ACCURACY OF SYSTEM STEP RESPONSE ROLL MAGNITUDE ESTIMATION FROM CENTRAL AND PERIPHERAL VISUAL DISPLAYS AND SIMULATOR COCKPIT MOTION

by

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ABSTRACT

The present experiment is an extension of work done in previous years, at Delft University, on the accuracy and temporal properties of visual roll attitude and roll rate perception.
In earlier perception tasks, discrete stimuli of roll attitude were presented on a central artificial horizon type display. Roll rate tests were done with the same display and with peripheral visual field displays showing moving checkerboard patterns.
From tracking tasks in a flight simulator it was found that cockpit motion improved tracking accuracy and the present experiment was designed to assess the improvements of perception due to cockpit motion.
As it is not possible to present and to manipulate discrete motion stimuli in a moving cockpit just as in the case of visual stimuli alone, a different set-up had to be chosen in which dynamic system step responses of roll angle were the stimuli to be presented.
After the onset of the motion, subjects were to make accuracte and quick estimates of the final magnitude of the roll angle step response by pressing the appropriate button of a keyboard device. The differing time-histories of roll angle, roll rate and roll acceleration caused by a step response will stimulate the different perception processes related the central visual field, peripheral visual field and vestibular organs in different, yet exactly known ways.
Experiments with either of the visual displays or cockpit motion and some combinations of these were run to asses the roles of the different perception processes.
Results show that the differences in response time are much more pronounced than the differences in perception accuracy.

1. INTRODUCTION

A few years ago a research program on pilot's motion perception was started at the Department of Aerospace Engineering of the Delft University of Technology. The aim is to investigate how the pilot perceives the state of the aircraft from the central visual field (artificial horizon), the peripheral visual field (outside world) and motion cues (aircraft motions).
The motive for this program was the wellknown fact that peripheral field

displays and simulator motion improve pilot's tracking performance and dynamic behaviour. See Refs 1, 2, 3 and 4.
It was assumed that, due to the fact that these improvements in tracking performance can be achieved only by changing the display configuration, these improvements resulted from changes in the perception proces.
It was hypothesised that only two reasons could exist for changes in the perception process. The first was that by adding peripheral visual cues and/or motion cues redundant information becomes available and the subject is able to use this information to improve the perception of the motion variables.
The second reason could be that due to the different (dynamic) characteristics of the neural processing of stimuli received by the central visual field, the peripheral visual field and the vestibular system the duration of the perception and the information handling process is changed. The aim of the research program was to test these hypotheses.

In Refs 5 and 6 experiments are described on the perception of roll attitude and roll rate from central - and peripheral displays.
It was shown that roll attitude can be perceived faster and more accurate than roll rate from the central display. In addition it turned out that roll rate could be perceived faster from the peripheral field display. After these facts had been established an experiment including motion cues was prepared.
An important difference between visual displays on one hand and motion systems on the other is, that motion systems have to move the simulator mass and have dynamic characteristics. Thus the choice of input stimuli is limited by the characteristics of the simulator motion system. It is not possible for instance to present or to manipulate pure attitude, rate or acceleration stimuli separately, since a motion stimulus is now to be considered as a mixture of these three variables.
After some evaluation, the step response of a dynamic system with rather low natural frequency was shown as the input stimulus to the subject. All combinations of the central and peripheral displays and motion were used in the experiment. After stimulus onset the subject was asked to predict the final magnitude of the step response and to answer by pressing the corresponding key on a keyboard. This subject's response corrected the input to the dynamic system and the resulting system output was displayed thus presenting a direct feedback to the subject.
The main output variables of the experiment were perception accuracy and response time. In the final experiment two dynamic systems (second order and third order) were used.

2. TEST FACILITY

All measurements were performed in the research simulator of the Department of Aerospace Engineering. In front of the right hand seat a central (foveal) CRT display (Tektronix 604 monitor), was mounted in the instrument panel. Peripheral visual cues were provided by two TV monitors (Bosch Fernseh Monitor) placed on either side of the simulator cockpit. See Fig. 1. Subjects gave their responses via a digital keyboard, see Fig. 2. The relative positions of the central and peripheral displays and the subject's eye reference point are shown in Fig. 3. In Fig. 3 the image on the central display, simulating the artificial horizon, is als shown. The repetition rate was 250 Hz. The peripheral displays showed a movable checkerboard pattern with squares

of 5x5 cm generated by a moving pattern generator (developed at Delft University) at a repetition rate of 30 frames per sec.
The three degrees of freedom motion system of the flight simulator has high fidelity motion characteristics, making the simulator a very suitable tool for the present experiment. The application, in this motion system of so called 'hydrostatic' bearings in the electrohydraulic servo actuators, assures a very smooth and almost rumble free simulator motion, see Ref. 7. The control of the motion system was compensated for its second order characteristics (ω_o = 43 rad/sec, ζ = 1.5) leading to a gain of unity and phase shift of around zero up to 15 rad/sec. All experimental runs were controlled by a hybrid computer (EAI Pacer 100).
The step response stimulus was generated by either a second or third order system simulated in the analog part of the computer installation. The maximum step magnitude of 12 degrees was well within the limitations of the motion system, see Table 1. The sequence of one stimulus interval is presented in Fig. 4. At the beginning of the n-th interval a new step input φ_{i_n} was given to the system. This event was marked by an audiotone.
The system outputs φ, $\dot{\varphi}$ and φ were used to control the central and peripheral field displays and the motion system, thus presenting the system response to the subject in a number of different ways. After observing the response onset, the subject was asked to respond by pressing the appropriate key of the keyboard in order to return the system output to zero.
The response magnitude is designated by φ_p. The keyboard response changed the input step magnitude of φ_i of the system to the error value $\Delta\varphi$

$$\Delta\varphi_n = \varphi_{i_n} - \varphi_{p_n}$$

In order to inform the subject about the error value and next to bring the simulator back to the zero roll angle, the system response to $\Delta\varphi_n$ is displayed first. Next the system input is reset to zero and the displays blanked as the simulator is being rolled back to the zero roll angle. The total interval length was approximately 7 sec.
During each run the variables φ_{i_n}, $\Delta\varphi_n$, φ_{p_n} and the subjects response time RT_n were recorded and stored on disk for subsequent analysis.

3. EXPERIMENT

As already mentioned the aim of the experiment was to investigate the accuracy with which subjects can perceive simulator motion by observing the central and peripheral displays and cockpit motion.
In Refs 5 and 6 experiments are described where in the perception of roll attitude and roll rate was investigated by using discrete stimuli presented on a central and peripheral displays. In the present experiment, however, the motion system of the simulator was involved. Discrete stimuli were not longer possible due to the limitations of the simulator (see Table 1) and for safety of the subjects.
Therefore a motion stimulus had to be chosen which would be comparable to normal aircraft motions and had characteristics from which the magnitude can be perceived and quantified by subjects. It was decided to use the step response of a second order system (ω_o = 2 rad/sec, ζ = 0.7) as the roll stimulus

for the experiment.

In Fig. 5a the roll angle φ, the roll rate $\dot{\varphi}$ and the angular acceleration $\ddot{\varphi}$ are shown for such a step response.

The advantage of the step response as a stimulus is that after some time a steady state roll attitude is reached. The task of the subject was to estimate the final steady state value of the roll angle. As shown in Fig. 5a the initial roll acceleration is rather sharp (4°/sec^2 for a 1 degree step input). This roll acceleration causes an initial lateral acceleration of the subjects head of 0.056 m/sec^2 for a step input of 1 degree. The roll and lateral acceleration, due to the maximum step input of 12 degrees caused rather strong proprioceptive cues. To prevent that these proprioceptive cues should have an undesirable effect on the results of the experiment a more gradual input stimulus was used for a limited number of display configurations. This stimulus was the step response of a third order system (ω_0 = 2 rad/sec, ζ = 0.7, τ = 0.5 sec). In Fig. 5b the roll angle φ, roll rate $\dot{\varphi}$ and acceleration $\ddot{\varphi}$ are shown. The maximum roll acceleration for a 1 degree step input decreased to 1°/sec^2.

The motion perception was investigated with all seven combinations of the central display C, the peripheral displays P and the cockpit motion M using the second order step response stimulus. The third order stimulus was used only for three display configurations (C, M and CM).

The step magnitudes used in the experiment were 0, ±2, ±4, ±6, ±8, ±10 and ±12 degrees. During one run 5 replications of these 13 magnitudes were presented in random order. Each subject replicated all 10 different runs 5 times.

4. SUBJECTS AND TEST PROCEDURE

Two subjects, University staff members and both qualified jet transport pilots, volunteered in the experiment. They were instructed to respond primarily as accurate as possible and secondly as quickly as possible to the presented stimuli. They were not required to fixate their eyes continually on the central display but were free to look at the keyboard when responding. If the central display was not used, subjects were asked to fixate on the central display just before the next stimulus was presented. Apart from the feedback of the error after each keyboard response, subjects were informed of the error standard deviation and the mean response time after each run.

For preliminary evaluation and training a total of 150 runs were made. After a steady level of performance was obtained the two parts of the experiment were carried out during morning sessions. The number of runs for the first part was 7x5x2 = 70 runs. For the second part 3x5x2 = 30 runs were carried out.

5. RESULTS

In Table 2 the means and standard deviations of the step response perception error and the response time are presented as a function of display configuration and system step response stimulus.

The means and standard deviations of the error as a function of step magnitude are shown in Fig. 6. There is a tendency to overestimate the step input for steps of 4, 6 and 8 degrees, while the step of 12 degrees is underestimated. This partly results from the limited range of stimuli of the experiment. The

subjects were aware of the fact that the maximum step input was 12 degrees. This made an overestimation of the maximum step vertually impossible, whereas underestimations still occured. However, overestimating small stimuli and underestimating large stimuli is also present in a pure rate perception task, see Ref. 8.
The error standard deviation is increasing as a function of step magnitude up to a step of 8 degrees. For steps of 10 and 12 degrees, the error standard deviation remains approximately constant. This is also found in the rate perception experiment of Ref. 8, but it is assumed that this phenomenon depends among others on the stimulus range of the experiment.
In Fig. 6c the error mean and standard deviation of the third order step response stimulus is shown. It is clear that the standard deviation for the step inputs of 0, 2 and 4 degrees increased relative to the case of the second order response stimulus, see Fig. 6a. This increase is significant only for the configuration including motion (M, CM) and is not surprising in view of the low value of the maximum roll acceleration during the third order step response, although this roll acceleration is well above threshold, see Ref. 9. The differences in mean value and standard deviation of the error for each configuration are in some cases significant ($\alpha < 0.01$). The error standard deviation of display configurations including motion are in general smaller than of those not including motion.

The differences between the response times are significant ($\alpha < 0.01$). Notable is the difference in interference between the central display on one hand and the peripheral displays and motion on the other. The response time with the central display C only is the longest. Peripheral displays P and motion M both cause shorter response times. The response times for the combinations CP, CM and CPM are in between those for C and P, C and M and C and PM respectively. For the combination PM however the effect is enhanced and the response time is shorter than for P and M separately.
For the third order system longer response times are found, just as could be expected, but the trend is the same as for the second order system. In Fig. 7 the response time is plotted as a function of stimulus magnitude. The change due to the step magnitude is significant and is found for all display configurations.

6. DISCUSSION AND CONCLUSIONS

As shown in the preceeding chapter the perception accuracy as expressed in error standard deviation is not essentially influenced by the display configuration or sort of input stimulus (second or third order system response). This is in agreement with an earlier experiment on rate perception where except for short exposure times no essential difference in perception accuracy was found between the display configurations central display, peripheral displays and central and peripheral displays. See Ref. 6.
Although the present experiment features notable differences in the time course of the roll angle, roll rate and roll acceleration - the primary input variables for the central visual field, the peripheral visual field and the vestibular system - it turns out that the step magnitude can be perceived equally well from the central display and the peripheral displays and slightly better with motion. Extension of the display configuration to CP, CM etc. did not influence the perception accuracy.

As explained in Chapter 4 the task of the subject was to respond primarily as accurate as possible and secondly as quickly as possible. For each display configuration and stimulus there should be an optimal response time, based on the fact that especially the peripheral and motion cues will vanish with time (see Figs 5a and b). Based on this notion it is next assumed that a change in subject's instruction (obtain maximum accuracy regardless of the response time) should hardly influence the perception accuracy.
It has been suggested that man, as an observer, should be able to combine in some optimal way, independent sources of information on attitude and motion. If in the present task perceptions from central and peripheral displays and from cockpit motion were independent and if indeed some kind of optimal or suboptimal combination were present, then greater accuracy of subjects estimates would appear in, for instance the CPM configuration when compared to the C, P and M configurations separately. Table 2 shows that this is not the case.

Comparison of the estimation error of the present experiment with the attitude perception experiment of Ref. 5 shows a same order of magnitude ($\sigma_{\Delta\varphi}$ present experiment configuration C = 1.393 degrees, $\sigma_{\Delta\varphi}$ attitude perception = 1.543 degrees).

As already mentioned in Chapter 5 the differences in response time due to the seven display configurations are significant. Part of these differences correspond remarkably well with the corresponding differences from the rate perception experiment in Ref. 6, see Table 3.
From the response times resulting from the second order and third order step-response stimuli it should be concluded that the trend of changes in response time due to different display configurations is independent of the stimulus but the actual values are dependent on the sort of stimulus, see Table 4.
From the data presented so far it may be concluded that addition of peripheral visual cues and motion cues to central visual cues does not essentially improve the perception accuracy but makes the perception process faster.
Going back to earlier experiments performed in Delft and by others (see Refs 1 to 4) it is well known that tracking performance can be improved by the addition of peripheral visual cues and motion cues. The question arose whether a connection can be established between the results of the present experiment and these tracking tasks experiments.
In Ref. 10 Levison and Junker describe an experiment investigating the influence of simulator motion system time delays on a roll tracking task. From this experiment data are plotted in Fig. 8 which clearly demonstrate the relation between time delay and tracking performance. This figure shows that in the particular experimental configuration motion cues had to be delayed by 0.26 sec to make tracking performance equal to that in the no motion configuration.
It is shown in the present experiment that motion cues speed up the response times. If these motion cues are delayed, the advantages of the motion cues are nullified. If the differences in response times of the present experiment can be ascribed to the perception proces alone, then these differences can be interpreted as differences in duration of the perception proces.
As described in the introduction this research program was started with a tracking task experiment, see Refs 3 and 4, wherein the same display configurations have been used as in the present experiment. With the tracking

performance of that experiment and the response times of the present experiment a comparable figure as Figure 8 can be drawn, see Fig. 9.
The results of three configurations (P, M, PM) however have to be excluded from this analysis due to the lack of accurate roll attitude information in the tracking task which has influenced the tracking performance.
The evident relation between tracking performance and response time, demonstrates that the improvements in tracking performance due to motion and peripheral visual cues results only from the shorter duration of the perception proces.

7. REFERENCES

1. Moriarity, T.E., Junker, A.M. and Price, D.R.
   Roll axis tracking improvements resulting from peripheral vision motion cues. Proceedings of the Twelfth Annual Conference on Manual Control, NASA TM-X-73, 1976.

2. Stapleford, R.L., Peters, R.A. and Alex, F.R.
   Experiments and a model for pilot dynamics with visual and motion inputs. NASA CR-1325, 1969.

3. Hosman, R.J.A.W. and Van der Vaart, J.C.
   Effects of visual and vestibular motion perception on control task performance. Proceedings of the First European Annual Conference on Human Decision Making and Manual Control, Delft, 1981.

4. Hosman, R.J.A.W. and Van der Vaart, J.C.
   Effects of vestibular and visual motion perception on task performance. Acta Psychologica 48 (1981) 271-287.

5. Hosman, R.J.A.W. and Van der Vaart, J.C.
   Accuracy of visually perceived roll angle and roll rate using an artificial horizon and peripheral display. Proceedings of the Second European Annual Conference on Human Decision Making and Manual Control, Bonn, 1982.

6. Hosman, R.J.A.W. and Van der Vaart, J.C.
   Perception of roll rate from an artificial horizon and peripheral displays. Proceedings of the 19th Annual Conference of Manual Control.

7. Den Hollander, J.G. and Baarspul, M.
   Measurement of motion quality of a moving base flight simulator. Delft University of Technology, Department of Aerospace Engineering. Memorandum M-264, 1977.

8. Van der Vaart, J.C. and Hosman, R.J.A.W.
   Mean and random errors of visual roll rate perception from central and peripheral displays. 20th Annual Conference on Manual Control, NASA Ames Research Center, 12-14 June, 1984.

9. Hosman, R.J.A.W. and Van der Vaart, J.C.
Vestibular models and thresholds of motion perception. Results of test in a flight simulator. Delft University of Technology, Department of Aerospace Engineering, Report LR-265, 1978.

10. Levison, W.H., Lancroft, R.E. and Junker, A.M.
Effects of simulator delays on performance and learning in a roll-axis tracking task. Proceedings of the fifteenth Annual Conference on Manual Control, AFFDL-7R-79-3135, 1979.

TABLE 1: Limits of the flight simulator motion system.

mode	maximum displacement	maximum rate	maximum acceleration
heave	0.3 m	0.65 mh	10 m/sec^2
pitch	16 degrees	44 deg/sec*	650 deg/sec^2*
roll	15 degrees	32 deg/sec*	340 deg/sec^2*

* computed values.

TABLE 2: Mean response time and perception error as a function if display configuration and input stimulus.

display configuration	2nd order step response				3rd order step response			
	$\overline{RT}$ sec	σ_{RT} sec	$\overline{\Delta\varphi}$ degrees	$\sigma_{\Delta\varphi}$ degrees	$\overline{RT}$ sec	σ_{RT} sec	$\overline{\Delta\varphi}$ degrees	$\sigma_{\Delta\varphi}$ degrees
C	1.163	0.162	0.148	1.343	1.563	0.251	0.332	1.439
P	1.098	0.174	0.317	1.388				
M	0.948	0.191	-0.062	1.194	1.260	0.248	-0.071	1.414
CP	1.127	0.178	0.028	1.339				
CM	0.992	0.231	0.018	1.216	1.353	0.282	0.148	1.267
PM	0.905	0.173	0.157	1.259				
CPM	0.940	0.212	0.092	1.253				

TABLE 3: Comparison of response times from the rate perception experiment (Ref. 6) and the present experiment.

	Rate perception experiment Ref. 6	Present step response experiment
RT_C	0.83 sec	1.16 sec
RT_P	0.77 sec	1.10 sec
RT_{CP}	0.80 sec	1.13 sec
RT_C-RT_P	0.06 sec	0.06 sec
RT_C-RT_{CP}	0.03 sec	0.03 sec
$RT_{CP}-RT_P$	0.03 sec	0.03 sec

TABLE 4: Comparison of response times resulting from the second order and third order step respons stimuli.

	2nd order stimulus	3rd order stimulus
RT_C	1.16 sec	1.56 sec
RT_M	0.95 sec	1.26 sec
AT_{CM}	0.99 sec	1.35 sec
RT_C-RT_M	0.21 sec	0.30 sec
RT_C-RT_{CM}	0.17 sec	0.21 sec
$RT_{CM}-RT_M$	0.04 sec	0.09 sec

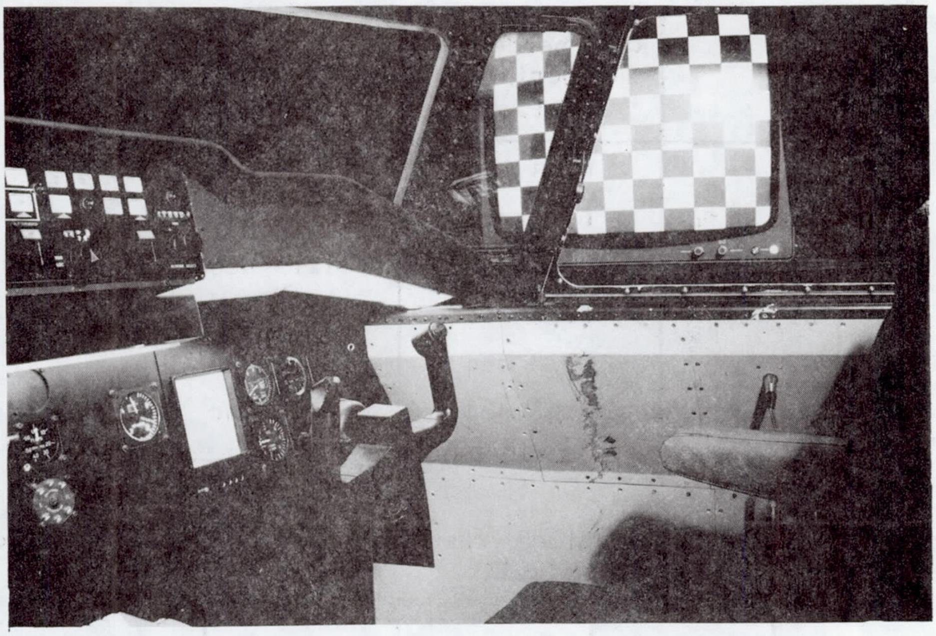

Fig. 1. Overview of the simulator cockpit with central display and the right hand peripheral display.

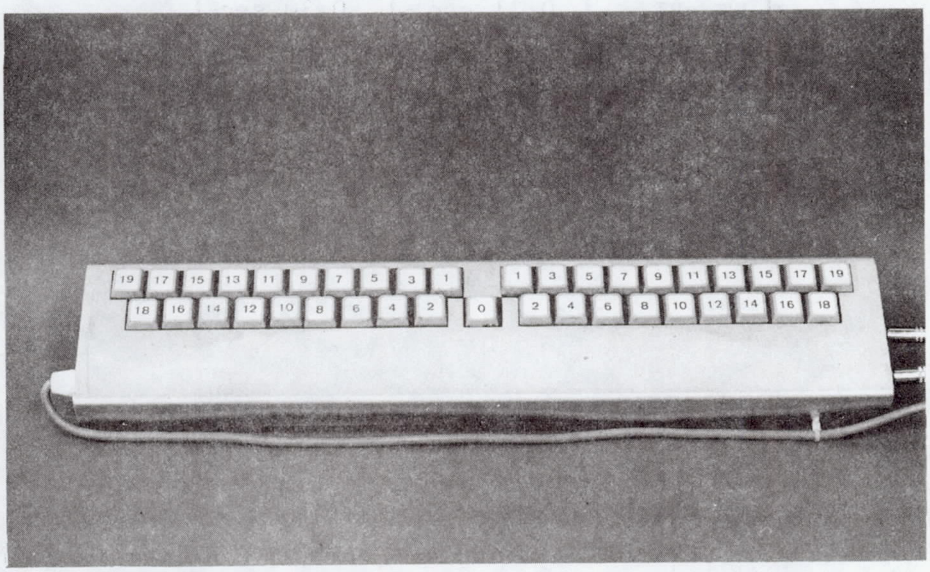

Fig. 2. Digital keyboard.

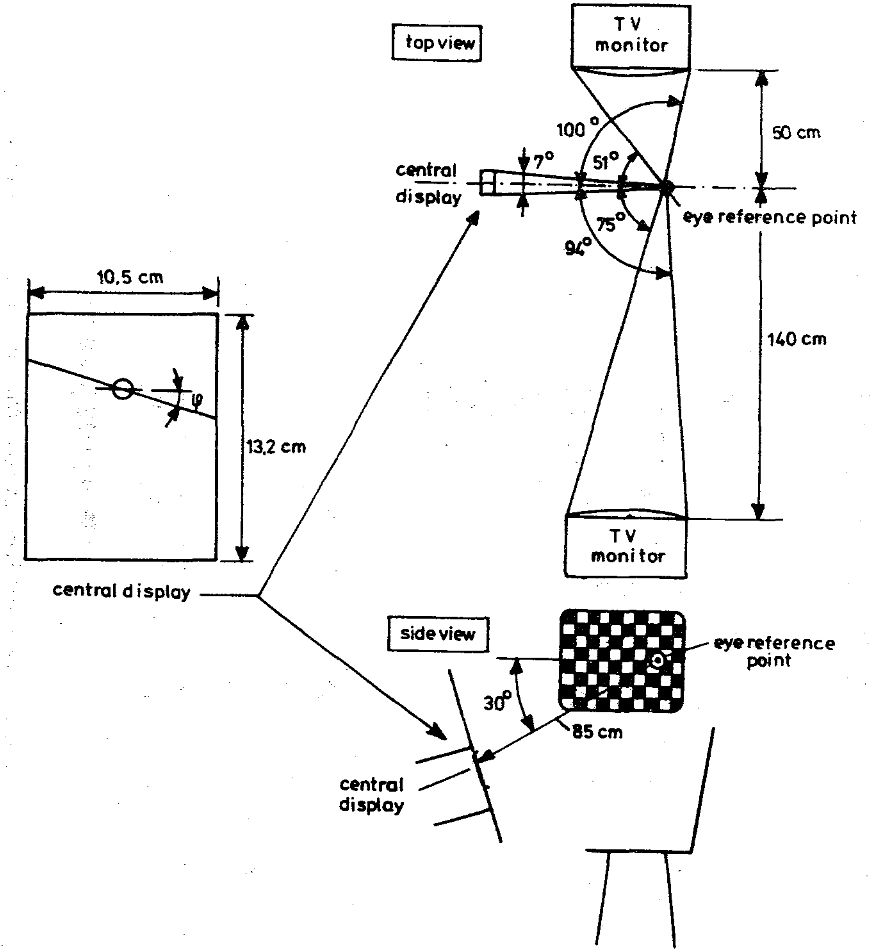

Fig. 3. Positions of displays relative to the subject's eye reference point. Central display image and dimensions.

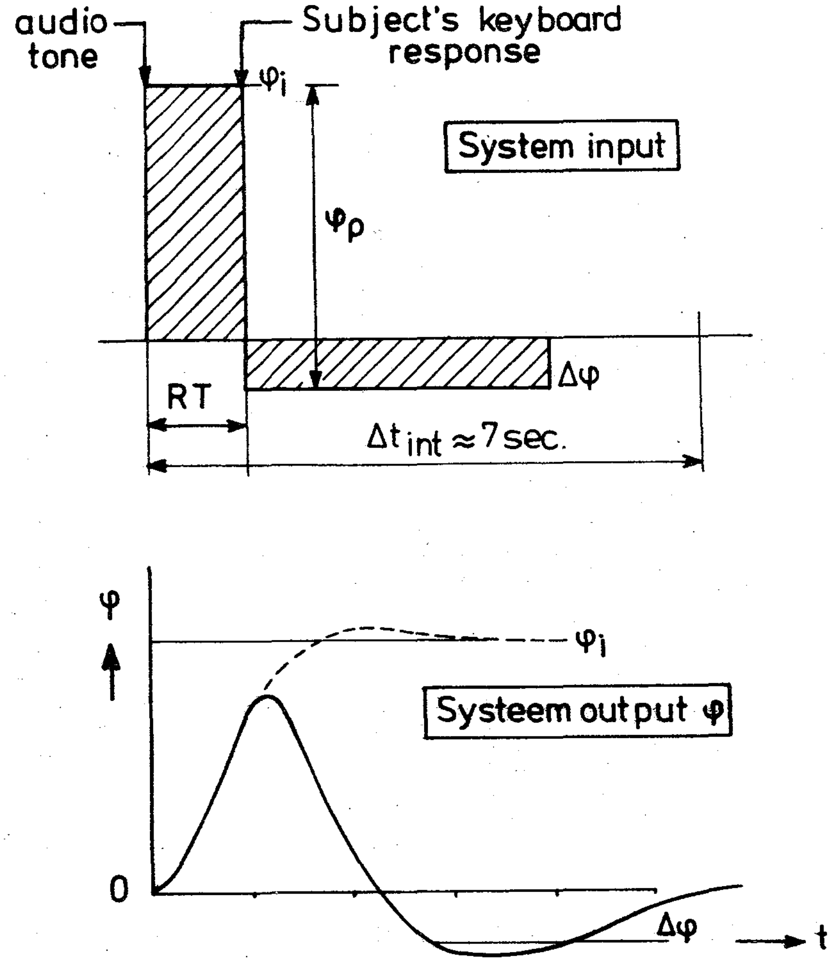

Fig. 4. Sequence of one interval of a test run.

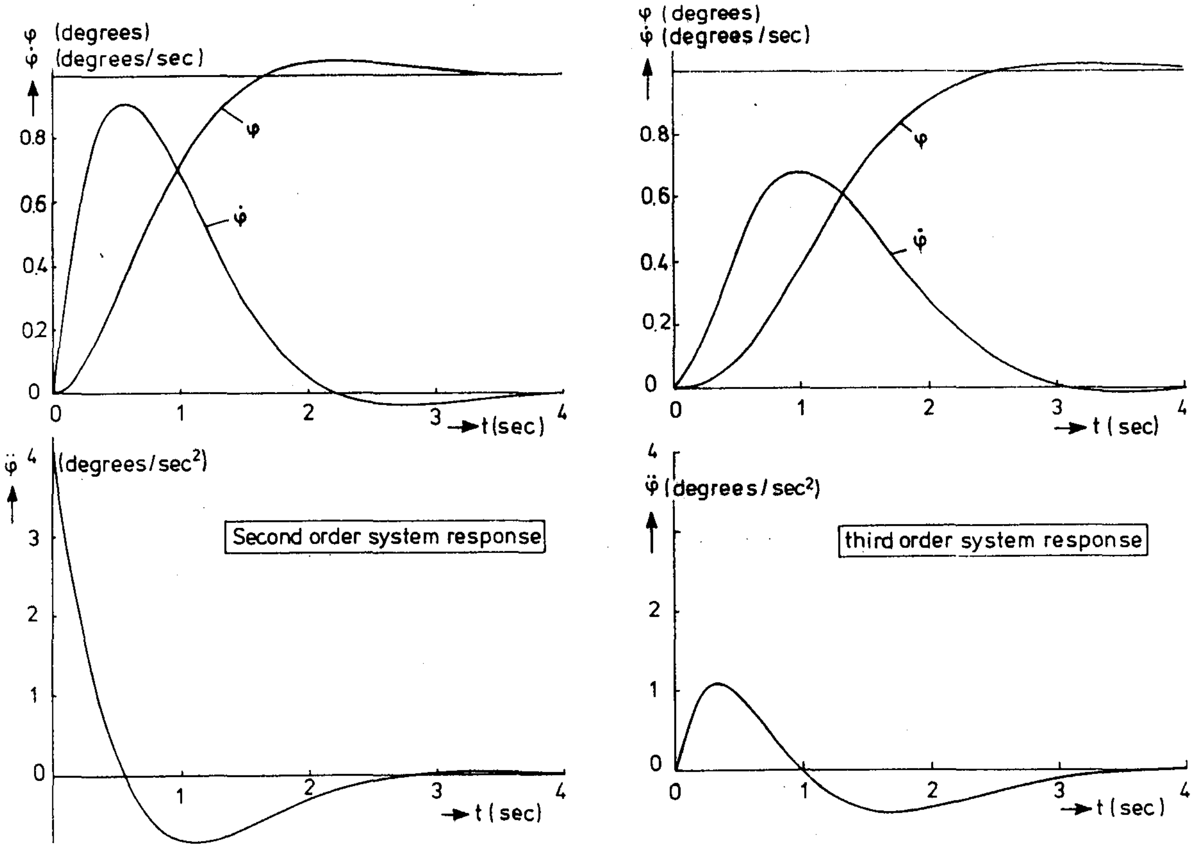

Fig. 5. The roll angle, roll rate and roll acceleration of the second and third order system step responses.

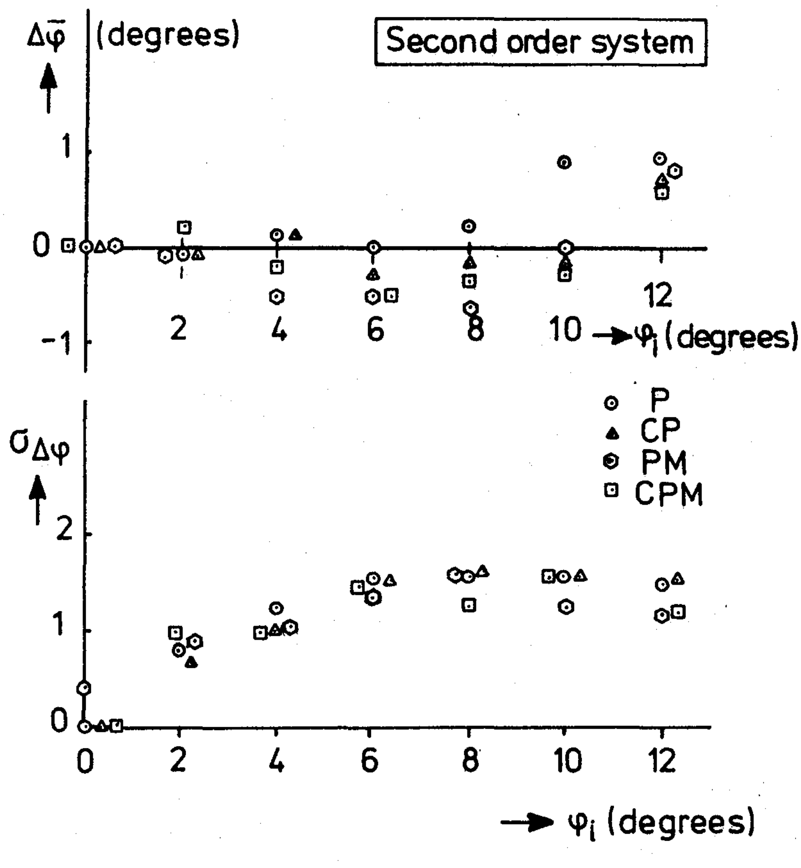

Fig. 6a. Mean roll angle perception error Δφ and its standard deviation as a function of stimulus magnitude.

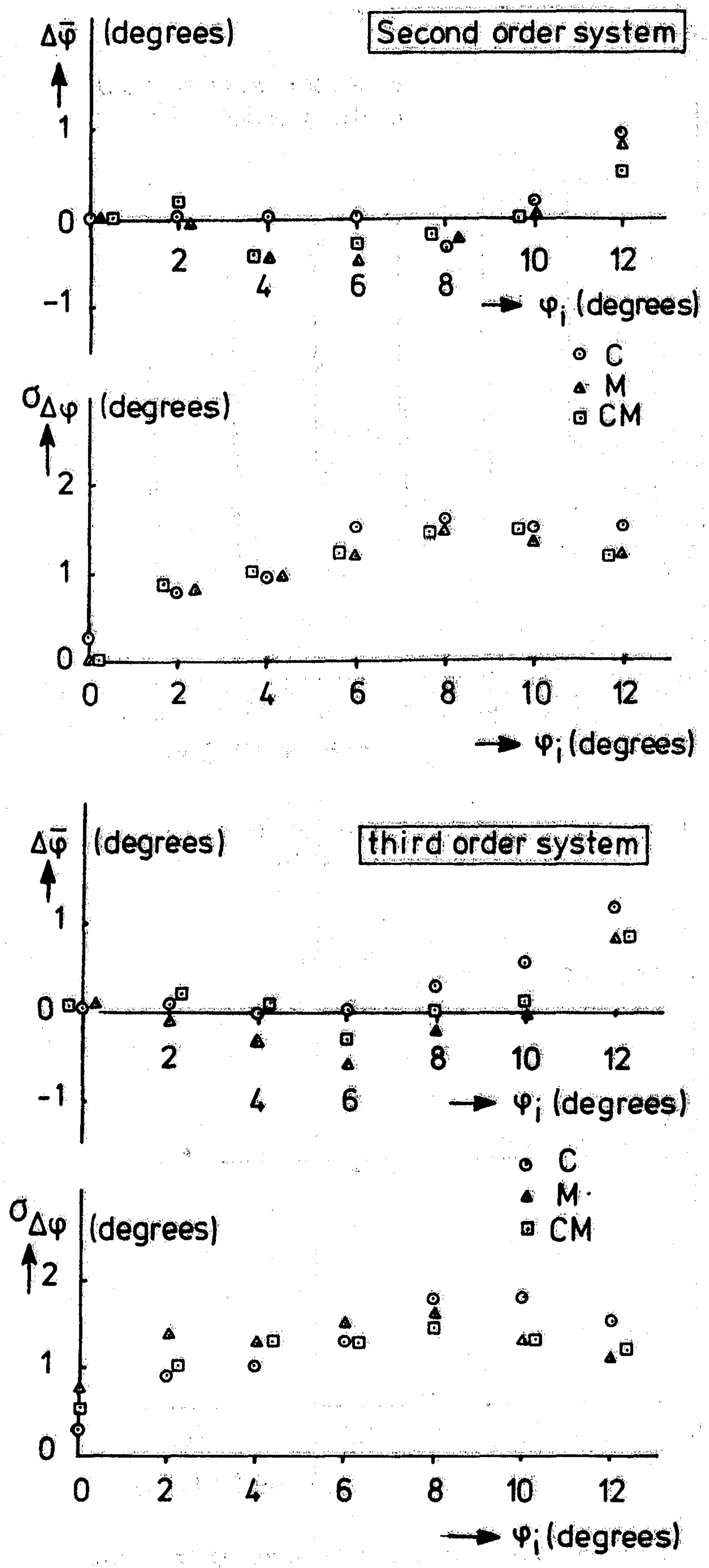

Fig. 6b. Mean roll angle perception error $\Delta\varphi$ and its standard deviation as a function of stimulus magnitude.

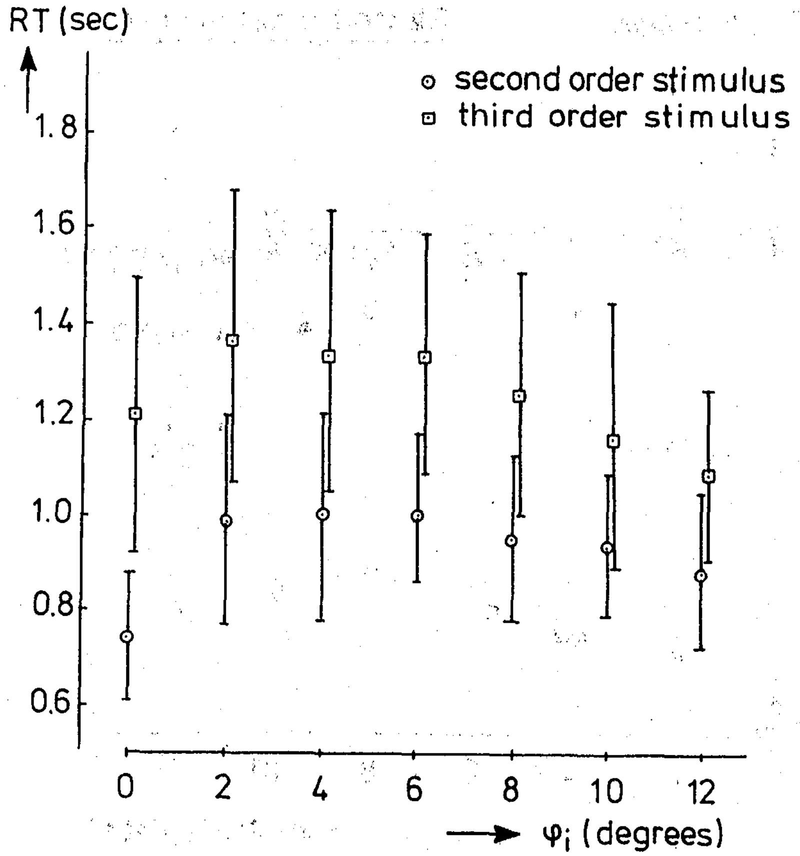

Fig. 7. Response time as a function of stimulus magnitude for the motion configuration M.

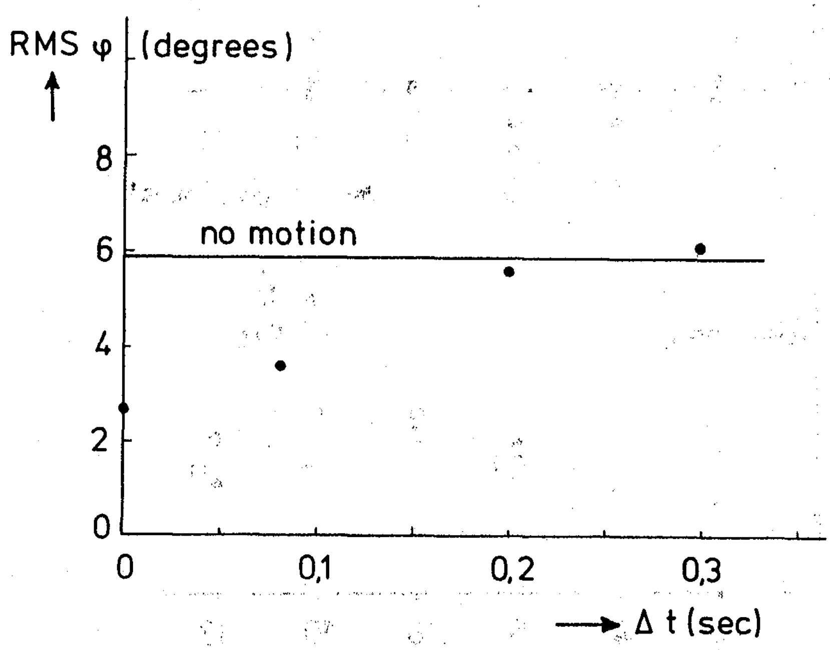

Fig. 8. Root mean square of the roll angle φ in a roll tracking task as a function of simulator motion time delay Δt compared with the no motion performance, from Ref. 10.

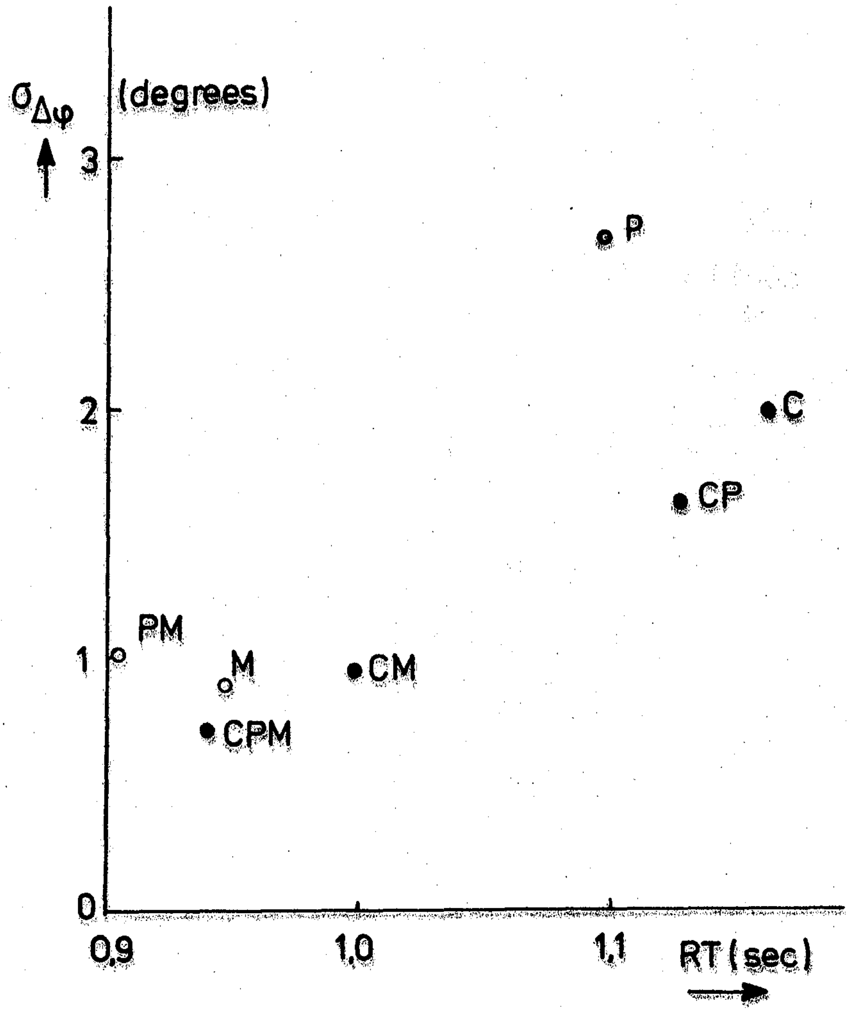

Fig. 9. Tracking performance σφ of the roll tracking task from Ref. 4 as a function of the response time RT of the present experiment for similar display configurations.