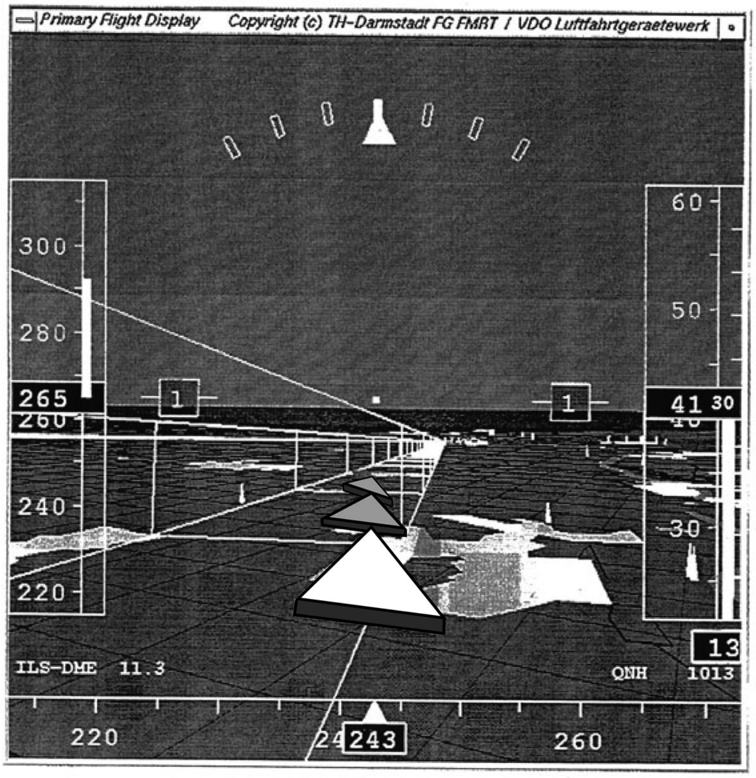


Fig B.1. The 4D solution Below & von Viebahn's present.

Comments on the flight path triangles

In the solution Below & von Viebahn present the flight path marker creates clutter in the display.

In the way in which the flight path marker, with its chancing color, indicates the aircraft's velocity the pilot's task is more 'keeping within the speed limits of the aircraft' than that of keeping the desired speed. However this can be changed easily into the speed limits of the 'safe field of travel'.

Another drawback of the concept is that, although temporal information is provided in a more or less spatial way, it is not really integrated in the tunnel. The pilot still needs to look at both elements separately.

SPATIAL LEAD PLANE

In the solution Snow et al give the trajectory is visualized as a 'highway in the sky'. The highway is made up of a string of path blocks drawn in perspective. 'Road signs' are placed next to the flight path. On these road signs, information that is relevant for that moment, like 'gear down' or navigation points, is placed.

A simplified (perspective) drawing of an aircraft provides the speed and position information. The task of the pilot is fly in formation with the 'follow-me aircraft'.

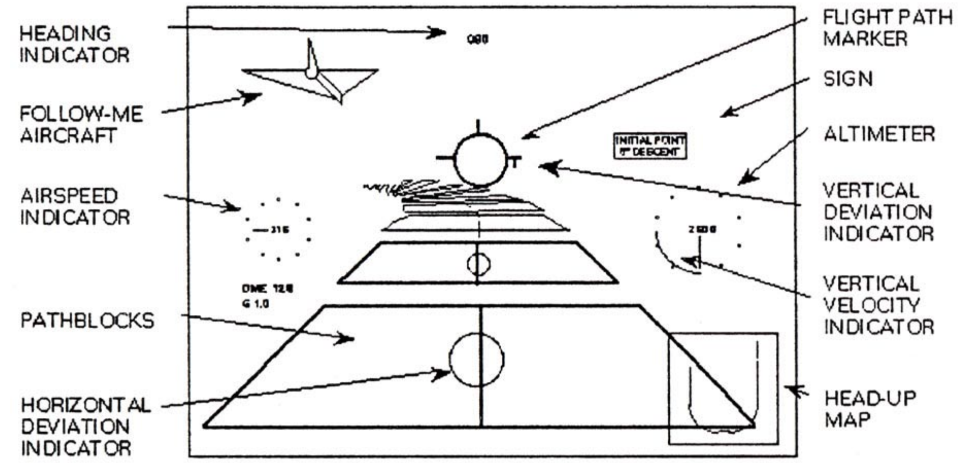


Fig B.2. The 'highway in the sky' display with the spatial lead plane

COMMENTS ON THE SPATIAL LEAD PLANE

In the described solution it is necessary to fly in formation with the 'follow-me aircraft'. This is a good solution for the military aviation where pilots are trained to fly in formation. However civil airline pilots are not trained for formation flying. For them the task will be less suited.

Another drawback of the concept is that formation flying can vary from very tight formations to very wide formations. The variation in distance to the 'follow-me aircraft' can therefore be high. Because of this the distance the pilot needs to keep and the boundaries he has are not very clear.

Analogue to the flight path triangles concept, a drawback of the concept is that, although temporal information is provided in a more or less spatial way, it is not really integrated in the tunnel. The pilot still needs to look at both elements separately.

Appendix C

Excerpts from 'A theoretical field-analysis of automobile-driving'

Excerpts from 'A theoretical field-analysis of automobile-driving'

Gibson and Crooks (1938) wrote a paper to create a systematic description with practical as well as psychological validity of what goes on when man drives an automobile. The title of the paper is 'A theoretical field-analysis of automobile-driving'. Excerpts from this article that are relevant for a better understanding of the safe field of travel and how this can be applied to the Bubble in the Sky visualizations can be found below.

"The safe field of travel is an indefinitely bounded field that lies within the boundaries of the road. It consists at any given moment of the field of possible paths, that the car may take unimpeded... Objects or terrain features with a negative 'valence' mainly determine the boundaries. The safe field of travel itself has a positive 'valence', especially on its middle line". (Valence refers to the meanings of objects by virtue of which we move towards some and away from others).

"The safe field of travel is not fixed in physical space, it moves with the car and has the driver as reference point. The field also exists objectively as an actual field in which the car can safely operate. The field is dynamic and changes continually depending on the obstacles and other factors".

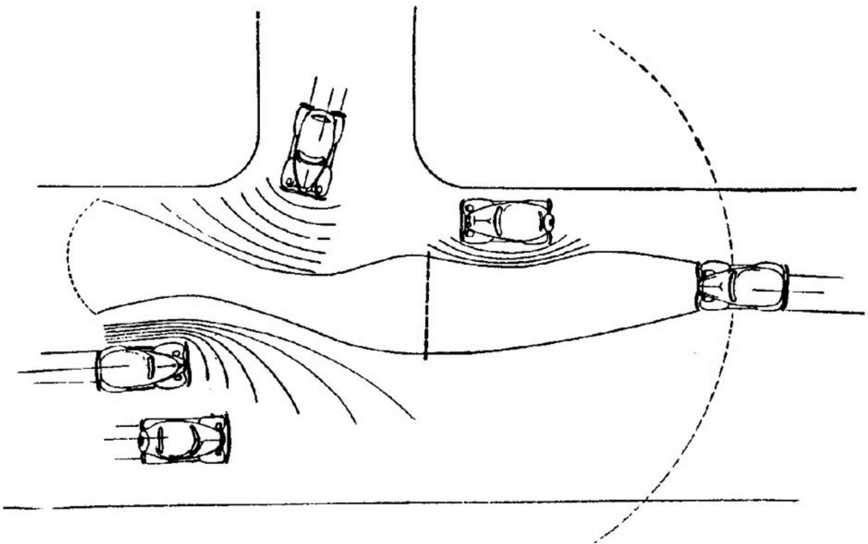


Fig C.1. The safe field of travel and the minimum stopping zone of a driver in traffic. The lines that extend from the front of the car form the safe field of travel. The dashed straight vertical line in this field depicts the boundary of the minimum stopping zone. The circle shaped line that extends from the car depicts the Field of View of the driver when he looks forward.
The lines around the other cars can be seen as 'equivalence' lines. These lines can be seen as a gradation of how hazardous the object is.

In order to avoid a collision, the driver can change the direction of motion, decelerate or stop. The former can be explained by describing steering as "a perceptually governed series of reactions by the driver so as to keep the car headed into the middle of the safe field of travel". For the latter we have to look at the reasons for decelerating

When somebody is driving, locomotion is maintained or even augmented to go somewhere. One will not just stop or decelerate for no reason. Decelerating occurs when "the safe field of travel visibly contracts". In this situation the driver needs to decelerate in order to avoid obstacles.

"The relation between contraction and deceleration can be explained by the minimum stopping-zone". This zone is a zone within the safe field of travel. The size is set by the minimum braking distance, which depends on the car speed, brake conditions and the road conditions. So in this zone the driver is able to stop, if he needs to.

"This zone is supposed to be present implicitly in every driver's field, whether it's accurate or not... The driver's awareness of how fast he's going does not consist of an estimate of speed (in an arbitrary unit, like km/h), but he's aware of the distance in which he can stop".

“Normally the forward margin of the minimum stopping-zone is well within the safe field of travel. The speed of the car can be increased up to where the zone meets the field”.
“When the field retracts, the driver’s reaction will be to keep the zone within the field. The deceleration will occur in proportion as the forward margin of the field recedes toward the minimum stopping-zone. The ratio between depth of field and depth of zone tends to be maintained in given traffic conditions for a given driver. The ratio can be seen as habitual and is an indication of cautiousness”.

“A perfectly clear highway offers a greatly expanded safe field of travel, so the speed of the car can be high. In this case the edge of the minimum stopping zone is determined by the limits of the human vision, since the driver’s attention must be fixed at greater distances”.
As said earlier, the road bounds the field of safe travel, but there are other factors that bound the safe field of travel as well. Other factors are:

- Natural boundaries like daylight, blinding headlights or fog, which limit the visibility.
- Inflexibility at higher speeds. The road-holding of the car sets limits to the speed the car can conform to the road, without skidding.
- Obstacles and their clearance lines. Each obstacle has a sort of halo of avoidance. In analogy with contour lines on a map, this halo can be represented by ‘lines of clearance’ (lines of equal valence). The driver tends to move toward the target and away from obstacles.
- Moving obstacles. In the case of moving obstacles, the clearance lines radiate from the point at which the obstacle is closest to the car.
- Potential obstacles. These obstacles are obstacles that can be found behind an occluding object. Because of the occluding object one can’t see the obstacle, but it can be there. An example of this is an occluding building at the corner of a crossing, one can expect that a car can come from behind the building.
- Legal obstacles and legal taboos. Signs that are applied by law can also bind the safe field of travel. These signs vary from road marks to traffic lights.

“Although driving is an individual activity, drivers take in account other drivers’ field of safe travel and can even manipulate their- and other’s safe field of travel”. For instance one can bluff ones way in a crossing by only slowing down a bit, so other drivers need to slow down to avoid a collision.
“The car itself can also be seen as a field. By the behavior, of the car (the feel, sounds, etc.) the car gives information to the driver”. Also in this field, perception and action imply one another.

APPENDIX D

TIME TO CONTACT

TIME TO CONTACT

Time to Contact information helps the pilot to keep the aircraft within the longitudinal boundaries of the 'safe field of travel' travel' and to support the error neglecting control nature of humans. The phenomenon will be described here.

When a perceiver approaches a solid surface, this approach causes an optical expansion in the visual field (figure D.1).

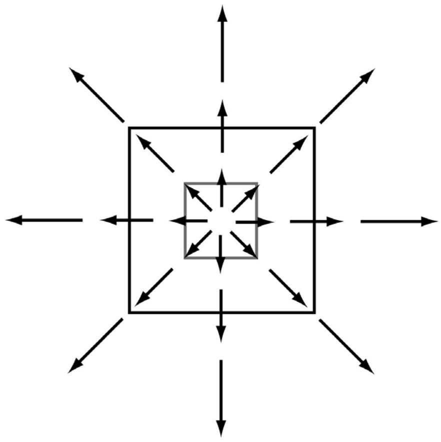


Fig D.1. Expansion of the visual field.

The observer sees the object coming towards him. When the observer keeps moving, the visual angle will eventually become 180° (theoretically). This optical effect is referred to as 'visual collision'. Visual information is sufficient to tell *when* the observer will collide. (Lee, 1980) (figure D.2). This figure shows an observer moving with speed V towards an object at distance D. Visually, the object occupies an angle, which is represented by the size w at unit distance.

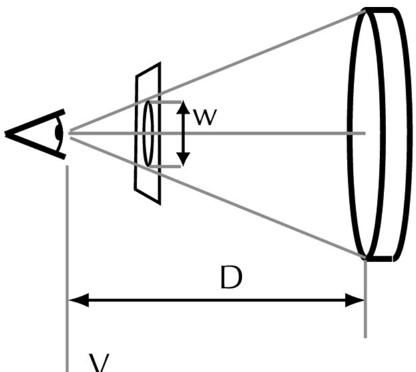


Fig D.2. Kinematics of Time to Contact.

When the observer approaches the object with a constant speed (V), he will 'hit' the object at $T_{contact}$ = D / V. Neither V nor D are optically specified. Optical information about D / V is available through the ratio (dw / dt) / w. This ratio represents the change to size ratio of the optical angle and is called 'Time to Contact' (τ). Since τ = w / (dw / dt) = D/V, Time to Contact can be derived from the optics, even when the spatial values of D and V are not known (Stappers, 1995).

In order to achieve contact without collision, the nested magnification must be made to cease. With help of the Time to Contact the observer can accomplish this goal.

APPENDIX E

NASA TASK LOAD INDEX

Rating Sheet

Subject: Block: Run:

Mental Demand
Low High

Physical Demand
Low High

Temporal Demand
Low High

Performance
Good Poor

Effort
Low High

Frustration Level
Low High

Rating Sheet Descriptions

Title	Endpoints	Descriptions
Mental Demand	Low, High	How much mental and perceptual activity was required? (Thinking, looking, deciding, etc.) Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	Low, High	How much physical activity was required? Was the task easy or demanding, slow or brisk, restful or laborious?
Temporal Demand	Low, High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occured? Was the pace slow and leisurely or rapid and frantic?
Performance	Good, Poor	How succesful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	Low, High	How hard did you have to work (mentally or physically)to accomplish your level of performance?
Frustration Level	Low, High	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Appendix F

Subject briefing & approach plates

TESTBRIEFING

The present day air structure, with its airways, dates from the 1950s and is based on the little air traffic and the technology of that day, e.g. electromechanical cockpit displays.
Nowadays the sky is getting crowded. One has estimated that till the year 2015, air traffic will expand with 200 or even 300 percent. This leads to congestion on the airways, which causes delays. This trend is already felt today. Changing the concept of airways can solve this problem. Airplanes should be given more autonomy in finding the best trajectory. This concept is known as 'Free Flight'.
The present day society asks for changes in the 'air structure' as well because of environmental and safety issues.
However, technology has evolved and the aviation industry has entered 'the world of digital information displays'. These displays offer the possibility to (radically) alter the way information is presented to pilots. These displays offer the opportunity to help solve the aforementioned problems.
One of the most prominent of these display types is the 'Tunnel-in-the-sky' (TIS) display. The TIS display is used to indicate safe or preferred paths of travel for a pilot. Currently these displays only specify the trajectory, it does not provide feedback where in the tunnel the you are supposed to be at what time. Because these tunnels depend on dynamic conditions, such as the flight behavior of other traffic, such timing information is essential.

In this experiment we are flying with this Tunnel in the Sky display to an airport. You have just been cleared and the trajectory you need to fly is known. You will see this trajectory presented as a tunnel through which you need to fly. Your task will be to stay inside this trajectory, and to fly at the right speed(s), in order to arrive on time at the airport (stay inside the bubble).
You will do this task with 4 different representations:

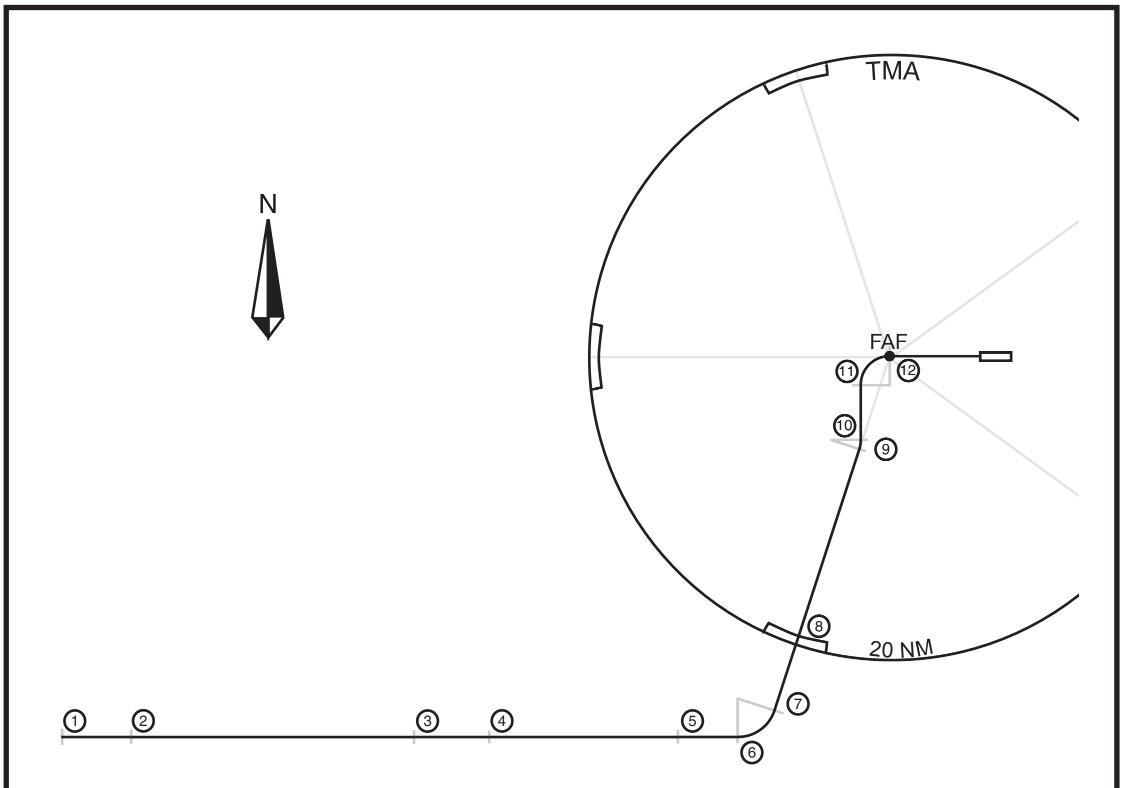
- The tunnel and a speed advisory indicator
- The primary bubble
- The bubble with a moving texture on the ground and an ellipse
- The bubble with a shadow representation

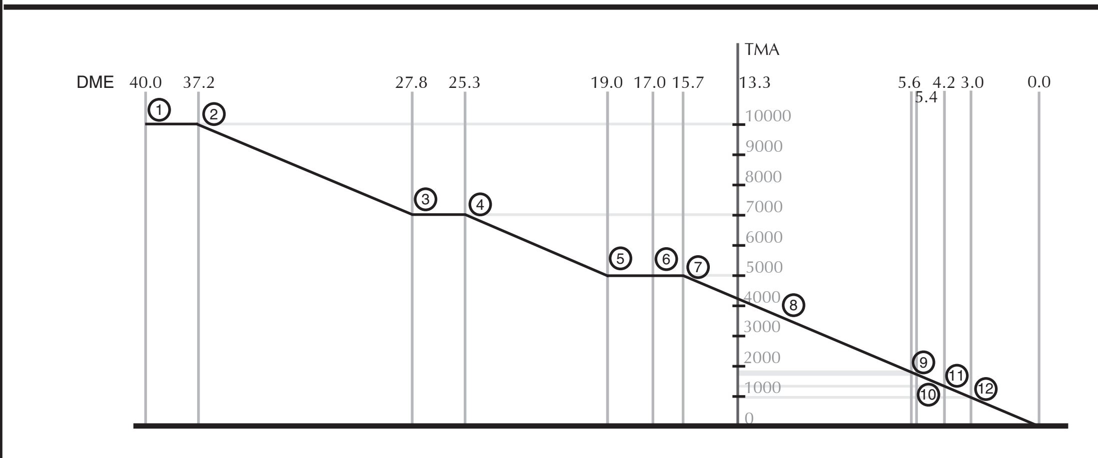
Also you will fly three different approaches. These approaches will be given to you in advance, on a sort of approach plate. You will have these approach plates with you, so you can always verify them during the flight. The approach plates also give information about which speed you need to fly in which section. This information will also be presented on the display above the airspeed indicator.
After each run you will be given a card with some questions that I would like you to answer. At the end of the trials you will get another set of questions that I would like you to answer.

Before we actually start the tests we will just fly through the tunnel one time to get more familiar with the simulator.

Do you have any questions?

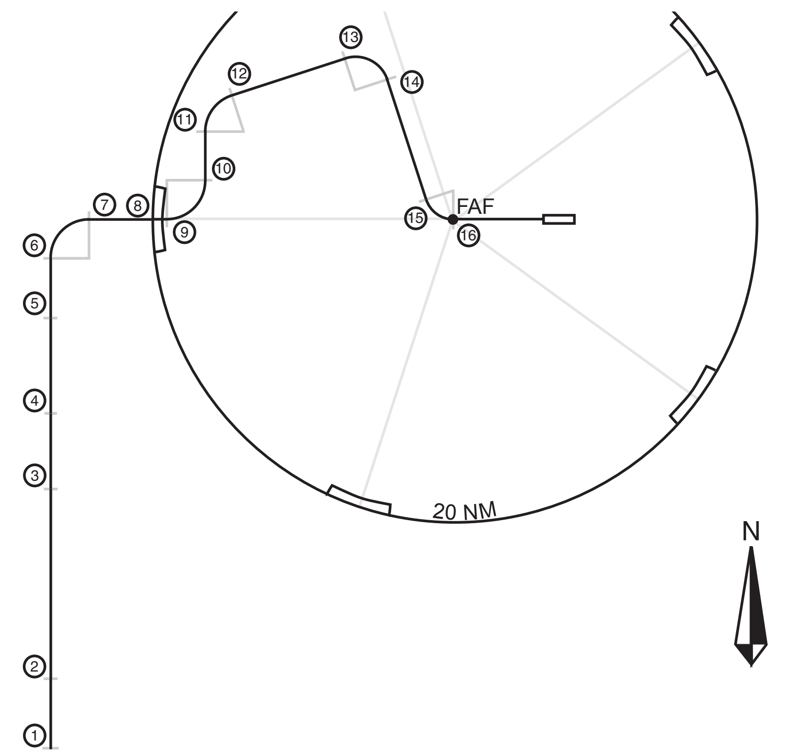
APPROACH 1 RWY 09 Wright State University

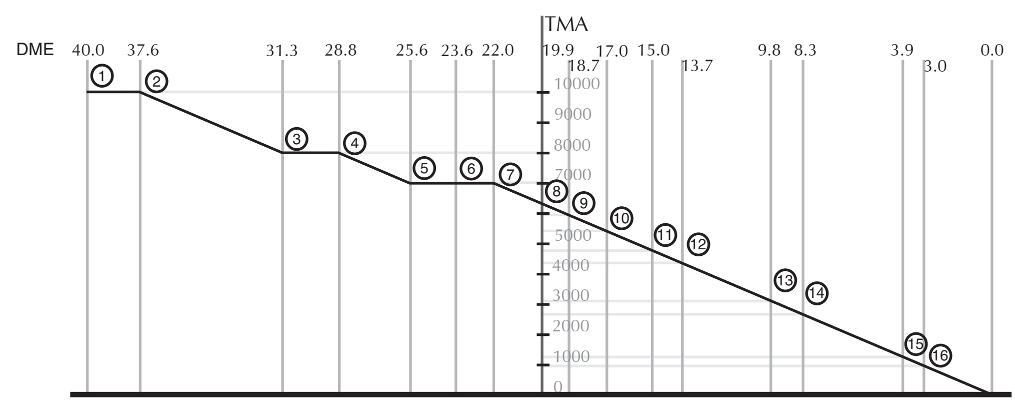




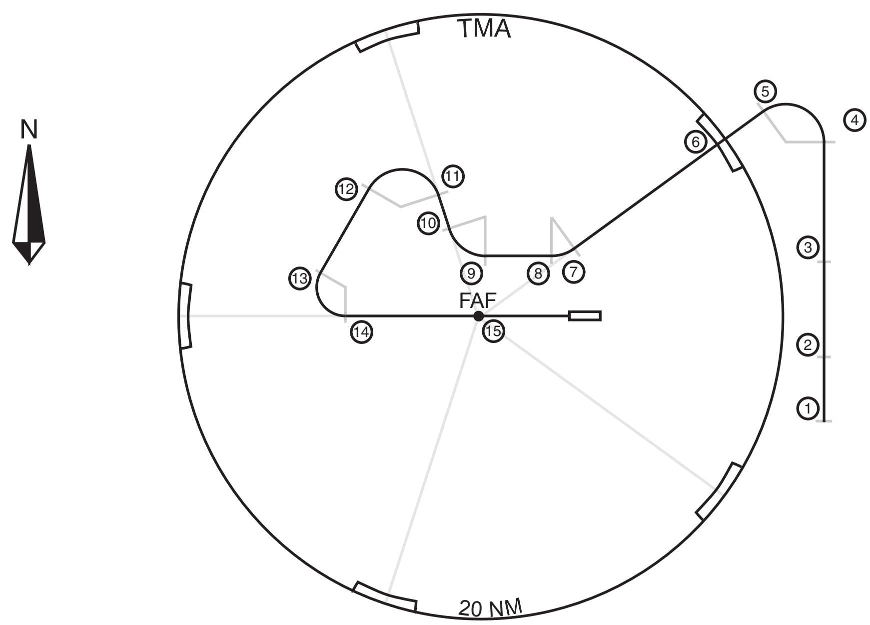
Approach speeds			
1	320 kts	11	180 kts
2	320 kts	12	180 kts
3	320 kts → 280 kts		Intentionally left blank
4	280 kts		
5	280 kts → 240 kts		
6	240 kts		
7	240 kts		
8	240 kts → 180 kts		
9	180 kts		
10	180 kts		

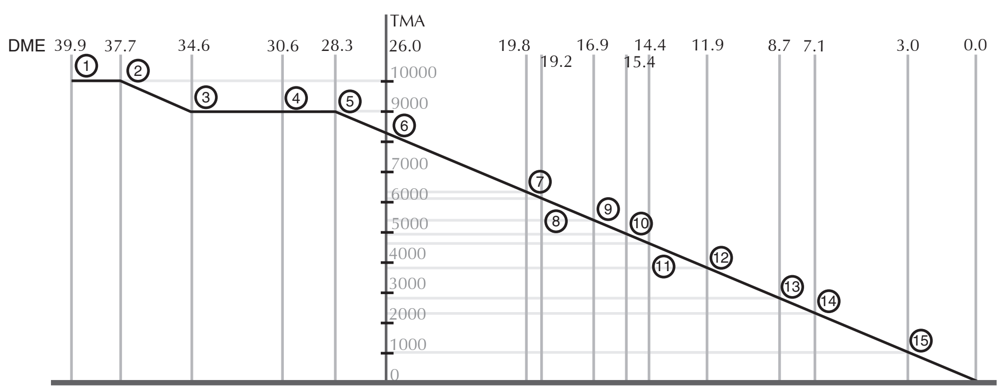
APPROACH 2   RWY 09   Wright State University





Approach speeds			
1	320 kts	11	240 kts
2	320 kts	12	240 kts → 210 kts
3	320 kts → 280 kts	13	210 kts
4	280 kts	14	210 kts → 180 kts
5	280 kts → 240 kts	15	180 kts
6	240 kts	16	180 kts
7	240 kts	Intentionally left blank	
8	240 kts		
9	240 kts		
10	240 kts		





Approach speeds			
1	300 kts	11	240 kts
2	300 kts	12	240 kts → 180 kts
3	300 kts → 240 kts	13	180 kts
4	240 kts	14	180 kts
5	240 kts	15	180 kts
6	240 kts	Intentionally left blank	
7	240 kts		
8	240 kts		
9	240 kts		
10	240 kts		

Appendix G

Questionnaire

Final Questions

Subject:

Block:

Date:

Flying experience:

Final Questions

Subject: Block:

1. Overal rating Concept 'Tunnel':

Mental Demand
Low High

Physical Demand
Low High

Temporal Demand
Low High

Performance
Good Poor

Effort
Low High

Frustration Level
Low High

2. Can you give comments on this concept, motivations why you've rated this concept, like you did?

3. In a future situation, like what you've flown today, would you like to use this display?

- ☐ Yes, always
- ☐ Maybe, sometimes
- ☐ No, never

Final Questions

Subject: Block:

4. Overal rating Concept 'Boxcar':

Mental Demand — Low … High

Physical Demand — Low … High

Temporal Demand — Low … High

Performance — Good … Poor

Effort — Low … High

Frustration Level — Low … High

5. Can you give comments on this concept, motivations why you've rated this concept, like you did?

6. In a future situation, like what you've flown today, would you like to use this display?

- ☐ Yes, always
- ☐ Maybe, sometimes
- ☐ No, never

Final Questions

Subject: Block:

7. Overal rating Concept 'Moving sides':

Mental Demand	Low	High
Physical Demand	Low	High
Temporal Demand	Low	High
Performance	Good	Poor
Effort	Low	High
Frustration Level	Low	High

8. Can you give comments on this concept, motivations why you've rated this concept, like you did?

9. In a future situation, like what you've flown today, would you like to use this display?

- ☐ Yes, always
- ☐ Maybe, sometimes
- ☐ No, never

Final Questions

Subject: Block:

10. Overal rating Concept 'Shadows':

Mental Demand — Low … High

Physical Demand — Low … High

Temporal Demand — Low … High

Performance — Good … Poor

Effort — Low … High

Frustration Level — Low … High

11. Can you give comments on this concept, motivations why you've rated this concept, like you did?

12. In a future situation, like what you've flown today, would you like to use this display?

- ☐ Yes, always
- ☐ Maybe, sometimes
- ☐ No, never

Final Questions

Subject: Block:

13. Put the concepts in a ranking order (1= best; 4=the least)

    1. ....

    2. ....

    3. ....

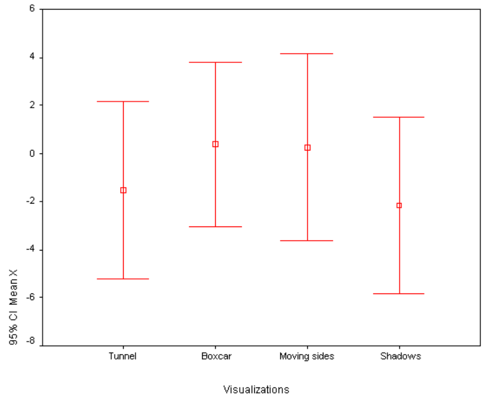
    4. ....

14. Additional Comments:

Appendix H

ANOVA results

Mean error X



3	f	p
concept	4.234	0.040

Post hoc: no significance

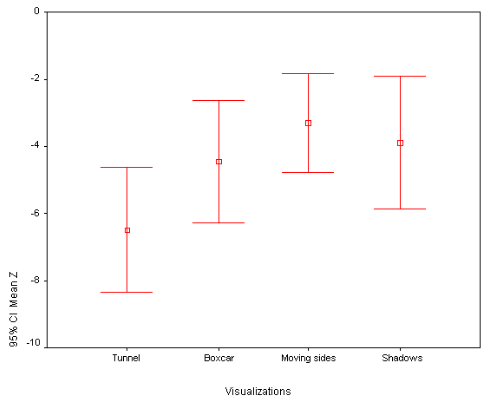
Variance error X

No significant results

RMS error X

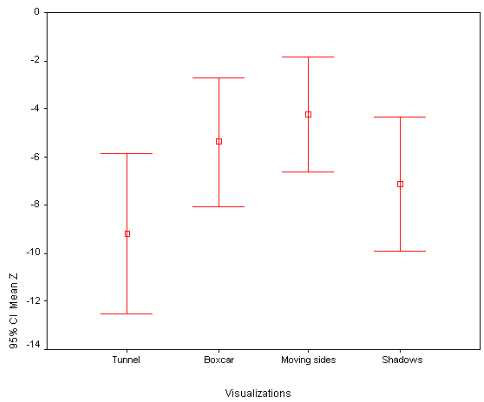
No significant results

Mean error Z



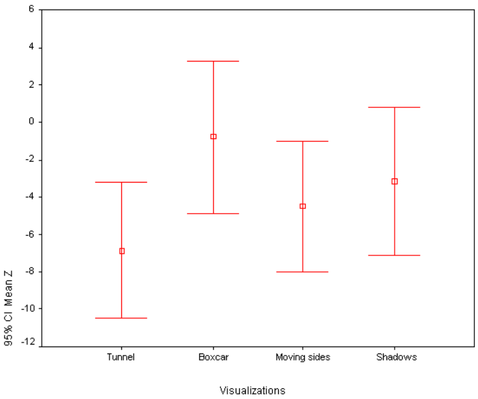
all	f	p
concept	2.966	0.090

Post hoc: 0 less then 1, 3 and 2



2	f	p
concept	4.232	0.040

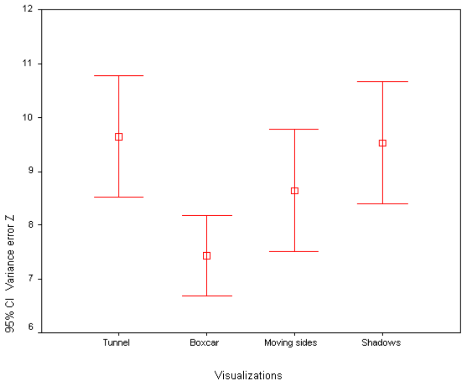
Post hoc: 0 less then 2



5	f	p
concept	3.915	0.048

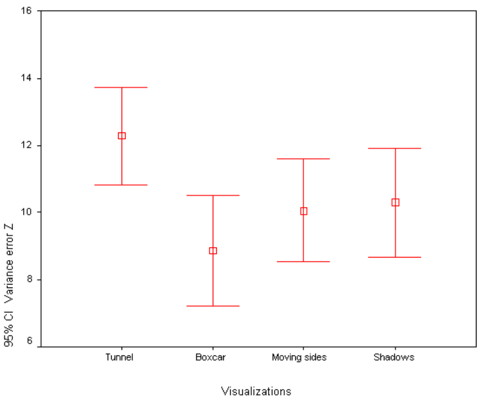
Post hoc: 0 less then 1

VARIANCE ERROR Z



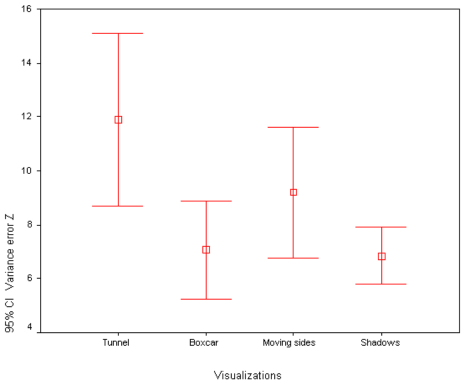
2	f	p
concept	5.844	0.017

Post hoc: 1 less then 0 and 3



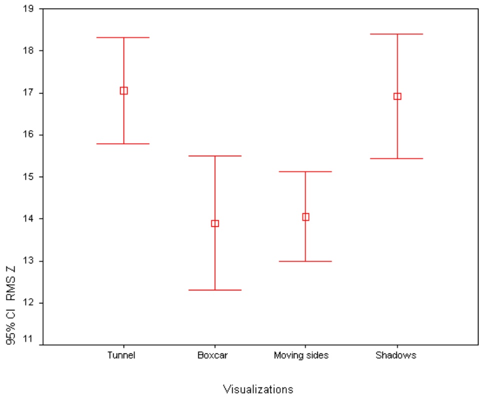
3	f	p
concept	3.251	0.074

Post hoc: 1 less then 0

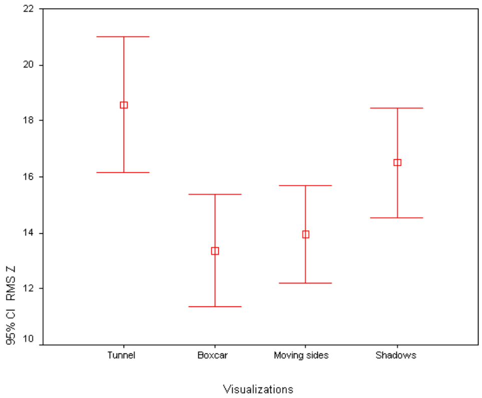


4	f	p	
concept	3.116	0.081	Post hoc: 1, 2 and 3 less then 0

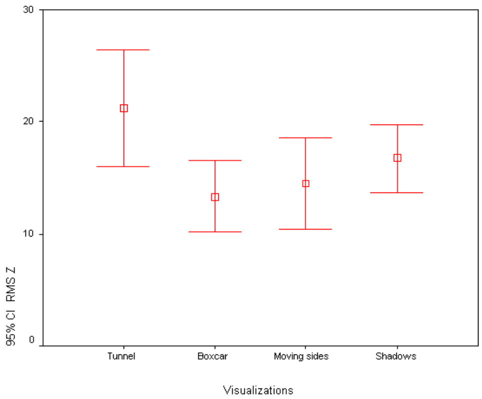
RMS Z



all	f	p	
concept	5.690	0.018	Post hoc: 1 and 2 are less then 3 and 0
segment	1.878	0.080	
con * seg	1.351	0.130	



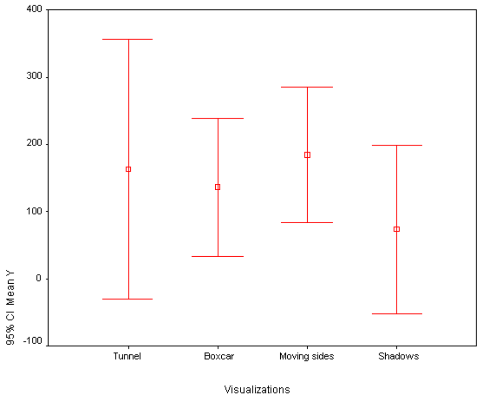
2	f	p	
concept	14.408	0.001	Post hoc: 1 and 2 less then 0



4	f	p
concept	3.372	0.068

Post hoc: 1and 2 less then 0

Mean error Y



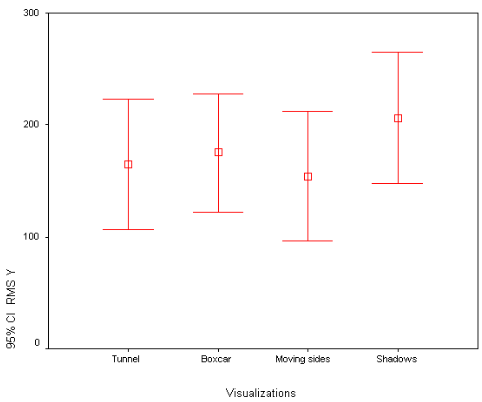
5	f	p
concept	3.759	0.053

Post hoc: no significance

Variance error Y

No significant results.

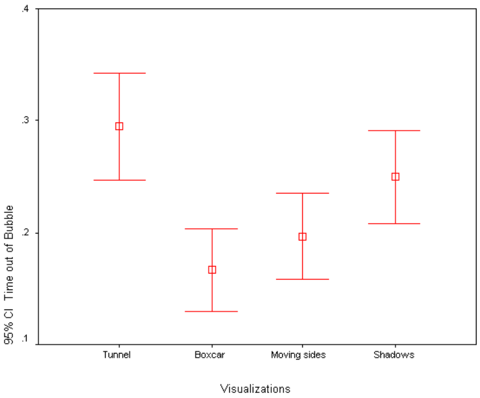
RMS Y



4	f	p
concept	5.390	0.021

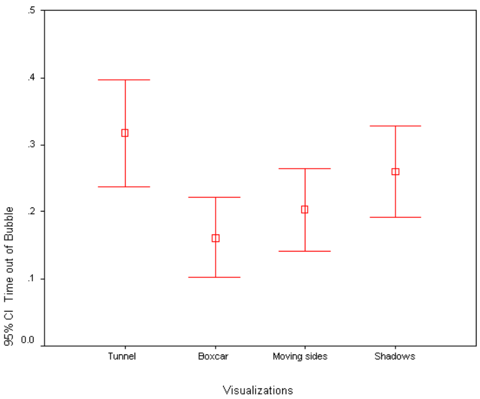
Post hoc: no significant difference

Time Out of Bubble



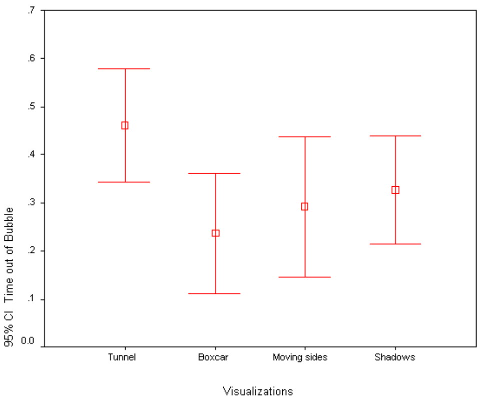
all	f	p
concept	7.476	0.008
segment	9.314	0.000
con * seg	1.950	0.006

Post Hoc 1 and 2 less then 3 and less then 0



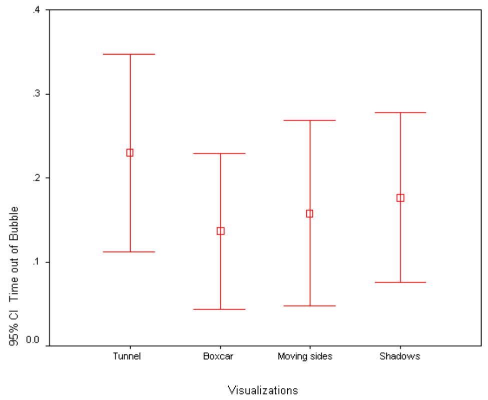
2	f	p
concept	5.968	0.016

Post hoc: 1 and 2 less then 0



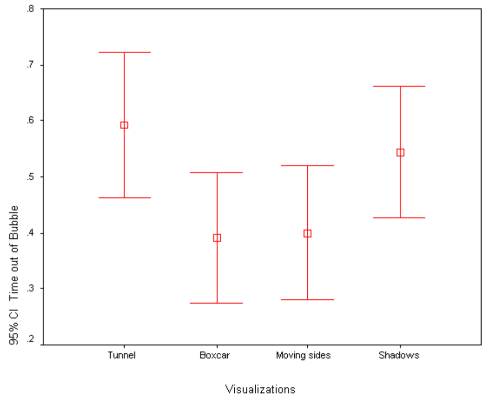
4	f	p
concept	3.359	0.069

Post hoc: no significant difference



5	f	p
concept	3.651	0.057

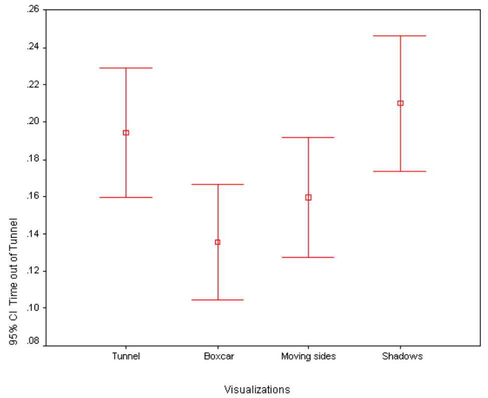
Post hoc: no significant difference



6	f	p
concept	4.185	0.041

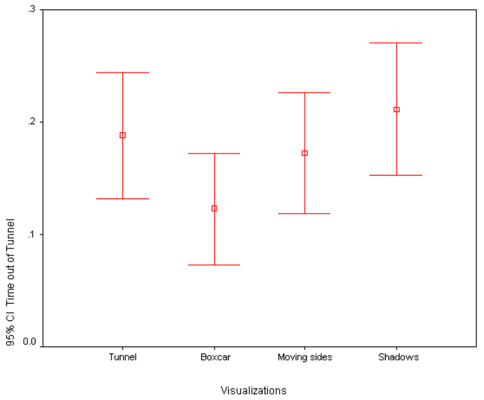
Post hoc: 1 and less then 3 and 0

Time Out of Tunnel



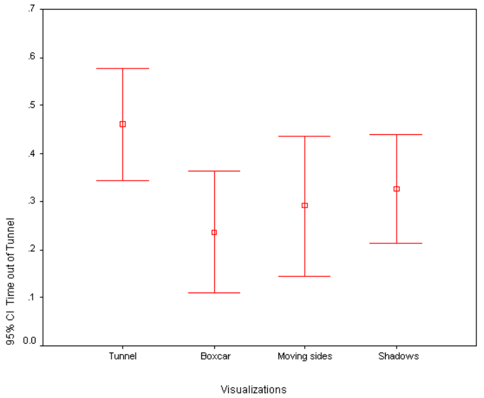
all	f	p
concept	5.024	0.026
segment	9.708	0.000
con * seg	1.216	0.228

Post hoc: 1 and 2 less then 0 and 3



2	f	p
concept	3.983	0.046

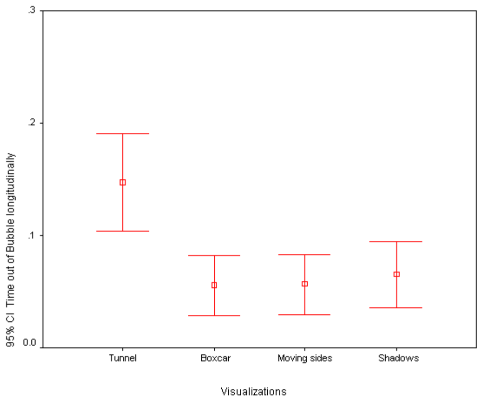
Post hoc: no significant difference



4	f	p
concept	3.359	0.069

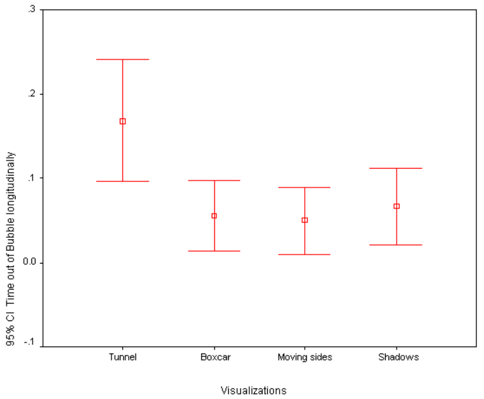
Post hoc: no significant difference

Time Out of Bubble Longitudinally



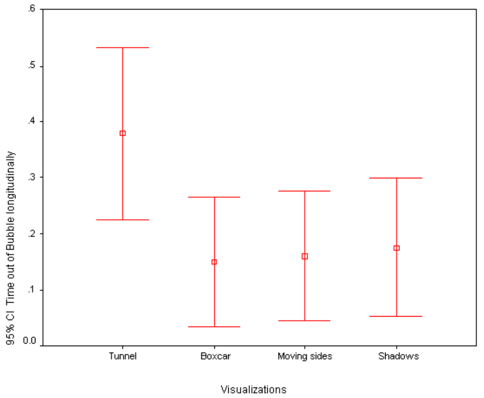
all	f	p
concept	9.437	0.004
segment	4.230	0.001
con * seg	6.031	0.000

Post hoc: 1, 2 and 3 less then 0



2	f	p
concept	10.979	0.002

Post hoc: 2, 1 and 3 less then 0



6	f	p
concept	7.074	0.010

Post hoc: 1, 2 and 3 less then 0

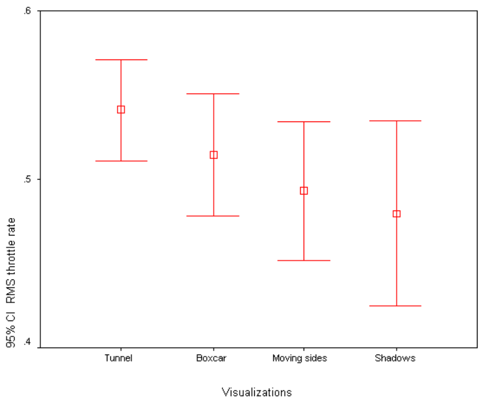
Stick X rate (elevator)

No significant results.

Stick Y rate (aileron)

No significant results.

Throttle rate



4	f	p
concept	3.552	0.061

Post hoc: no significant difference

Appendix I

Legend Approach 1

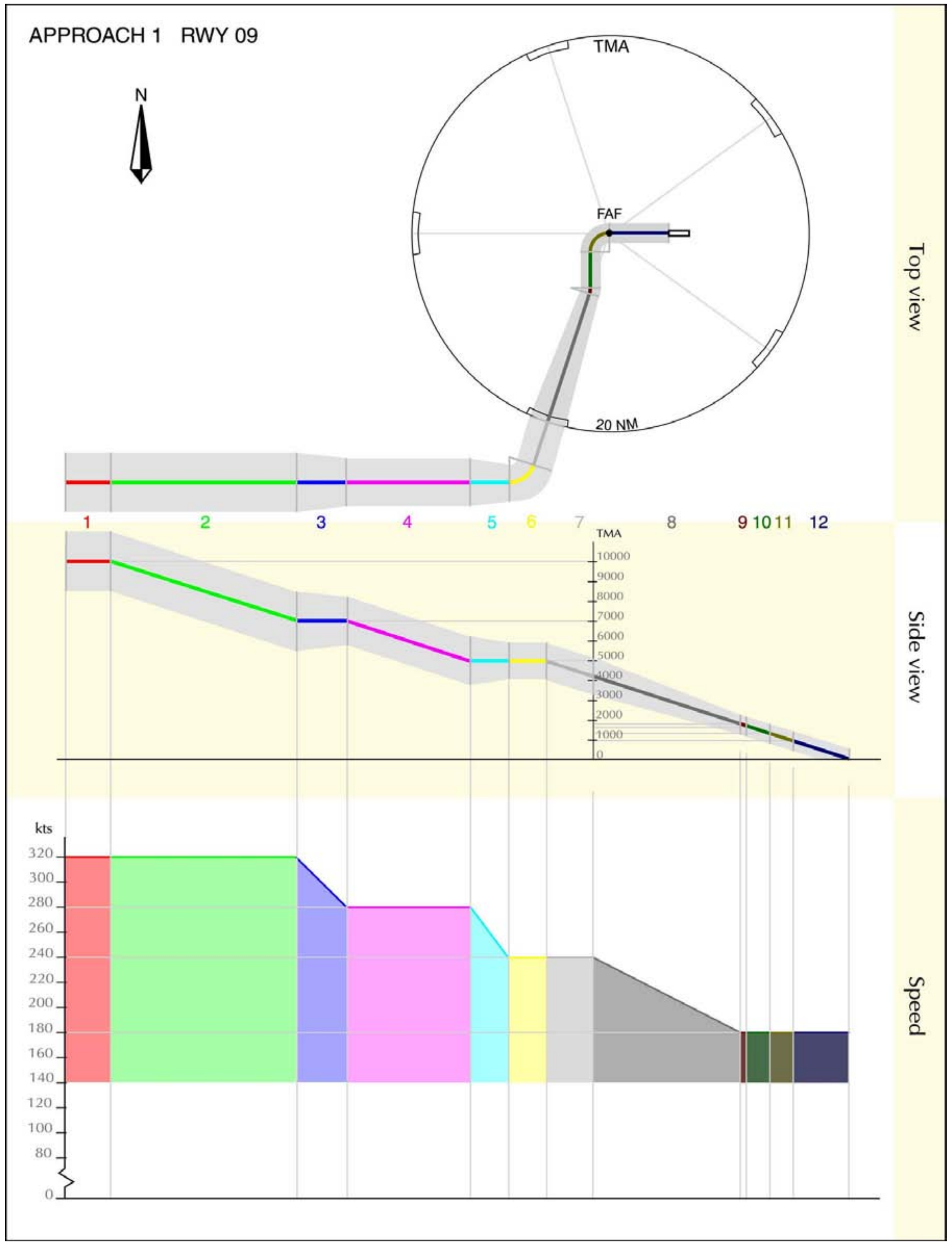


Fig I.1. Top- and side view and speed profile of the analyzed approach-to-land. The colors of the segments correspond with the colors in the graphs. The gray area around the approach trajectory depicts the varying tunnel size. The speed profile indicates the required speed in each segment. The colored area does not go below the 140 kts to indicate the margin between the advised speed and the stall speed of the aircraft.

The TMA (Terminal Maneuvering Area) is a small area around an airport that can only be entered with authorization from Air Traffic Control. The FAF (Forward Approach Fix) is the point from where the aircraft needs to be on a stable and straight course to land.

WRIGHT STATE UNIVERSITY

ID Studio Lab

TU Delft

Delft University of Technology