# Flight-path Vector Symbology in Tunnel-in-the-sky Displays

Max Mulder Delft University of Technology, Faculty of Aerospace Engineering, Control and Simulation Division P.O. Box 5058, 2600 GB Delft, The Netherlands E-mail: m.mulder@lr.tudelft.nl

# Abstract:

The tunnel-in-the-sky display is a viable candidate to become the primary flight display of future aircraft cockpits. The tunnel display shows the flight trajectory to be flown in a synthetic threedimensional world. The synthetic nature of the tunnel display allows the display to be augmented with symbology designed to improve the pilot's performance. An example is the flight-path vector (FPV) symbol that explicitly presents the aircraft direction of motion relative to the world. The paper provides a theoretical discussion regarding the potential benefits of presenting the FPV symbol for the pilot's guidance and control task. Furthermore, it describes an experiment which has been conducted to assess the use of a flight-path vector in the task of following a straight tunnel trajectory.

Keywords: Aircraft control, cockpit displays, information analysis, cybernetics.

# Introduction

The volume of air transport grows continuously: for the next two decades a doubling is forecasted. New technologies are being developed with the dual objective of increasing the *efficiency of air traffic management* and enhancing *flight safety*. One of the expected measures is to increase the flexibility in air traffic control by allowing curved approach profiles. Flying these - inherently more complex – curved approaches increases the pilot task demand load and requires enhanced levels of situation awareness. Improving the presentation of information to the pilot by means of intuitive displays can alleviate these problems considerably (Oliver, 1990). A promising candidate to become the primary flight display of future cockpits is the *tunnel-in-the-sky* display (Fig. 1), which shows a spatial analog of the planned trajectory. Previous research indicated that the perspective tunnel display outperforms conventional flight displays in the pilot manual and supervisory tasks (Grunwald, 1984).

At the Delft University of Technology a research project was initiated to investigate the applicability of a tunnel display for the pilot manual control task. In contrast to other studies the project goal was not to compare the tunnel display with current displays in terms of pilot performance, situation awareness, and workload. Rather, the objective was to obtain an understanding of *how* pilots use the tunnel display as their main source of information in the aircraft guidance task. A methodology has been developed, labelled the *cybernetic approach*, which allows substantial in-sight into the effects of varying display designs on pilot-behaviour (Mulder, 1999). The paper will discuss the characteristics of pilot/display interaction in the task of manually controlling the aircraft along a straight trajectory. The subject of interest is the flight-path vector (FPV) symbol, an elementary form of display augmentation. In Section 2 the optical information conveyed by the basic tunnel display will be discussed. Section 3 introduces the flight-path vector symbol that explicitly shows the aircraft instantaneous direction of motion relative to the environment. The usefulness of the FPV in the pilot manual control task depends

on a number of variables, and to assess the effects of these variables experimentally an experiment has been conducted, discussed in Section 4. The experimental display results are summarised in Section 5 and are put into perspective in Section 6. The conclusions are stated in Section 7.

## **Optical Information in Straight Tunnel Segments**

A tunnel display shows the trajectory to be followed in a synthetic three-dimensional world. The task of the pilot is to guide the aircraft along this trajectory.



Figure. 1. The Tunnel-in-the-Sky display. In this figure, 1) depicts the aircraft symbol, 2) the tunnel geometry, 3) the aircraft velocity (in [knots]), 4) the aircraft altitude (in [ft]), 5) the horizon line, 6) the heading angle indicators, and 7) the bank angle indicator.

To fulfil this task, the pilot estimates the state of the aircraft with respect to the trajectory and, based on this estimated state, decides upon and activates the necessary control actions. In order



Fig. 2. A snap-shot of the tunnel image when flying through a straight tunnel section. Besides the elements referred to in the main text, H shows the horizon line, C the fixed aircraft reference symbol and 1 to 4 the frame numbers  $f_i$ 

to comprehend the pilot-display interaction it is essential to understand the underlying *state* estimation process. This has been investigated from two perspectives. In (Mulder, 1994) it was examined what effects a spatial display could have on pilot control behaviour: the HUMAN was the main issue. The questions that were addressed were the availability, the usefulness and the potential utilisation, or, *information-processing*, of the various kinds of spatial sources of information present in the real world or in a synthetic representation of that world. In (Mulder, 1999) the MACHINE side was the main issue, and an attempt was made to make an inventory of all optical cues in a generic tunnel display. Here, irrespective of the human, mathematical expressions were derived that express the aircraft state with respect to the trajectory in terms of the spatial cues: *information-transfer*. Based on the investigations from both a human and a machine-centered perspective, the characteristics of pilot-display interaction were put into a theoretical framework (Mulder, 1999).

Straight Tunnel Sections



(a) The longitudinal tunnel cues (1)-(2).



(b) The lateral tunnel cues (3)-(4).



(c) The vertical tunnel cues (5)-(6).

Fig. 3. The three subsets of static optical cues in a straight tunnel section. The (U, V) and (U', V') axes represent the fixed and rotated central viewplane axes, respectively. The perpendicular dotted lines through the infinity point represent the horizontal and vertical pseudo-horizons.

The analysis of optical information for the *recti-linear* reference flight condition along a straight trajectory starts with defining a generic tunnel. Fig. 2 shows the tunnel image corresponding with the situation considered here. The optical cues originate from the projection of the main elements of the tunnel geometry- the *frames* F, the altitude *poles* A and the *longitudinal lines*  $L_i$  connecting the frames - on the viewplane. The aircraft is positioned in the tunnel (tunnel width  $W_i$ , height  $H_i$  and downslope  $\Gamma_i$ ) with an arbitrary position ( $x_e$ ,  $v_e$ ) and attitude ( $\psi, \phi, \theta$ ) with respect to the tunnel centreline.

#### Information-transfer

*Static optical cues:* Positioning the aircraft with an arbitrary position and attitude with respect to the trajectory yields the tunnel image of Fig. 2. The main static cues of (Mulder, 1999) are described at the hand of Fig. 3 showing three subsets of cues resulting from the projection of the longitudinal (Fig. 3(a)), lateral (Fig. 3(b)) and vertical (Fig. 3(c)) elements of the tunnel geometry:

- (1) The position of the *infinity point*  $u_{\omega}$ ,  $v_{\omega}$ ), defined as the projection on the viewplane of an arbitrary point of the tunnel when the viewing distance  $D_t$  into the tunnel goes to infinity.
- (2) The *optical splay angles*  $\Omega_i$  (i = 1 4), defined as the angles of the longitudinal frame lines with respect to the horizon. Another optical splay angle can be defined for the 'virtual' line connecting the tops of all altitude poles ( $\Omega_5$ ).
- (2) The *lateral displacements*  $\varepsilon_i$  (left) and  $\eta_i$  (right) of the vertical frame lines (frame *i*) with respect to the rotated viewplane centreline *V*'. The displacements  $\pi_i$  of the altitude poles are similar.
- (4) The *relative lateral displacements*  $\varepsilon_{ij}$  (left), (right) and  $\eta_{ij}$  of the vertical frame lines and the altitude poles of frames *i* and *j*.
- (5) The vertical displacements  $\mu_i$  (bottom) and  $v_i$  (top) of the lateral frame lines (frame i) with respect to the rotated viewplane centreline U'.
- (6) The *relative vertical displacements*  $\mu_{ij}$  (bottom) and  $v_{ij}$  (top) of the lateral frame lines of frames *i* and *j*.

Mathematical expressions are derived that relate the optical cues to the aircraft state with respect to the straight tunnel trajectory (Mulder, 1999). First, the position of the *infinity point* (1) on the display shows the attitude of the aircraft longitudinal axis with respect to the trajectory (heading angle error  $\psi_e$  and relative pitch  $(\theta + \Gamma_i)$ ). It marks the crosspoint of the *vertical* and *horizontal pseudo-horizons* that form the main optical reference for the relative displacement cues (4) and (6). Second, the *changes* in the optical splay angles (2) are a function of the lateral and the vertical position error only (Mulder, 1996). As a consequence, the optical splay *rates* are only a function of the aircraft relative motion, i.e. flight-path, with respect to the centreline. Third, the relative *lateral* displacements (4)  $\varepsilon_{ij}$  and  $\eta_{ij}$  of the tunnel frames *i* and *j* located at distances  $D_i$ and  $D_j$  (with  $D_j = D_i + \Delta D$ ), and  $\Delta D$  the fixed distance between two successive frames) are a function of only the *lateral* position error  $x_e$ . Similarly, the relative *vertical* displacements (6)  $\mu_{ij}$ and  $v_{ij}$  are only a function of the *vertical* position error  $\varpi_e$ . Again, the derivatives of the relative displacements are only a function of the aircraft relative motion, i.e. flight-path, with respect to the centreline.

Dynamic optical cues: The dynamic optical cues are essential in the perception of an important referent of rectilinear motion, i.e. the *flight-path angle error*. In (Mulder, 1999) it is shown that there are two, basically identical forms of dynamic optical cues. First, there are the derivatives of the static optical cues, labelled the *indirect* dynamic cues. Second, there are the *direct* dynamic cues originating from the global optic flow field, illustrated in Fig. 4.



Fig. 4. Radial flow pattern in recti-linear motion. In this figure, the dotted lines show the theoretical radial flow pattern originating from the focus of radial outflow (circle). The dashed lines show the viewplane centrelines. The dash-dot lines mark the position of the infinity point. The arrows show the velocities of the tunnel frame elements on the viewplane. The aircraft attitude angles ( $\psi$ , $\theta$ ), aerodynamic angles ( $\alpha$ , $\beta$ ) and flight-path angles ( $\chi$ , $\gamma$ ) are as indicated. The following state is plotted:  $W_t = H_t = 45$  [m];  $\Gamma_t = 3^\circ$ ,  $V_{tas} = 70$  [m/s];  $\beta = +3^\circ$ ;  $\alpha = +7^\circ$ ;  $\psi = +4^\circ$ ;  $\theta = +3^\circ$ ;  $\gamma_e = +1^\circ$ ;  $\chi_e = +7^\circ$ ;  $x_e = -15$  [m];  $v_e = +5$  [m].

#### Information Processing

Based on the findings listed above and a literature survey on human visual motion processing the usefulness of the optical cues in aiding the pilot in monitoring the aircraft states is analysed in (Mulder, 1999).

The aircraft *attitude* angles  $\phi$  and  $\theta$  - presented with the horizon line - are important as inner loop attitude control variables. They can be perceived directly from the display. The aircraft *heading angle error*  $\psi_e$  defined with respect to the tunnel centreline, can be perceived directly through the position of the *infinity point*. The *position errors*  $x_e$  and  $v_e$  can be perceived through the optical splay angles ( $\Omega_i$ ) and through the relative displacements of the tunnel frames ( $\eta_{ij}$ ,  $\varepsilon_{ij}$ , and  $\pi_{ij}$ ) the latter especially when taken with respect to the vertical and horizontal pseudo-horizons. The optical gradients of perspective (splay) and density/compression (displacements) are generally considered to be the main invariants directing human behaviour (Gibson, 1986). The aircraft *flight-path* angle error ( $\chi_e$  and  $\gamma_e$ ) can be perceived with the global optic flow field and the gradients of local elements in the visual field. In (Mulder, 1999) it is argued that it are especially the *local gradients* of motion perspective, i.e the splay angle rates and the compression rates, that form the basis of flight-path estimation.

### Assessing the Use of Flight-path Vector Symbology

#### **Display** Augmentation

Irrespective of the cockpit displays mediating the aircraft state to the pilot, the main issues that are of concern to the pilot in the aircraft guidance task are probably those of 'where am I?' and 'where am I going?' The advantage of electronic displays over their (electro-)mechanical predecessors is that they can be *augmented with synthetic symbology* designed in particular to help pilots in conducting their tasks and to improve their performance. The synthetic enhancements are generally a form of *augmenting cues*, which can be defined as "*a perceptual event auxiliary to the basic display that is used to enhance an important characteristic of the display*" (Eberts, 1987). The synthetic nature of the tunnel-in-the-sky display allows these virtual enhancements to be integrated in a way that is compatible with the guidance task. In the past, numerous investigations have been conducted addressing the usefulness of synthetic symbology in two-dimensional (Gold, 1965; Merhav & Grunwald, 1978; Hynes, Franklin, Hardy, Martin, & Innis, 1989) and three-dimensional (Grunwald & Merhav, 1978; Roscoe & Jensen, 1981; Jensen, 1981; Grunwald, Robertson, & Hatfield, 1981) aircraft guidance displays. The fact that visually presented augmenting cues have often shown to improve human performance can be understood using two basic principles (Eberts, 1987):

- (1) a well-designed display augmentation transforms the task at hand from a *computational* to a *perceptual* task; and,
- (2) it provides a means of establishing or improving the *compatibility* between the display and the operator's mental model of the system and the corresponding task.

### The Flight-path Vector Symbol

The flight-path vector has become almost a standard feature of the modern cockpit Primary Flight Display (PFD) and the Head-Up Display (HUD). It shows the attitude of the aircraft velocity vector with respect to the longitudinal Body axis, allowing a pilot to directly perceive the aircraft's angle of attack  $\alpha$  and angle of slip  $\beta$ . This is aircraft *status* information that can be measured with any common on-board sensor (Kayton & Fried, 1997). To estimate the vertical direction of the aircraft motion relative to a horizontal plane, the angle of climb y, a pilot can simply *perceive* the vertical deflection of the FPV with respect to the horizon line. To estimate the lateral direction of the aircraft motion relative to a ground track, the aircraft track angle  $\chi$ ,  $(= \psi + \beta)$ , the pilot must *mentally combine* the angle of slip ( $\beta$ ) information from the PFD with the heading information ( $\psi$ ) obtained from the Navigation Display (ND). The FPV has proved to be very useful in many ground-referenced aircraft manoeuvering tasks (Hynes et al., 1989). For instance, when approaching the runway the pilot can simply steer the FPV symbol to the desired touchdown point on the runway (Gold, 1965). Or, to fly a horizontal turn at constant altitude, the pilot only has to keep the FPV on the horizon line. The FPV symbol can be regarded as a natural addition to the basic display, enhancing an important characteristic of that display. Up to some point this holds for the application of a FPV on a standard, *planar*, PFD, since it allows a pilot to establish a one-to-one mapping of the aircraft flight-path to a symbol on the display moving with respect to the horizon. But it is certainly true for the presentation of a FPV on the *pictorial* threedimensional tunnel-in-the-sky display. Recall that the spatial information mediated by the tunnel display allows a pilot to directly perceive the motion of the aircraft relative to the tunnel, a ground-referenced element of the artificial world (the focus of radial outflow in Fig. 4). The direction of one's egomotion relative to the environment is directly coded in the *changing* optical array mediated by the spatial display: it is a *feature* of the display. Either the *indirect* dynamic cues, i.e. the derivatives of the gradients of optical splay and optical density, or the *direct* dynamic cues of the optic flow field allow a pilot to perceive the direction of motion.

There remains some dispute, however, regarding the accuracy of the human visual motion perception and, as a result, the functionality of this perception in maneuvring tasks (Johnston, White, & Cumming, 1973; Warren, Morris, & Kalish, 1988; Warren & Hannon, 1990; Grunwald & Kohn, 1993). Presenting the direction of egomotion *explicitly* on the display can therefore be expected to be a *very useful synthetic enhancement of the natural environment*. The FPV allows a *direct* perception of the aircraft direction of motion from the display, even from a *static* representation, with the optical gradients of motion perspective as alternative cues.

# Variables Affecting the Use of a Flight-path Vector

For a pilot in manual control of the aircraft an important piece of information is the relative motion of the aircraft relative to the surrounding air mass. The air mass itself, however, may move relative to the earth. Hence, since most aircraft guidance tasks are conducted with respect to ground-fixed references such as the runway or a virtual earth-fixed tunnel, it is essential for a pilot to be aware of the relative motion of the aircraft relative to the ground surface (Watler & Logan, 1981; Hynes et al., 1989). The advantage of a flight-path vector is that it may be used to show, in an intuitive fashion, either the relative motion of the aircraft with respect to the air mass or the relative motion with respect to the earth. Although the flight-path vector has become a standard feature on modern PFDs and HUDs, only a few studies have been conducted so-far addressing its functionality (Grunwald & Merhav, 1978). The obviousness and simplicity of the idea to present a flight-path vector to the display is not expected to affect the control strategy of a pilot, as argued above.

Grunwald and Merhav's study on display augmentation: In (Grunwald & Merhav, 1978) the influence of the vehicle dynamics and the bandwidth of the external disturbances on the effectiveness of different forms of synthetic symbology representing higher order aircraft state components was investigated. The manual control task used in the study was the remote control of the lateral-longitudinal motion of a flight vehicle using an elementary three-dimensional display. The vehicle response dynamics varied from 'slow', in terms of bandwidth, to 'fast'. The bandwidth of the turbulence shaping filter used to generate external disturbances varied between 0.1 and 3.2 [rad/s]. The experiment showed that a positive effect of a FPV presentation on the performance of the closed loop pilot-vehicle system depends on the specific combination of vehicle dynamics and disturbance bandwidth, and the extent in which the FPV information is perturbed by the disturbances. The higher the order of the state elements of the vehicle dynamics, the more these state elements are influenced by the disturbances (Etkin, 1972). In case of slow vehicle dynamics the higher frequencies in the response of the vehicle and the presented symbology are much less prominent compared to the case of fast vehicle dynamics. In case of fast vehicle dynamics this results in rapid and unpredictable motions of those types of symbology that are driven by higher order state information.

*Effects of Turbulence:* The work of Grunwald and Merhav (1978) showed the relevance of including effects *other* than those regarding the display presentation, such as turbulence. Consider the influence of the turbulence. The shaping filter for the disturbance  $v_g$  (or  $\beta_g = v_g/V_{tas}$ ) on the *lateral* component of the aircraft velocity vector, v, is given by (Mulder & van der Vaart, 1994):

$$H_{w}^{v_{g}}(j\omega) = \sqrt{\frac{L_{g}}{V_{tas}}} \sigma_{v_{g}} \frac{1 + \sqrt{3} \frac{L_{g}}{V_{tas}}(j\omega)}{\left(1 + \frac{L_{g}}{V_{tas}}(j\omega)\right) \left(1 + \frac{L_{g}}{V_{tas}}(j\omega)\right)} (1)$$

where  $V_{tas}$  is the aircraft velocity,  $L_g$  (in [m]) the so-called *scale length* of the turbulence, and  $\sigma^2_{vg}$ the intensity of the turbulence  $v_g$  which is independent of  $L_g$  and  $V_{tas}$  The white noise w is coloured through the first order filter (zero at  $s = -1/3 \sqrt{V_{tas}/L_g}$  concatenated with a second order low pass filter (two poles at  $s = -V_{tas}/L_g$ ). The scale length indicates the spatial extent of the correlation. The quotient  $V_{tas}/L_g$  determines the bandwidth of the turbulence and shows that this bandwidth is a function of the characteristics of the turbulence itself  $(L_g)$  and of the velocity of the aircraft moving through it. E.g., flying through a turbulence field (fixed  $L_g$ ) with a smaller velocity yields a smaller bandwidth of the disturbances and thus less high-frequent perturbations. Because the aircraft velocity also determines to some extent the bandwidth of the aircraft dynamics, manipulating  $V_{tas}$  and  $L_g$  allows the experiment of Grunwald and Merhav (1978) to be repeated. There were some reasons that motivated this repetition. Grunwald and Merhav (1978) used the Optimal Control Model (OCM) to model their results without an attempt to *identify* the model from the experimental data. The experiments in (Mulder, 1999) showed that the identification of pilot models leads to a much deeper understanding of the mechanisms behind the observed behaviour. Therefore the present experiment was believed to increase the general understanding of how presenting a FPV influences pilot behaviour.

#### Experiment

#### Goal of the Experiment

An experiment has been conducted to investigate the effects of presenting the flight-path vector symbol on pilot performance, control activity, control behaviour, and mental workload in the pilot guidance task of following a straight trajectory.

Apparatus and Setup: Subjects were seated in a chair in a darkened, noise-free room in front of a 17 inch CRT monitor. The control manipulator was a servo-controlled hydraulic side-stick with common characteristics. The display update-rate was 20 [Hz]. The tunnel was presented as a grey wireframe on a black-and-white background. The lateral/longitudinal aircraft motions of a small business jet, a Cessna Citation I, were simulated in the experiment. The aircraft motions were disturbed with three independent random disturbance signals (Fig. 7), representing a relatively strong atmospheric turbulence field.

Subjects and Instructions to Subjects: Four professional pilots participated in the experiment. They were instructed to control the lateral/longitudinal aircraft motion through the tunnel as accurately as possible.

Independent Measures: Three independent measures were manipulated in the experiment. First, the <u>flightpath vector symbol</u> was either presented on the tunnel display or not. Second, three <u>scale lengths</u> Lg of the lateral turbulence were applied: 750, 250 and 85 [m]. The intensity of the turbulence field was kept constant at  $\sigma^2_{\nu g} = 1 \text{ [m^2/s^2]}$ . Third, the aircraft moved through the turbulence field with three <u>velocities</u>: 70, 100 and 130 [m/s]. The consequences of combining the three turbulence scale lengths and the three aircraft velocities on the properties of the disturbances are discussed below.

*Experimental Design:* A full-factorial within-subjects design was applied, consisting of a total of 18 conditions  $(2 \times 3 \times 3)$ . The conditions were randomised over the experiment. Each subject conducted four familiarisation sessions (72 runs) before completing six replications of all experimental conditions (108 runs) that served as the measurements.

**Procedure:** During the course of two days a subject conducted 180 experimental runs, divided in 30 blocks of six runs each. A single run lasted 120 [s], consisting of a run-in time  $T_i$  of 15 [s] and a measurement time  $T_m$  of 105 [s]. The pace of the experiment was such to allow sufficient time for subject preparation and to prevent fatigue.

Dependent Measures: Seven variables were selected as dependent measures: (i,ii) the subject's aileron control signal  $\delta_a$  and its derivative; (iii,iv) the aircraft angle of roll  $\phi$  and its derivative; (v) the heading angle error  $\psi_e$ ; (vi) the track angle error  $\chi_e$ , and (vii) the cross-track error  $x_e$ . Note that because of the disturbance on the lateral component of the aircraft velocity vector,  $v_g$ , the track angle error  $\chi_e$  and not the heading angle error  $\psi_e$  represents the *true* aircraft lateral motion relative to the trajectory, i.e.  $\chi_e = \psi_e + \beta_g$ .

Experimental Hypotheses: It is hypothesised that, first, when a FPV is presented on the display, the pilot will apply a strong feedback loop on  $\chi_e$  Second, accordingly, when no FPV is presented the pilot is hypothesised to use the information on  $\psi_e$ , which is directly available from the display, as a first estimate of the track angle error. The motion perspective cues could help the pilot in improving this initial estimate. Furthermore, when the FPV is presented it is hypothesised that, third, due to the explicit information on  $\chi_e$  the path-following performance will be superior. For smaller turbulence scale lengths  $L_g$  and higher aircraft velocitie  $V_{tas}$  the bandwidth of the disturbance signal becomes larger, resulting in rapid motions of the FPV symbol on the display. Therefore, it is hypothesised that, fourth, pilot performance decreases in these conditions. Fifth, when no FPV is presented, it is hypothesised that pilot performance also deteriorates for smaller  $L_{e}$ s and for larger aircraft velocities, but to a significantly less extent than in the FPV conditions. This is because the effects of the turbulence are not directly visible from the display but must be perceived from the motion perspective cues. The implicitness of the flight-path angle error information leads to a decreasing pilot bandwidth of this variable. In other words, a pilot would ignore rapid changes in the flight-path angle error rather than rapidly trying to correct for them. Sixth, it is hypothesised that at the high velocity conditions the performance in terms of  $\psi_e$  and  $\chi_e$  will improve because for these conditions small changes in these quantities rapidly lead to large position errors.

### Results

### Results from a Pilot Questionnaire

Sources of information and control strategies: Without the FPV pilots claimed to use the relative displacements of the tunnel frames,  $\varepsilon_{ij}$  and  $\eta_{ij}$  and especially the relative displacements of the altitude poles,  $\pi_{ij}$ , to perceive the lateral position with respect to the trajectory. The lateral aircraft motion is perceived primarily using the derivatives of the relative lateral displacements of the tunnel altitude poles,  $\pi_{ij}$ . Surprisingly, no reference whatsoever was made by the subjects on the use of splay angles and their derivatives for controlling the aircraft. Subjects commented very favourably on the presence of a flight-path vector symbol. When the FPV is present, subjects considered their main task was to keep the symbol positioned on the tunnel's infinity point ( $\psi_e = \chi_e \longrightarrow \beta_g = 0$ ). Then, when this was achieved, the lateral position errors were

estimated using in particular the relative displacements of the tunnel poles  $\pi_{ij}$ . These position errors were corrected by positioning the FPV symbol away from the infinity point towards the more distant tunnel wall. Again, no reference was made upon the use of splay or splay-rate in these conditions. The aircraft velocity was believed to have no important effect at all on the control strategy. One pilot commented, however, that because of the larger aircraft pitch angle for higher velocities, the perception of the altitude poles' displacements became more difficult. Concerning the influence of the turbulence scale length no comments were made except that for the smaller  $L_{gs}$  (higher bandwidths), attending the relative movements of the FPV with respect to the tunnel's infinity point was considered to contribute to visual workload.

*Effort Ratings:* The effort ratings show that the control task was judged considerably more difficult when the flight-path vector was not available, Fig. 5. The task was judged somewhat less difficult for the high velocity conditions. Furthermore, the effort ratings become *smaller* when the scale length of the turbulence decreases from 750 to 85 [m] for all velocities and independent of the presence of the FPV.

# Statistical Analysis

A full-factorial mixed-model Analysis of Variance was conducted to analyse the time domain data. The independent measures were the presence of the flightpath vector (F) (2 levels), the turbulence scale length (S) (3 levels) and the aircraft velocity (V) (3 levels). The ANOVA results are summarised in Table 1. The means and 95% confidence limits of six of the seven dependent measures are shown in Fig. 6.

*Pilot Control Activity:* Pilot control activity, Fig. 6(a), decreases for the larger velocity conditions ( $\delta_a$ : F<sub>2,6</sub> = 15.233, p <0.01;  $\dot{\delta}_a$ : F<sub>2,6</sub> = 7.481, p =0.024), increases when the FPV is presented ( $\delta_a$ : F<sub>1,3</sub> = 5.494, p=0.100;  $\dot{\delta}_a$ : not significant) and increases only marginally when  $L_g$  decreases, Fig. 6(a). A post-hoc analysis (Newman-Keuls, p=0.05) revealed that the differences in control activity for the three velocity conditions are indeed all significant.

*Inner loop Measures:* Figs. 6(c) and 6(b) indicate that the roll angles and the roll rates increase for higher velocities ( $\phi$ : F<sub>2,6</sub>=22.463, p <0.01;  $\dot{\phi}$ : F<sub>2,6</sub>=6.461, p =0.032) and for smaller turbulence scale lengths ( $\phi$ : F<sub>2,6</sub>=16.022, p <0.01;  $\dot{\phi}$ : F<sub>2,6</sub>=5.542, p =0.043). The presence of a FPV symbol yields lower roll angle deviations (not significant) and higher roll angle rates (F<sub>1,3</sub>= 7.187, p =0.075). When the velocity increases the effect of the FPV on  $\phi$  becomes larger. Posthoc analyses (NK, p=0.05) showed that the differences in  $\phi$  and  $\dot{\phi}$  for the three velocity conditions were indeed all significant. The roll angle differences between the smallest and the largest scale lengths are the only ones that are significant.

Path-following Performance: The heading angle error and the track angle error decrease significantly for the high velocity conditions ( $\psi_e$ : F<sub>2,6</sub>=62.569, p <0.01;  $\chi_e$ : F<sub>2,6</sub>=67.531, p <0.01), Figs. 6(d) and 6(e). When the FPV is not presented,  $\psi_e$  is unaffected by the turbulence scale length. When the FPV is presented,  $\psi_e$  increases for the smaller scales, especially at the low velocity conditions, leading to a significant FxS-interaction (F<sub>2,6</sub>=16.643, p <0.01). Presenting the FPV leads to a significant decrease in track angle error  $\chi_e$  and position error  $x_e$  ( $\chi_e$ : F<sub>1,3</sub>=16.022, p =0.028;  $x_e$ : F<sub>1,3</sub>=27.437, p =0.014), i.e. performance improves significantly. Decreasing the turbulence scale length yields larger track angle errors  $\chi_e$  and, at least when the FPV is presented, larger position errors ( $\chi_e : F_{2,6}=69.091$ , p <0.01;  $x_e$ : F<sub>2,6</sub>=5.411, p =0.045).

When the FPV is not presented, the decreasing turbulence scale leads to *smaller* position errors, resulting in the significant F x S-interaction ( $F_{2,6}=30.363$ , p <0.01). The F x S interaction of  $\chi_e$  ( $F_{2,6}=33.973$ , p <0.01) is caused by the fact that when the FPV is presented the effects of changing the turbulence scale are somewhat larger. The effect of the scale length on  $\chi_e$  is stronger for the low velocity conditions, yielding the significant S x V-interaction ( $F_{4,12}=5.093$ , p =0.012). The same holds for the presence of the FPV as indicated by the significant F x V-interaction ( $F_{2,6}=14.163$ , p <0.01). Finally, Fig. 6(f) shows clearly that position errors increase for the higher velocities ( $F_{2,6}=8.113$ , p =0.020). Post-hoc analyses (NK, p=0.05) indicated that the differences in  $\chi_e$  as caused by the different velocities, the presence of the FPV symbol, and also those caused by the different turbulence scale lengths are all significant.

The only exception is the effect of turbulence scale on  $\chi_e$  when the FPV is not presented. Here, only the results for the smallest scale length differ significantly from the others. Furthermore, the position errors differ significantly only for the smallest scale length of 85 [m], independent of the presence of the flight-path vector.



Fig. 5. Z-scores of the effort ratings for all 18 conditions of experiment X5. In this figure, and in the following the insets show the three velocity conditions (in lengths (in [m/s]). The numbers 750 - 85 represent the turbulence scale lengths (in [m]). The dashed and the continuous lines represent the data with and without a flightpath vector, respectively. The numbers below the figure depict the experimental conditions.

	control activity		inner loop measures		path-following performance		
	$\delta_a$	$\dot{\delta_a}$	φ	Ø		<u>χ</u> ε	<i>x</i> <sub>e</sub>
main effe	ects						
F	•	•		o	· ·	*	*
S		•	**	*	•	**	*
V	**	*	**	*	**	**	*
2-way in	teractions						
F×S	J .		· ·	•	**	**	**
F×V		•	•	•	•	**	•
S×V	•	•	•	· .	•	*	*
3-way in	teraction						
F×S×V	· ·	•	· .	•	·	•	•

Table 1. Results of a full-factorial ANOVA (X5) on the dependent measures involving control activity, inner loop measures and path-following accuracy (in this table '\*\*', '\*' and 'o' represent chance levels of p < 0.01, 0.01 and <math>0.05 .

#### Results from the Model-based Analysis

The insertion of three independent forcing function signals in the closed loop allows the three primary pilot feedback loops to be estimated *directly*. Another difference with previous investigations reported in (Mulder & Mulder, 1998; Mulder, 1998) that results from inserting *three* signals in the loop is that the aircraft flight-path error equals the heading error added with the random disturbance signal :  $\chi_e = \psi_e + \beta_g$ , where  $\beta_g = i_3$ . When  $i_3$  equals zero the aircraft flight-path is identical to its heading which can be perceived directly from the display. Otherwise, the



Fig. 6. The means and 95% confidence limits of the STDs of the dependent measures (all subjects). Here, the squares connected with the continuous lines and the circles connected with the dashed lines represent the data for the configurations without and with a FPV, respectively. The horizontal dashed lines and the shaded rectangles show the values of these quantities for an earlier experiment referred to as X1 reported in (Mulder & Mulder, 1998), where the disturbance on flight-path (in Figure 7) was zero.

heading angle only *suggests* the direction of motion whereas the true direction of motion - the flight-path - must be estimated from the motion perspective of the wireframe tunnel.

This has important consequences for modelling, as will be discussed next, at the hand of Fig. 7.



Figure 7. The composition of the three components of the aircraft dynamic model and the three disturbances inserted in the closed loop. This figure illustrates the fact that, dependent of the presence of the FPV symbol on the display, a pilot can close the middle loop using either  $\psi_e$  or  $\chi_e$ , where  $\chi_e = \psi_e + i_3$  and  $i_3 = \beta_g$ .

*Multi-loop Pilot Models:* The non-parametric identification of the pilot frequency responses from the experimental data revealed that the following findings were consistent for all pilots:

- when no flight-path vector was presented on the display the pilots use the heading angle error feedback,  $\Psi_e$ , to dampen their response to a position error  $x_e$ ;
- when a flight-path vector was presented on the display the pilots use the flight-path angle error feedback,  $\chi_e$ , to dampen their response to a position error  $x_e$ .

This is an important result because it proves the hypotheses that, first, when no flight-path vector is available pilots are unable to perceive flight-path angle error *well enough* to use as their middle loop feedback, and they simply revert to the heading angle error for this purpose. Second, when a FPV is available pilots can directly perceive their flight-path angle from the display and use it as their middle loop feedback, leading them to basically ignore the heading angle error.

In other words, when no FPV is available pilots successively close the  $\phi$ ,  $\psi_e$  and  $x_e$  loops - and  $\chi_e$  is ignored. When an FPV is available pilots successively close the  $\phi$ ,  $\chi_e$  and  $x_e$  loops - and  $\psi_e$  is ignored. From an identification perspective, these findings lead to the use of *two* pilot models. The first pilot model corresponds with the feedback of  $\phi$ ,  $\chi_e$  and  $x_e$  for the conditions without a flight-path vector. With this model the three pilot frequency responses can be identified *directly* in the frequency domain using the (3 x 1) identification method of (Mulder, 1999). The second pilot model corresponds with the feedback of  $\psi$ ,  $\chi_e$  and  $x_e$  for the conditions with a flight-path vector. In this model the middle and outer loops are identified in the frequency domain as a single, *combined* outer loop, i.e. because  $x_e = V_{tas}$ .  $\chi_e$ , the same (2 x 1) identification procedure can be applied as in the experiments of (Mulder & Mulder, 1998; Mulder, 1998).

# Discussion

In the following, the experimental findings of will be elaborated along three themes of investigation. These are, first, how does the presentation of the flight-path vector symbol affect

pilot performance and control behaviour? Second, how is the pilot control behaviour affected by the characteristics of the flight-path disturbances? And third, what happens with pilot behaviour after the insertion of a disturbance on the aircraft flight-path in respect to the situation where this was not the case?

# The Effects of Showing a Flight-path Vector

The experimental hypotheses concerning the use of a flight-path vector could be confirmed. Probably the most important finding of all has been that in determining the pilot model *structure* - the non-parametric identification phase of estimating the pilot frequency responses - it was found that two models had to be applied to describe the observed pilot control behaviour. That is, when no FPV is presented, a pilot successively closes the aircraft attitude, heading angle error and position error feedback loops. This is evidence for the hypothesis that without the FPV pilots are unable to perceive the aircraft direction of motion relative to the tunnel trajectory ( $\chi_e$ ) well enough to use this information for purposes of control. Rather, they revert to the best alternative for  $\chi_e$  which can be perceived directly from the display, namely through the position of the infinity point, i.e. the heading angle error  $\psi_e$ . Secondly, when a FPV is presented, showing the aircraft flight-path angle error explicitly on the display, pilots use this flight-path information as their middle loop feedback, whereas the heading angle error can be ignored. Subjects stated that their aim was to continuously put the FPV symbol located on the tunnel's infinity point. The questionnaire revealed further that in particular the relative displacements of the tunnel altitude poles,  $\pi_{ij}$  and  $\dot{\pi}_{ij}$ , were used for position control. These findings demonstrate that the optical cues of motion perspective mediated by the generic wireframe tunnel are not salient enough for pilots to perceive the aircraft direction of motion directly from the display, at least not with the accuracy needed for purposes of control, and not with the current characteristics of the flightpath disturbances. This result has considerable theoretical implications and should be addressed further in future experiments.

The experimental findings provide evidence for the hypothesis that showing a flight-path vector significantly improves pilot performance. Pilot control activity,  $\delta_a$  and  $\delta_a$ , is considerably higher with a FPV as well as the magnitude of the aircraft roll angle rates. The heading angle errors have the same order of magnitude as those found for the conditions without an FPV. Hence, although this variable is not used for control purposes, the performance in terms of  $\psi_e$  is similar to that when the heading angle error *is* used for control. Path-following performance in terms of the flight-path angle error  $\chi_e$  as well as the position error  $x_e$  becomes markedly better when the flight-path vector is presented. Furthermore, the pilot effort ratings are considerably lower when the FPV is available and pilots comment very favourably for the synthetic enhancement.

The pilot modelling efforts, discussed in detail in (Mulder, 1999), indicate for the conditions with an FPV a consistent shift in pilot attention to the feedback of flight-path angle error, at the cost of the position error feedback but especially the control of the inner loop of aircraft attitude. In other words, the bandwidth of the middle loop feedback is significantly higher and the bandwidth of the outer loop significantly lower in the case where an FPV is presented. In the inner loop, bandwidth is sacrificed in order to gain extra phase margin when the FPV is presented, clarifying the results stated above that in these conditions the roll angle errors and roll angle rates increase significantly. The finding that the increase in pilot inner loop lead occurs mainly at the low velocity conditions, matches the relatively high effort ratings in these conditions.

#### The Effects of the Turbulence Bandwidth

Recall that the bandwidth of the turbulence acting on the aircraft's flight-path is determined by the inverse quotient of the scale length  $L_g$  of the turbulence field and by the velocity  $V_{tas}$  Of, the aircraft moving through it. The questionnaire revealed that pilots judge the simulation more realistic for higher bandwidths  $(V_{tas}/L_g)$  of the flight-path perturbation. Although they did comment on a higher visual workload when bandwidth increased, the effort ratings show a contrary effect, independent on the presentation of the FPV, namely that of lower workload when the scale length decreases. The experimental data confirms the hypothesis that the pilot's use of the FPV is harmed when the bandwidth of the turbulence increases. Especially the scale length  $L_g$  affects pilot behaviour considerably, judged by the higher roll angles and roll angle rates but in particular the rapidly deteriorating performance in terms of  $\chi_e$ , for smaller  $L_gs$ . The heading angle errors remain unaffected by the manipulation of  $L_g$ , which can be explained by the fact that with an FPV this variable is ignored, whereas in the conditions without the FPV this variable is used for control. The modelling data further support the finding that the feedback of  $\chi_e$ deteriorates when the bandwidth of the disturbance acting on it increases, resulting to a shift in pilots' attention from the middle loop feedback (flight-path) to the outer loop feedback (position). Apparently, the rapid and unpredictable motions of the FPV on the display cause pilots to pay less attention to the FPV symbol. The bandwidth of the inner loop further deteriorates when  $L_g$  decreases indicating a further need of the pilots to put their efforts into controlling the two outer loops.

When no FPV is presented, the effects of the bandwidth are smaller and less consistent among subjects. Not surprisingly, performance in terms of aircraft heading angle error is not influenced by the bandwidth. Whereas the flight-path angle error  $\chi_e$  increases for higher bandwidths, independent of the presentation of an FPV, the position error performance improves in these conditions, a finding which contradicts the pre-experimental hypothesis. This improvement could be attributed to the fact that, first, the feedback of  $\psi_e$  applied in these conditions is not harmed at all by the increasing turbulence bandwidth, allowing subjects to maintain the bandwidth of their heading angle error feedback loop. Second, however, with a *fixed* turbulence intensity an increasing turbulence bandwidth yields larger amplitudes of the disturbance high-frequency components and lower amplitudes of the low-frequency components. Now, the fixed outer loop vehicle dynamics, an integrator-like system, acts as a low-pass filter weakening in particular the high-frequency components of the disturbance, yielding smaller position errors. This artifact due to the design of the experiment, is *independent* of the presence of the FPV. As mentioned above, without the FPV the increasing bandwidth of the disturbances yields an improved path-following performance in terms of the position error, which makes sense. With a FPV, however, pilots apparently insist in correcting the rapid flight-path disturbances, decreasing the performance significantly: the FPV harms pilot performance in these conditions.

The Effects of the Disturbance on the Aircraft Flight-path: Although the additional disturbance on the aircraft flight-path complicates a comparison of the experimental results with those found in an earlier experiment, reported in (Mulder & Mulder, 1998), and referred to as Experiment XI, with otherwise exactly the same definition (and subjects, of course), such a comparison could shed a light upon the effects that the insertion of this disturbance has had on pilot behaviour. Recall that without the flight-path disturbance the track angle equals the heading angle and the aircraft direction of motion can be perceived directly from the display using the infinity point. The *trends* in the present data concerning the effects of manipulating the aircraft velocity are *exactly the same* as those found in XI. That is, independent of the presence of the flight-path vector symbol, when the aircraft velocity becomes larger the pilot control activity decreases, the aircraft roll angles and roll rates increase, the heading angle errors as well as the track-angle errors decrease and the position errors increase.

The magnitudes of the performance data, however are markedly different. Pilot control activity,  $\delta_a$  and  $\delta_{a}$ , is higher than that found in XI, as well as the roll angle rates and especially the roll angles themselves. The heading angle errors  $\psi_e$  are also considerably higher. Note that when the FPV is presented, performance in terms of  $\chi_e$  equals the performance in terms of  $\psi_e$  found in XI, a finding that can be explained by the fact that in both cases the aircraft direction of motion with respect to the tunnel can be perceived directly from the display. The performance in  $\chi_e$  deteriorates fast, however, when the bandwidth of the disturbances becomes larger. Generally, independent of the presence of the FPV, the pilot middle loop bandwidth is significantly higher and the pilot inner loop bandwidth considerably lower than those found in XI, indicating the relative importance of controlling the aircraft direction of motion in the current experiment.

When no FPV is presented, path-following performance, in terms of  $\chi_e$  and  $x_e$ , is much worse than that found in Xl, although the current position performance data approximates those of Xl when the bandwidth of the turbulence increases. Surprisingly, when the FPV is presented, performance in terms of  $x_e$  is much better than that found in Xl. This is a remarkable result because, due to the insertion of a third disturbance on the aircraft flight-path angle, the task as such was expected to become increasingly difficult. It could be caused by the fact that the feedback of the flight-path, the middle loop, is indeed so much stronger (higher bandwidth) as compared to the situation in Xl where the heading must be perceived through the position of the infinity point. Again, when the bandwidth of the flight-path disturbance increases, in particular when the scale length  $L_g$  decreases, the present experimental data approximate those of Experiment Xl, without the flight-path disturbance.

### Conclusions

In this experiment it is shown that presenting the flight-path vector symbol significantly improves pilot path-following performance and yields pilot effort ratings that are considerably lower. A model-based analysis revealed that without the FPV pilots are unable to perceive the aircraft direction of motion relative to the tunnel trajectory well enough to use this information for purposes of control. The pilots' use of the FPV is significantly harmed when the bandwidth of the turbulence acting on the vehicle increases. In the high-bandwidth conditions, the pilots could have performed even better *without* the FPV (Mulder, 1999).

### References

- Eberts, R. E. (1987). Internal Models, Tracking Strategies, and Dual-Task Performance. Human Factors, 29(4).
- Etkin, B. (1972). Dynamics of Atmospheric Flight. New York: John Wiley & Sons.
- Gibson, J. J. (1986). *The Ecological Approach to Visual Perception*. Hillsdale (NJ): Lawrence Erlbaum Associates. (originally published in 1979)
- Gold, T. (1965). Quickened Manual Flight Control with External Visual Guidance. *IEEE Transactions on Aerospace and Navigational Electronics, ANI-11* (9), 151-156.

- Grunwald, A. J. (1984). Tunnel Display for Four-Dimensional Fixed-Wing Aircraft Approaches. Journal of Guidance and Control, 7(3), 369-377.
- Grunwald, A. J., & Kohn, S. (1993). Flight-Path Estimation in Passive Low-Altitude Flight by Visual Cues. Journal of Guidance, Control, and Dynamics, 16(2), 363-370.
- Grunwald, A. J., & Merhav, S. J. (1978). Effectiveness of Basic Display Augmentation in Vehicular Control by Visual Field Cues. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-8(9),* 679-690.
- Grunwald, A. J., Robertson, J. B., & Hatfield, J. J. (1981). Experimental Evaluation of a Perspective Tunnel Display for Three-Dimensional Helicopter Approaches. *Journal of Guidance and Control*, 4 (6), 623-631.
- Hynes, C. S., Franklin, J. A., Hardy, G. H., Martin, J. L., & Innis, R. C. (1989). Flight Evaluation of Pursuit Displays for Precision Approach of Powered-Lift Aircraft. *Journal of Guidance*, 12(4), 521-529.
- Jensen, R. S. (1981). Prediction and Quickening in Perspective Flight Displays for Curved Landing Approaches. *Human Factors*, 23(3), 355-363.
- Johnston, I. R., White, G. R., & Cumming, R. W. (1973). The Role of Optical Expansion Patterns in Locomotor Control. *The American Journal of Psychology*, 86(2), 311-324.
- Kayton, M., & Fried, W. R. (1997). Avionics Navigation Systems (2nd. ed.). New York: John Wiley & Sons.
- Merhav, S. J., & Grunwald, A. J. (1978). Display Augmentation in Manual Control of Remotely Piloted Vehicles. *Journal of Aircraft*, 15(3), 182-189.
- Mulder, J. A., & van der Vaart, J. C. (1994). Aircraft Responses to Atmospheric Turbulence. Lecture notes D-47, Faculty of Aerospace Engineering, Delft University of Technology.
- Mulder, M. (1994). Displays, Perception and Aircraft Control. A survey of theory and modelling of pilot behaviour with spatial instruments (Report No. LR-762). Delft: Faculty of Aerospace Engineering, Delft University of Technology.
- Mulder, M. (1996). Modelling Manual Control of Straight Trajectories with a Tunnel-in-the-Sky Display. Proceedings of the XVth European Annual Conference on Human Decision Making and Manual Control, Soesterberg, The Netherlands, June 10-12, 1.2.1-1.2.12.
- Mulder, M. (1998). Tracking Curved Trajectories with a Tunnel-in-the-Sky Display. Proceedings of the XVIIth European Annual Conference on Human Decision Making and Manual Control, Valenciennes, France, December 14-16, 197-206.
- Mulder, M. (1999). Cybernetics of a Tunnel-in-the-Sky Display. Ph.D. dissertation, Faculty of Aerospace Engineering, Delft University of Technology.

- Mulder, M., & Mulder, J. A. (1998). Tunnel Size in a Tunnel-in-the-Sky Display: A Cybernetic Analysis. Proceedings of the Seventh IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man-Machine Systems, Kyoto Japan, September 16-18, 335-340.
- Oliver, J. G. (1990). Improving Situational Awareness Through the Use of Intuitive Pictorial Displays. Society of Automotive Engineers, SAE Technical Paper 901829, 1-6.
- Roscoe, S. N., & Jensen, R. 5. (1981). Computer- Animated Predictive Displays for Microwave Landing Approaches. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-11* (11), 760-765.
- Warren, W. H., & Hannon, D. J. (1990). Eye Movements and Optical Flow. Journal of the Optical Society of America, 7(1), 160-169.
- Warren, W. H., Morris, M. W., & Kalish, M. (1988). Perception of Translational Heading From Optical Flow. Journal of Experimental Psychology: Human Perception and Performance, 14(4), 646-660.
- Watler, J. F., & Logan, W. B. (1981). The Maneuvering Flight Path Display An Update. Proceedings of the Fifth Advanced Aircrew Display Symposium, 138-162.