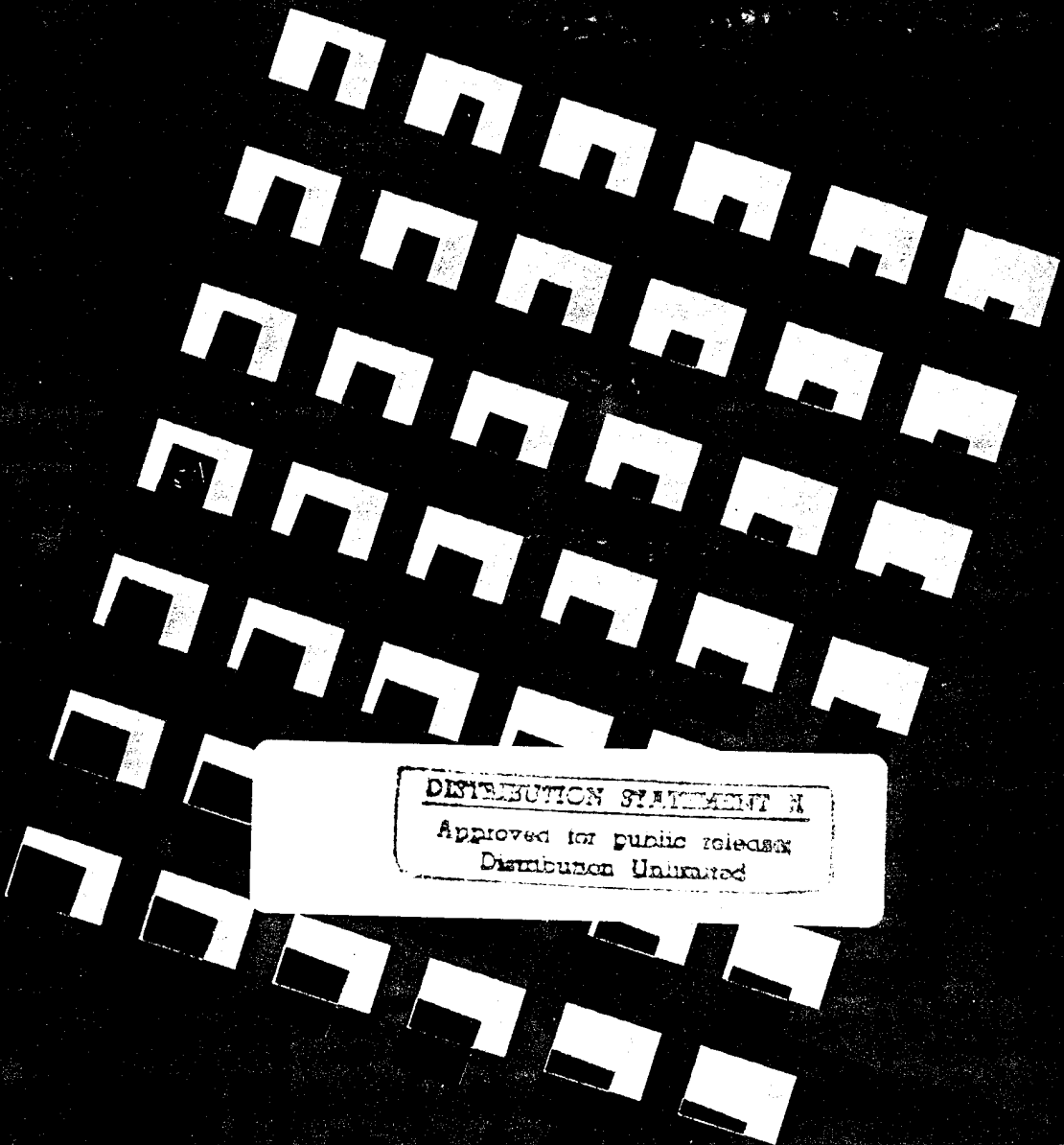


TNO-report
TNO-TM 1995 A-73

title
Tactical situation displays: integrated
versus separate information presentation

TNO Human Factors
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**Tactical situation displays: integrated
versus separate information presentation**

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30 November 1995

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auteurs : Dr.ir. P.O. Passenier en drs. J.H. van Delft
datum : 30 november 1995
opdrachtnr. : A90/KLu/320
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In opdracht van de Koninklijke Luchtmacht wordt door TNO Technische Menskunde onderzoek verricht naar de effectiviteit van informatiepresentatie in de cockpit van moderne gevechtsvliegtuigen, teneinde nieuwe concepten op te stellen en te toetsen voor de presentatie van gevechts- en vluchtgegevens in de cockpit van gevechtsvliegtuigen.

Ontwikkelingen op het gebied van sensor-, computer- en displaytechnologie bieden de mogelijkheid tot een computer-gegenereerde presentatie van missie- en vluchtgegevens in de cockpit. In een simulatorexperiment zijn twee vormen van informatiepresentatie, geïntegreerd op basis van het 'highway in the sky' concept respectievelijk separaat volgens het 'sideward-downward looking' concept, met elkaar vergeleken.

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Report No.: TNO-TM 1995 A-73

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Authors: Dr.ir. P.O. Passenier and Drs. J.H. van Delft

Institute: TNO Human Factors Research Institute
Group: Information Processing

Date: November 1995

DO Assignment No.: A90/KLu/320

No. in Program of Work: 787.3

SUMMARY

In the scope of a study on tactical situation displays in the cockpit of modern fighter aircraft, a simulator experiment has been conducted on integrated ('highway in the sky') versus separate presentation of flight information. Results of the experiment show that the 'highway in the sky' especially for 'slow' tasks (slow in relation to aircraft dynamics) leads to more accurate flight performance because of the integrated feedback of the aircraft state, when compared to separate information presentation. However, for 'rapid tasks', where the emphasis is on feedforward control, the separate information presentation is to be preferred because of the more constant preview as a result of the decoupling of the information presentation along different dimensions.

Tactische situatie schermen: geïntegreerde versus separate informatiepresentatie

P.O. Passenier en J.H. van Delft

SAMENVATTING

In het kader van een studie naar tactische situatie schermen in de cockpit van moderne gevechtsvliegtuigen is een vergelijkend experiment uitgevoerd naar een geïntegreerde ('highway in the sky') versus separate presentatie van vluchtgegevens. Uit de resultaten bleek dat de 'highway in the sky' door de geïntegreerde terugkoppeling van statusinformatie met name geschikt is voor een nauwkeurige vliegprestatie bij 'langzame vliegtaken' (langzaam in relatie tot vliegtuigdynamica). Voor 'snelle' taken, waarbij de nadruk meer komt te liggen op 'feedforward control', verdient de separate presentatie de voorkeur door de meer constante 'preview' die deze presentatiewijze biedt.

1 INTRODUCTION

Under contract to the Royal Netherlands Airforce (contract nr. A90/KLu/320), the TNO Human Factors Research Institute investigates the effectiveness of information presentation in the cockpit of modern fighter aircraft.

New developments in the areas of database, sensor and display technology open the possibility for a computer-generated information presentation in order to support the fighter pilot. An example is given by the presentation of mission and tactical overlays in combination with terrain information ('Digital terrain systems'; International Cockpit Review Team, 1989). According to this concept, a central database serves as the basis for the fusion of planning information (knowledge-based, typically non-real time) and status information (sensor-based, typically real-time). Combining this centralized storage of information with a powerful display system, a maximal flexibility is obtained for the presentation of information, making use of techniques like 'pictorial formats', 'overlays', 'windows', 'shading' and colour coding (Arnson, 1981; Lerner, 1981; Reising, 1982). Furthermore, by using computer-generated imagery (CGI), a continuum of presentations can be achieved, ranging from fully planar (e.g. 'horizontal situation') to fully perspective (e.g. 'vertical situation').

The present study describes an experiment aimed at a systematical comparison of two different modes of presentation, which both fall in this range. The first mode refers to a fully integrated presentation of flight information, according to the 'highway in the sky' concept. The second mode separates the presentation of flight information in a so-called 'sideways-looking flight profile display' and a 'downward-looking horizontal situation display' (Roscoe, 1980).

1.1 Integrated and separate information presentation

Previous studies on the comparison of two-dimensional (planar) displays with three-dimensional (perspective) displays in an aviation context, have generally resulted in favour of the three-dimensional display (for a review of these studies see Haskell & Wickens, 1993). In nearly all cases, the task to be performed by the pilot was a task of aircraft landing, which required the integration of information across different spatial dimensions. Although three-dimensional displays have advantages regarding this integration of information, Haskell and Wickens mention the following limitations:

- less accurate representation of depth perception,
- three-dimensional displays are often subject to display clutter,
- with three-dimensional displays the variation in certain dimensions may distort or disrupt the perception of change in the other dimensions (Garner, 1970).

Regarding the third limitation, apparently the prime characteristic of the three-dimensional display, that changes in all variables are integrated into one object, is not an absolute factor all over in favour of this type of information presentation. Rather, the answer to the question whether or not this property can be considered as an advantage or a limitation should be decided on the basis of task characteristics.

For this reason, Wickens divides task types into those requiring the integration of information across sources and those requiring the focusing of attention onto information from a single source. Clearly, aircraft landing is an integration task, and therefore the three-dimensional display should be superior for this type of task.

However, a factor not considered so far, but possibly of special relevance to flight control in combat situations, are the dynamic task characteristics (or 'task dynamics'), which may require different needs of information presentation for a task which at the basis still can be considered as an integration task.

For 'slow tasks' (slow in relation to aircraft dynamics), feedback of the aircraft's status (actual and desired) and change of status immediately after the control setting plays a major role. Clearly, for this case, having several orthographic ('two-dimensional') displays would require pilots to integrate information across separate spatial locations in order to obtain a full appraisal of the current status, whereas the three-dimensional display would directly support this integration process. Therefore, for slow tasks it is expected that pilots would show better flight performance for the three-dimensional display.

For 'rapid tasks', however, presentation of the necessary preview for the three-dimensional display may become degraded just as a consequence of the third limitation of this type of displays (possibly in combination with the second), as mentioned above. Thus, with regard to presentation of the future status, the three-dimensional display may cause negative interference between the different dimensions, whereas for the two-dimensional display status presentation along the different dimensions by definition is decoupled. Therefore, for rapid tasks the superior performance of the three-dimensional display is expected to decrease in favour of the two-dimensional display.

Resuming, an interaction can be expected between display type (integrated versus separate) and task type (slow versus rapid).

For slow tasks it is predicted that pilots would show better flight performance with the three-dimensional than with the two-dimensional display. For rapid tasks, however, it is expected that this effect would decrease or even may reverse.

1.2 Forcing functions

In the previous section the notion of 'task dynamics' was introduced, as a factor of possible influence on the effect different modes of information presentation may have on flight performance. In order to be able to vary this task characteristic in a systematic way in relation to the aircraft control characteristics, a procedure is proposed in a manner similar to the one as described by Schuffel (1986) in his study on human ship control behaviour. According to this procedure, the process (in this case aircraft) response to open-loop 'zig-zag' manoeuvres is used as a basis for the derivation of 'forcing functions' (desired tracks) to be flown by the pilot. In this way pilot tracking performance can be interpreted

with respect to the aircraft flight dynamics, thus relating the notion of 'slow' or 'rapid' tasks to the aircraft's inherent controllability.

Another issue of interest to the present study, is the amount of integration necessary to perform the flight task. For this purpose the concept of tracking tasks on the basis of forcing functions may be extended to three dimensions, by defining both horizontal and vertical forcing functions. As a result, the overall tracking task may be characterized as 'single' or 'combined', referring to either single or combined forcing functions. Accordingly, besides the influence of task dynamics, integration-specific performance degradations can be determined in a more direct manner by comparing tracking performance along separate dimensions for single and combined forcing functions (cross-dimensional interference).

Resuming, the flight task may be manipulated in a systematic way according to both task dynamics and task integration, by translating this task into an experimental tracking task in three dimensions on the basis of the forcing function procedure.

With regard to the effect of information presentation on tracking performance, the above predicted interaction between display type and task dynamics is expected to be most pronounced for the combined forcing functions, which require a maximum amount of integration.

2 METHOD

2.1 Subjects

Seven pilots of the Royal Netherlands Airforce served as subjects. The subjects were all in active service either as F-16 or helicopter pilot. Actual flight experience ranged from 300 to 3000 flight hours.

2.2 Task

The subjects were asked to fly a simulated fighter aircraft, comparable to a F-16, by means of continuous attitude control (roll and pitch) as accurately as possible along different forcing functions at a constant air speed of approximately 500 knots. The forcing functions were visible on a flight display, either in the form of a separate ('2D') or integrated ('3D') flight path projection.

2.3 Experimental design

Three variables were combined factorially. Presentation (2 levels: PR='2D'; '3D') and task dimension (2 levels: TD='Single'; 'Combined') were varied within subjects. The 'Single' condition consisted of single forcing functions (either horizontal or vertical), whereas the

'Combined' condition consisted of combined forcing functions in both directions. Task dynamics was specified by the forcing function index (FFI), defined as the ratio of the double amplitude (4396 feet) and the half of the period length (l). This variable, related to the slope of the forcing function, was also varied within subjects (5 levels: FFI=0.1; 0.2; 0.3; 0.4; 0.5), with for each forcing function a total length of five periods. The testing order was balanced.

2.4 Instrumentation

The experiment was carried out on a part-task flight simulator, consisting of an ESIG 2000 system for the generation of an outside view and HUD information, a Silicon Graphics Iris graphics workstation for the generation of the flight display and a HP vectra computer for the aircraft model and sidestick interface. See the Appendix for details on the flight simulator.

Subjects were seated at the primary flight display, on which the forcing functions were presented, on top of which the outside view and attitude information were presented on a separate display (HUD). For continuous attitude control a 2°-of-freedom sidestick was used, where lateral deviations controlled the aircraft's roll rate and forward/backward deviations controlled the aircraft's pitch rate. During the experimental trials, the throttle was fixed. Forcing functions were defined as sine-wave tracks along the y-axis (see Fig. 1), either horizontal (in the xy-plane), vertical (in the yz-plane) or combined.

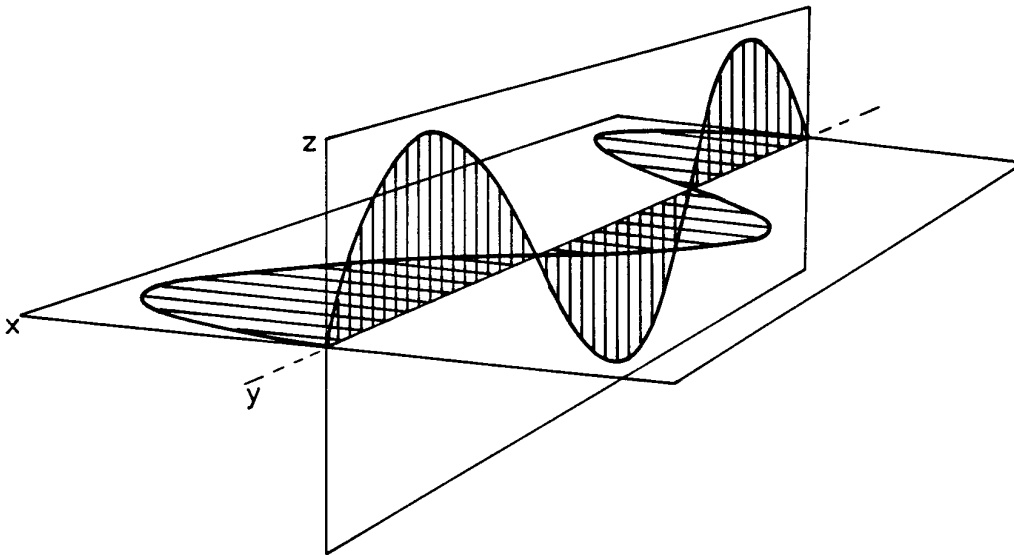


Fig. 1 Definition of forcing functions along the y-axis in the xy- and the yz-plane.

Presentation of the forcing functions on the flight display was according to two modes:

In the '2D' condition, flight information was presented according to the 'sideward/downward looking display' concept: vertical (yz-plane) and horizontal (xy-plane) components of the

forcing functions were presented in two separate windows, both oriented in parallel to the y-axis according to Fig. 2. Tops of the forcing functions, as well as the aircraft's azimuth and elevation were indicated by separate markers.

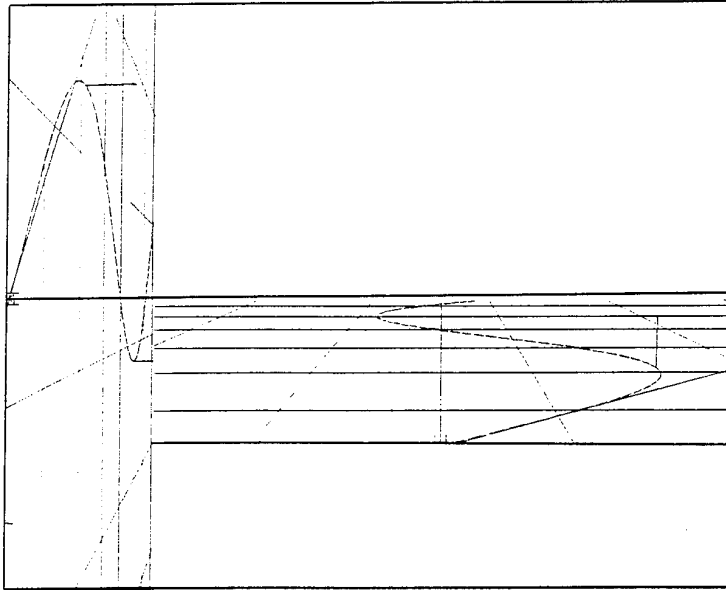


Fig. 2 '2D' presentation condition of the experiment, according to the 'sideward-downward looking display' concept.

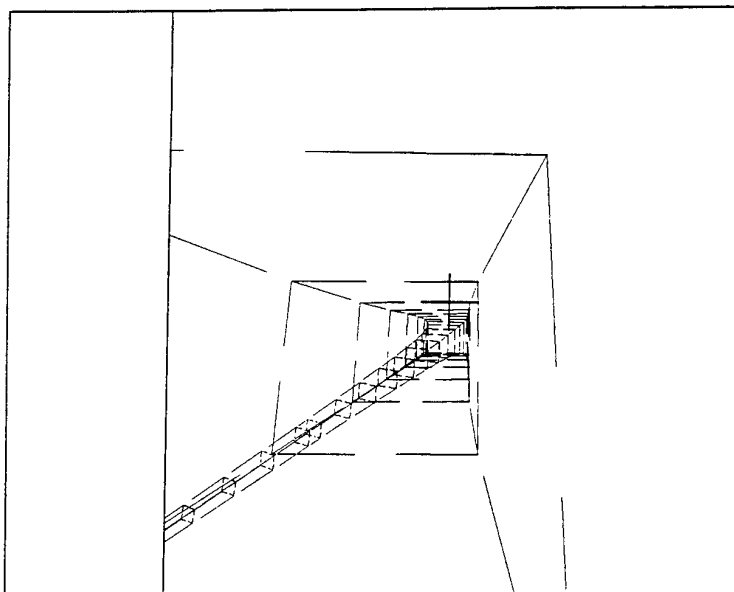


Fig. 3 '3D' presentation condition of the experiment, based on the 'highway in the sky' concept.

In the '3D' condition forcing functions were presented as a perspective tunnel with a cross-section of 100×100 feet wide ('highway in the sky concept', see Fig. 3). For this presentation mode, tops of the forcing functions were marked by using colour coding.

For both presentation modes, feedback of the aircraft roll information in combination with the outside view was provided by a head-up display (HUD) according to Fig. 4.

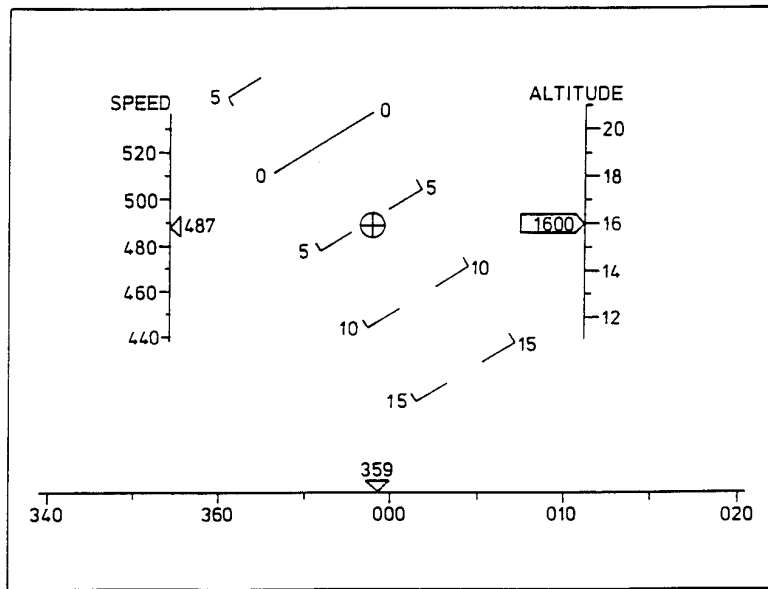


Fig. 4 Head-up display for a combined presentation of the aircraft's attitude and outside view information.

2.5 Training and instruction

Subjects were familiarized with the flight simulator by means of a period of 'free flight', succeeded by several practice trials with increasing forcing function indices (FFIs) for both presentation modes ('2D' and '3D'). After each practice trial, direct feedback was given with regard to tracking performance. Thereafter the subjects completed fifteen forcing functions (five FFIs horizontally, vertically and combined) for each presentation mode.

The subjects were instructed to fly the forcing functions as accurately as possible, with the highest priority for the tops of the sine-wave tracks.

2.6 Procedure

Each subject took part in the experiment for one day. In the morning familiarization and instruction took place, followed by a series of practice trials. After a half-hour lunch break, in the afternoon thirty forcing functions were completed. Each trial took about 5 min. There was a break of approximately 10 min after each 40 min of flying.

2.7 Scoring and analysis

Tracking performance was measured according to the root-mean-square error (RMS-error), amplitude-ratio (α) and phase-shift (l_y) between the actual and the desired track, both for the horizontal (xy-plane) and vertical (yz-plane) components of the forcing functions.

- The *root-mean-square error* can be considered as an overall measure of tracking performance, purely based on the difference between the desired and actual outcome of the tracking process (*accuracy*).
- The *amplitude-ratio* and the *phase-shift* give a more specific insight into the dynamical properties of the combined pilot/aircraft system, in a way analogous to standard frequency response analysis methods for dynamical systems (*controllability*).

RMS-error

In the xy-plane, the RMS-error is defined as:

$$\text{RMS-error} = \sqrt{\left(\frac{\sum_{i=1}^n (x_{fi} - x_i)^2}{n} \right)} \quad (1)$$

- with i the i^{th} sampling interval with a length of 200 ft
 n the total number of samples
 x_{fi} function value of the forcing function in the xy-plane at interval i ,
 $2198 \sin(2\pi/l_f \cdot y_i)$ in feet
 x_i function value of the actual path in the xy-plane, measured as the distance between subject's projected position in the xy-plane and the y-axis at interval i in feet
 l_f length of one period of the forcing function in feet
 y_i distance from origin on the y-axis at interval i in feet.

For the yz-plane, x_{fi} and x_i in this expression have to be replaced by z_{fi} and z_i .

Amplitude-ratio α

The amplitude-ratio α is defined as the ratio of the amplitude of the actual and the desired track.

Phase-shift l_y

The phase-shift l_y indicates the shift in y-axis direction from the actual track to match maximally the desired track.

For each forcing function index FFI, both α and l_y can be calculated on the basis of standard Fourier series techniques according to:

$$\alpha = \frac{2\sqrt{(C_p^2 + S_p^2)}}{a} \quad l_y = \tan^{-1}\left(\frac{C_p}{S_p}\right) \cdot \frac{l_p}{2\pi} \quad (2)$$

For the xy-plane, the input signal $x_{\bar{n}}$ at interval i is given by:

$$x_{\bar{n}} = a \sin \left(\frac{2\pi}{l_p} \cdot y_i \right) \quad (3)$$

with $a = 2198$ feet, the amplitude of the forcing function.

The Fourier series coefficients of the output x_i at frequency $2\pi/l_p \cdot y_i$ are given by:

$$C_p = \sum_{i=1}^n \frac{x_i \cos(2\pi/l_p \cdot y_i)}{n} \quad S_p = \sum_{i=1}^n \frac{x_i \sin(2\pi/l_p \cdot y_i)}{n} \quad (4)$$

with i the i^{th} sampling interval with a length of 200 ft

n the total number of samples

x_i function value of the actual path in the xy-plane, measured as the distance between subject's projected position in the xy-plane and the y-axis at interval i in feet

l_p length of one period of the sine-wave p in feet

y_i distance from origin on the y-axis at interval i in feet.

For the yz-plane, $x_{\bar{n}}$ and x_i in these expressions have to be replaced by $z_{\bar{n}}$ and z_i .

The scores were subjected to an analysis of variance (ANOVA) with PR (2 levels), TD (2 levels), FFI (5 levels) and Subjects (7 levels) as variables.

3 RESULTS

3.1 RMS-error

In Fig. 5 the results are presented for the RMS-error as a function of presentation and forcing function, averaged over subjects, with a distinction between single (left panel) and combined forcing functions (right panel).

The ANOVA showed that the RMS-error was significantly larger ($F=29.2$; $df=1,6$; $p<.005$) for the combined forcing functions (1174 ft) than for the single forcing functions (698 ft). Furthermore, the main effect of forcing function index was highly significant ($F=40.1$; $df=4,24$; $p<<.0001$). No main effect was found with regard to information presentation. However, separate ANOVAs for the individual forcing function indices showed a significant effect of information presentation at FFI = 0.1 ($F=115$; $df=1,6$; $p<.02$). At this FFI the RMS-error for the 2D presentation was significantly larger (182.15 ft) than for the 3D presentation (84.73 ft). For the other FFIs, no significant effect of information presentation was found.

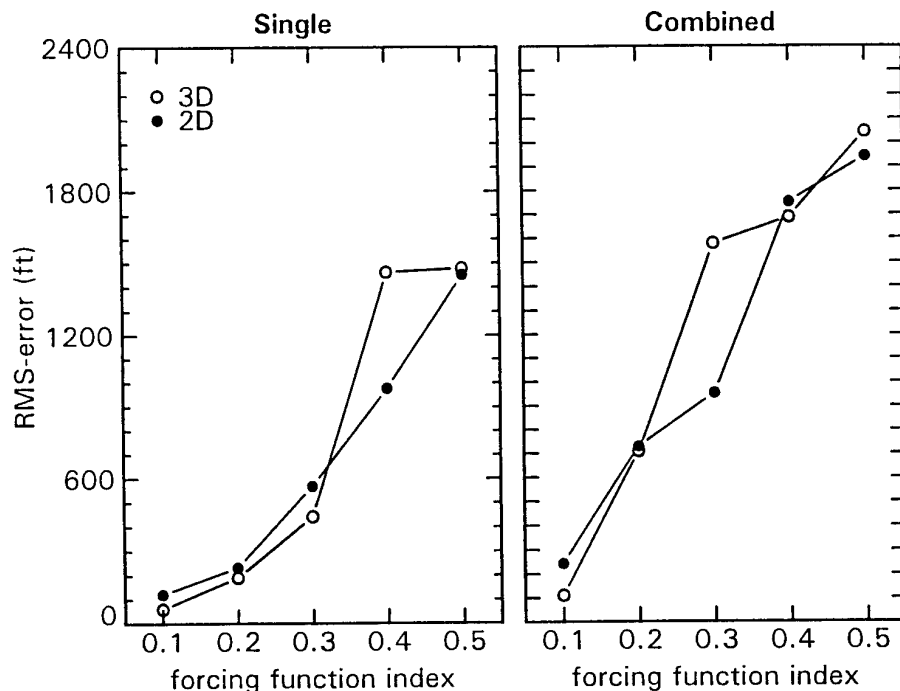


Fig. 5 The RMS-error as a function of presentation ('3D'; '2D') and single (left panel) and combined forcing functions (right panel), averaged over subjects.

3.2 Amplitude-ratio

The results for the amplitude-ratio are presented in Fig. 6. Besides significant main effects with regard to single or combined forcing functions ($F=15.0$; $df=1,6$; $p<.001$) and forcing function index ($F=28.5$; $df=4,24$; $p<.0001$), the ANOVA showed a significant main effect of information presentation ($F=30.6$; $df=1,6$; $p<.005$). Furthermore, the ANOVA showed an interaction between presentation and forcing function index (significant, $F=11.9$; $df=4,24$; $p<.0001$) and between presentation and task dimension (trend, $F=5.6$; $df=1,6$; $p<.06$). Separate ANOVAs for the individual FFIs showed a significantly higher ($F=8.24$; $df=1,6$; $p<0.05$) amplitude-ratio for the 3D condition (0.9889) than for the 2D condition (0.9693) at FFI=0.1. At FFIs higher than 0.2 the amplitude-ratio for the 3D presentation was significantly lower than for the 2D mode. At FFI=0.3 a significant interaction between presentation and task dimension was found ($F=8.73$; $df=1,6$; $p<0.03$).

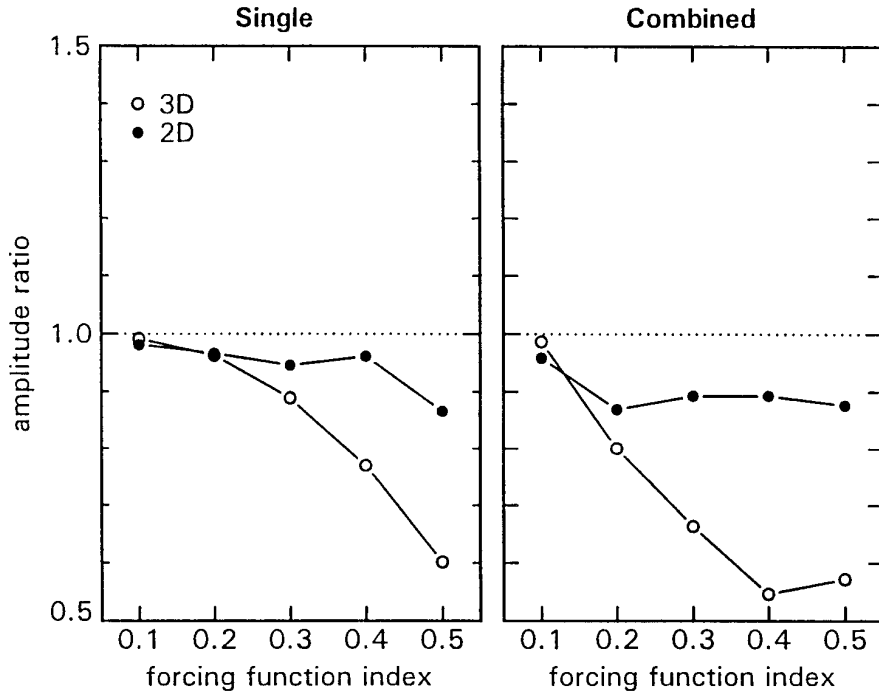


Fig. 6 The amplitude-ratio as a function of presentation ('3D'; '2D') and single (left panel) and combined forcing functions (right panel), averaged over subjects.

3.3 Phase-shift

The ANOVA for the phase-shift (Fig. 7) showed only a significant main effect for the forcing function index ($F=5.1$; $df=4,24$; $p<.01$). Again, as for the amplitude-ratio, the ANOVA showed an interaction between presentation and forcing function index (significant, $F=3.1$; $df=4,24$; $p<.05$) and between presentation and task dimension (trend, $F=4.6$; $df=1,6$; $p<.08$). Separate ANOVAs for the individual FFIs showed a significantly larger phase lead for the 2D condition than for the 3D condition at FFI=0.1 ($F=13.8$; $df=1,6$; $p<.05$) and FFI=0.2 ($F=11.9$; $df=1,6$; $p<.05$). At these FFIs also a significantly larger phase lead for the combined forcing functions was found ($p<.05$). At FFIs higher than 0.2 no significant differences with respect to phase-shift were found.

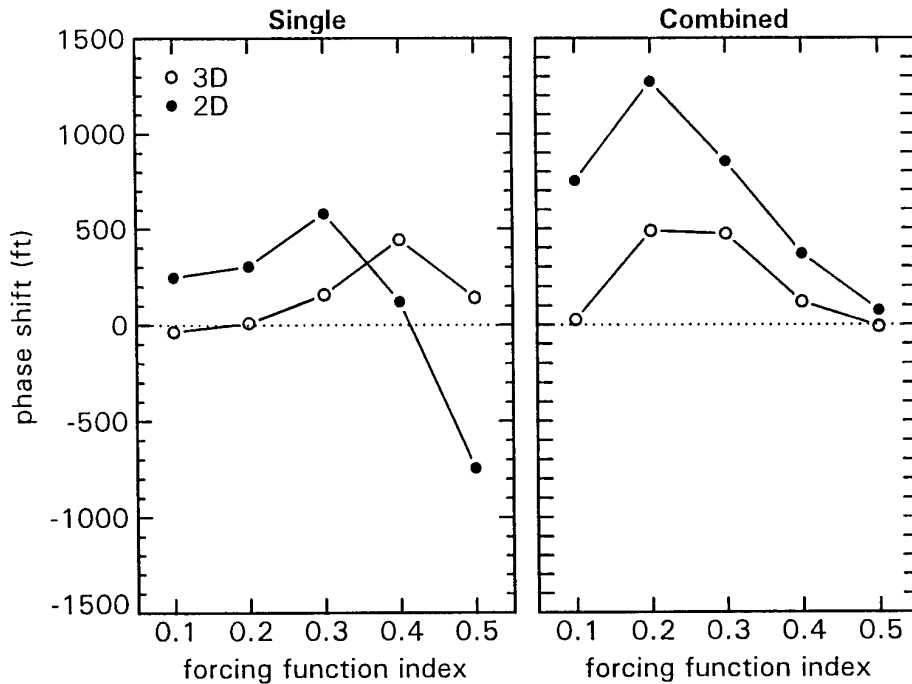


Fig. 7 The phase-shift as a function of presentation ('3D'; '2D') and single (left panel) and combined forcing functions (right panel), averaged over subjects.

4 DISCUSSION

4.1 Summary of results

With respect to tracking accuracy, the results only show significant differences between the 3D and 2D presentation modes at the low forcing function index of 0.1. The RMS-error at this FFI approximated 85 ft for the 3D presentation mode, while the error amounted to 182 ft in the 2D presentation mode. The results of the amplitude-ratio and phase-shift showed that this lower tracking accuracy for the 2D mode corresponded to both a lower amplitude-ratio and a larger phase lead at this low forcing function index. For increasing forcing function indices, tracking accuracy decreased with no remaining significant differences between the two presentation modes.

Regarding controllability, especially at high forcing function indices the 2D presentation mode yields a significantly higher amplitude-ratio, indicating that for this presentation mode the sine wave characteristics of the forcing functions on the average can be better reproduced.

The effects described here were found to be most pronounced for the combined forcing functions.

4.2 Performance for slow tasks

As was expected, for 'slow tasks' (forcing functions with an index of 0.1–0.2) pilots showed better flight performance for the 3D display. Clearly, when compared to the separate information presentation, in this task domain the integrated presentation of the aircraft's status and change of status immediately after the control setting provided a superior feedback for a more accurate error compensation. Compared to this presentation mode, for the separate presentation the integration process is less well supported, resulting in sub-optimal control characteristics. This is illustrated more specifically by the results for amplitude-ratio and phase-shift, which for 'slow tasks' show a significantly larger phase lead for the 2D presentation, in combination with a lower amplitude-ratio. Evidently, the lack of support in integration manifests itself in sub-optimal timing of control actions, which on the average are carried out too early. This is further supported by the fact that this effect is most pronounced for the combined forcing functions, which require a maximum amount of coordination of control actions in both dimensions.

4.3 Performance for rapid tasks

For 'rapid tasks' (forcing functions with an index of 0.3–0.5) with respect to flight performance a clear distinction has to be made between tracking accuracy and controllability.

With respect to accuracy, both presentation modes lead to inaccurate tracking performance, confirming the influence of task dynamics on flight performance.

However, with respect to controllability, the results show a substantially sharper 'fall off' of the amplitude-ratio for the 3D presentation mode. Clearly, in this task domain control performance is not so much determined by the quality of feedback of state and change of state, but more by factors as quality of preview and corresponding feedforward control. As expected, because of the decoupling of preview along different dimensions for the separate presentation feedforward control is better supported, manifesting itself in a higher bandwidth of the overall pilot-aircraft system.

Again, this effect is most pronounced for the combined forcing functions, demonstrating that in this combined task domain for the 3D mode the maximum amount of integration support for low task dynamics goes with a maximum amount of interference for high task dynamics, when compared to the 2D mode.

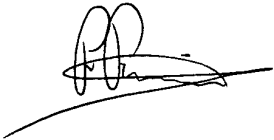
5 CONCLUSION

Results of a simulator experiment show that an integrated presentation of flight information especially for 'slow' tasks (slow in relation to aircraft dynamics) leads to more accurate flight performance because of superior feedback of the aircraft state, when compared to separate information presentation. However, for 'rapid tasks', where the emphasis is on feedforward control, the separate information presentation is to be preferred because of the more constant preview as a result of the decoupling of the information presentation along different dimensions.

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Soesterberg, 30 November 1995



Dr.ir. P.O. Passenier

APPENDIX Flight simulator specifications

Image Generation System

Manufacturer:	Evans & Sutherland, type ESIG-2000
Principle:	computer generated images
Channels:	maximum 4
Resolution:	1,0 M pixels per channel at 30 Hz (3 channels) 0,5 M pixels per channel at 60 Hz (3 channels)
Field of view:	programmable
Number of polygons:	1500 to 2000 polygons/channel at 30 Hz, 1000 polygons/channel at 60 Hz
Colours:	1024 colours excluded texture and shading effects
Hidden surface removal:	Binary Separation Planes (BSP)
Shading:	smooth, flat, Gouraud shading
Anti-aliasing:	yes, not through transparent polygons
Moving objects:	maximum 252 independent objects
Lag time:	2½ update cycle + 1 refresh cycle. At 30 Hz update and 60 Hz refresh: 100 ms, at 60 Hz update: 58 ms
Texturing:	maximum 256 (128 × 128) texture maps (4,2 Mtexel), dynamic texturing possible
Atmosphere:	day, night, dusk, lightning
Level of detail:	automatic, overload management
Light point:	yes
Line of sight ranging/ laser ranging:	yes
Collision detection:	yes
Terrain interaction:	yes, maximum 40 points
FLIR:	yes
Animation:	yes
Graphics overlay:	mixed in image by video-keying
Video-output:	programmable

Tactical Situation Display

Manufacturer:	Silicon Graphics, type IRIS 4D
Principle:	Graphical processor, colour
Resolution:	1280 × 1024 pixels at 15 Hz
Field of view:	60° × 45°
Colours:	max nr. 1024
Video output:	standard video RGB-S line frequency up to 72 kHz

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<p>14. SUPPLEMENTARY NOTES</p>		
<p>15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)</p> <p>In the scope of a study on tactical situation displays in the cockpit of modern fighter aircraft, a simulator experiment has been conducted on integrated ('highway in the sky') versus separate presentation of flight information. Results of the experiment show that the 'highway in the sky' especially for 'slow' tasks (slow in relation to aircraft dynamics) leads to more accurate flight performance because of the integrated feedback of the aircraft state, when compared to separate information presentation. However, for 'rapid tasks', where the emphasis is on feedforward control, the separate information presentation is to be preferred because of the more constant preview as a result of the decoupling of the information presentation along different dimensions.</p>		
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