MEAN AND RANDOM ERRORS OF VISUAL ROLL RATE PERCEPTION FROM CENTRAL AND PERIPHERAL VISUAL DISPLAYS

by

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ABSTRACT

A large number of roll rate stimuli, covering rates from zero to plus or minus 25 deg/sec, were presented to subjects in random order at 2 sec intervals. Subjects were to make estimates of magnitude of perceived roll rate stimuli presented on either a central display, on displays in the peripheral field of vision, or on all displays simultaneously. Response was by way of a digital keyboard device, stimulus exposition times were varied.
The present experiment differs from earlier perception tasks by the same authors in that mean rate perception error (and standard deviation) was obtained as a function of rate stimulus magnitude, whereas the earlier experiments only yielded mean absolute error magnitude. Moreover, in the present experiment, all stimulus rates had an equal probability of occurrence, whereas the earlier tests featured a gaussian stimulus probability density function.
Results yield a good illustration of the non-linear functions relating rate presented to rate perceived by human observers or operators.

INTRODUCTION

Earlier and related experiments

The perception accuracy experiment reported here is a part of a large series of experiments on motion perception in piloting tasks that was started off with a moving base simulator experiment by the same authors (Ref. 1). A better performance and notable changes in pilot control behaviour were found in roll tracking tasks whenever peripheral visual field motion and/or cockpit motion was added to the basic display configuration of a central, artificial (CRT) horizon display. Peripheral field motion could be displayed by moving checkerboard patterns on TV-monitors mounted on either side of the cockpit, in the peripheral field of vision of the subjects.
These results and the subsequent questions raised about the rôle of motion perception and that of mental processing of perceived motion by pilots in the control of an aeroplane, resulted in a long-term research program, at the Department of Aerospace Engineering of Delft University, into visual and whole-body motion perception by pilots in a typical flight-deck situation.
By lack of data on the accuracy of motion perception, a rather extensive series of experiments was carried out on accuracy and speed of visual roll

attitude and roll motion perception, on target-time estimation accuracy and, more recently, on accuracy of visual and vestibular motion perception in a moving base flight simulator. In order to assure a sound basis of comparison, the experimental apparatus remained basically unchanged throughout the entire series.

Experiments on visual motion perception

Accuracy and speed of visual perception of roll attitude and roll rate, from the same visual displays as used in the tracking experiment of Ref. 1, were assessed in tests where subjects were required to make accurate and quick estimates of the magnitude of discrete stimuli of roll angle or roll angular velocity (Refs 2 and 3). Subjects responded by pressing the appropriate button of a digital keyboard device, followed by immediate feedback of errors by displaying error angle or rate after each response. The temporal aspect of motion perception appeared to be twofold.

Firstly, there is the exposure duration necessary for a subject to attain a reasonably accurate estimate of the stimulus magnitude. By varying exposure times, it was shown that attitude (roll angle) perception could very accurately be done down to exposure times as short as 0.05 sec, whereas roll rate perception appeared to deteriorate badly at exposure times shorter than 0.4 sec.

Secondly, there is the time taken by subjects to decide on the magnitude of their estimate and to press the appropriate key. It was shown that response times for attitude stimuli were around 0.1 sec shorter than those to roll stimuli, but response times to roll stimuli were slightly, but significantly quicker if peripheral field motion was present.

As to the accuracy of responses, it was shown that peripheral field motion decreased overall standard deviation of the response error for short exposure duration.

Target-time experiments

The perception tests were succeeded by a series of target-time estimation tests (Refs 4 and 5) where subjects were to combine roll attitude and roll rate, as perceived from a rotating horizon line, to obtain an estimate of the time of zero-crossing (target-time).

The accuracy of subject's responses in this sort of interception or motion extrapolation tasks could be shown to be partly related to the known accuracy of rate perception, but some other questions could not be answered due to lack of certain data on rate perception.

Present experiment

Unfortunately, in the rate perception experiments of Refs 2 and 3 only the mean error and standard deviation over a completed run, and absolute errors as a function of rate were determined. Moreover, the discrete stimuli in these experiments were generated by quantization of a random, zero mean, gaussian white noise process. This resulted in rather few data points at the extremes of the range of stimuli and considerable scatter in results for large rates was found.

Therefore, the present tests on rate perception accuracy were carried out, featuring a straight distribution of stimuli and a set-up yielding mean errors, standard deviation of the mean and standard deviation of total error as a function of stimulus rate magnitude.

TEST FACILITY AND DATA REDUCTION

Tests were done in a low-noise room where, in front of the subject's seat, a central (foveal) CRT display (Tektronix 604 monitor), was mounted in a dull gray panel. Peripheral visual field motion was provided by two TV-monitors (Bosch Fernseh Monitor) placed on either side of the subject's seat, see Fig. 1. Subjects gave their responses via a digital keyboard device, see Fig. 2.
The relative positions of central and peripheral displays and the subject's eye reference point are shown in Fig. 4. No head restraint was used. Subjects were free to sit relaxed and at ease, just as in an actual airline cockpit. Also shown in Fig. 4 is the image of the central display, simulating an artificial horizon. The repetition rate was 250 Hz and the position of the horizon line was updated at 50 Hz.
The peripheral displays showed a black and white checkerboard pattern with squares of 5x5 cm, generated by a moving pattern generator (developed at Delft University), at a rate of 30 frames per second. The patterns on the displays moved in conjunction with the rotating horizon line.
All experimental runs were controlled by a hybrid computer (EAI Pacer 100).

A single run consisted of 105 discrete stimuli, presented in random order at fixed intervals of 2 seconds, the sequence during one interval being as follows, see Fig. 3.
At the beginning of the n-th presentation within a run, a random discrete value $\dot{\varphi}_{st}(n)$ of roll rate was presented and this event was marked by a short audiotone in the subject's headphone. After observing the stimulus, the subject was required to respond by pressing the appropriate key of the keyboard. The response magnitude is designated here by $\dot{\varphi}_p(n)$ (perceived rate magnitude). Immediately after the response, the rate error value

$$\Delta\dot{\varphi}_e(n) = \dot{\varphi}_p(n) - \dot{\varphi}_{st}(n) \qquad (1)$$

was shown on the display, thereby giving the subject immediate knowledge of the result after a single presentation and response.
According to eq. (1) a positive value of $\Delta\dot{\varphi}_e$ would indicate an overestimation of rate for positive stimulus rates. In order to facilitate the combination of results of clockwise and counter-clockwise stimuli, the error $\Delta\dot{\varphi}_e$ was computed as

$$\Delta\dot{\varphi}_e(n) = \{\dot{\varphi}_p(n) - \dot{\varphi}_{st}(n)\}.\mathrm{sign}(\dot{\varphi}_{st}(n)) \qquad (2)$$

so that positive $\Delta\dot{\varphi}_e$ indicates overestimation of absolute rate magnitude throughout.
For reasons to be explained below, a next (n+1) rate stimulus magnitude was set by

$$\dot{\varphi}_{st}(n+1) = \Delta\dot{\varphi}_e(n) + \Delta\varphi_i(n+1) \qquad (3)$$

where $\Delta\varphi_i(n+1)$ is a discrete, random value of rate magnitude, set by a random number sequence in the program software.
The stimulus exposure time Δt_{exp} could be varied and was set at a constant value by the experimentor prior to each run.

In one particular experimental condition, exposure was retained until the subject's keyboard response. In all other conditions, the stimulus was made to disappear at the end of the preset exposure time by entirely blanking the displays. In that case, subjects were required to give responses only after exposure termination, responses during exposure time being neglected by the program software. Provisions were also made to neglect responses later than 2.0 sec after exposition onset. Very few missed responses (only one or two in thousand) occurred during actual tests.

During a run, the values of $\dot{\varphi}_{st}(n)$, $\Delta\dot{\varphi}_e(n)$ and the response time RT were recorded and stored on disk for subsequent analysis. Immediately after a run, a printout of overall means and standard deviations of $\Delta\dot{\varphi}_e$ and RT was available.

From replicated runs, overal means and standard deviations of $\Delta\dot{\varphi}_e$ and RT were computed, together with an error score parameter, defined by

$$S_c = \frac{\sigma^2_{\Delta\dot{\varphi}_t}}{\sigma^2_{\dot{\varphi}_{st}}}$$

where $\sigma^2_{\Delta\dot{\varphi}_t}$ is the total error variance defined below.

In addition, means and standard deviations of $\Delta\dot{\varphi}_e$ and RT were computed, together with the standard deviation of total error (relative to zero mean), per stimulus rate level. Total error variance $\sigma^2_{\Delta\dot{\varphi}_t}$ was computed according to

$$\sigma^2_{\Delta\dot{\varphi}_t} = \frac{\Sigma(\Delta\dot{\varphi}_e)^2}{n-1}$$

whereas variance of mean rate error was obtained by

$$\sigma^2_{\Delta\dot{\varphi}_e} = \frac{\Sigma(\Delta\dot{\varphi}_e - \overline{\Delta\dot{\varphi}_e})^2}{n-1}$$

EXPERIMENT

The experimental design was similar to that described in Refs 2 and 3, except for the frequency distribution of the rate stimulus magnitude. The former experiment featured a quantized gaussian white noise stimulus, the present one was run with a range of 0 ± 10 levels of discrete stimuli having an equal probability of occurrence.

The range of stimuli was, just as in the former experiments chosen to be representative of routine airline flight ($\varphi_{max} = \pm 25$ deg/sec). The range of keys to be used nominally was set again at ±10, corresponding with ±25 deg/sec on the displays. Including zero rate, a number of 21 rate levels was obtained. The discrete values of $\Delta\dot{\varphi}_i$ were set by a random number sequence in the program

software in such a way that each rate level was replicated 5 times during a run, bringing the number of presentations at 105 per run.
During pre-experimental evaluation, the rate stimulus magnitude was first set by

$$\dot{\varphi}_{st}(n) = \Delta\varphi_i(n)$$

giving a completely 'fresh' stimulus for each presentation. In this way, the complete range of stimuli was covered and was replicated five times when the random sequence was completed. As a consequence, only zero errors or underestimation of absolute rate can occur at the extreme rate magnitudes, since subjects are very soon aware of the fact that no rates larger than those corresponding with ±10 keys on the keyboard, will occur. This peculiarity was suspected to be the cause of a measured tendency for negative mean errors towards the extremes of the range of rates.
In order to remove this phenomenon from the range of rates of interest, it was decided to present a next stimulus according tot eq. (3). Given the fact that errors will be made, this arrangement will cause stimuli greater than ±25 deg/sec to occur frequently. In this way, the possible artifact could be excluded, without having to increase the nominal range of rates and the number of presentations within a run.

Based on the results of Refs 2 and 3, the exposition times in the present experiments were set at 0.1 sec, 0.3 sec and equal to the response time (Δt_{exp} = RT). Just as in the former experiments, three display configurations were used i.e. central display only (configuration C), peripheral displays only (configuration P) and all displays (configuration CP). With the three exposition times this yielded 9 types of experimental runs, each subject replicating 5 times the 9 types of runs.
After checking that no systematic differences occurred due to clockwise and counter-clockwise rotations of the horizon line, results for positive and negative rates were taken together. Since each stimulus rate level was (nominally) replicated 5 times within a run, a total number of approximately 5x5x2 = 50 replications per non-zero rate level per subject was obtained.

SUBJECTS AND TEST PROCEDURE

Two subjects, who also participated in the other experiments mentioned above, volunteered in the experiment. They are University staff members and both qualified jet transport pilots.
They were instructed to respond primarily as accurate, and secondly as quickly as possible to the presented stimuli. They were not required to continually fixate their eyes on the central display, but were free to look at the keyboard device when giving responses. When only peripheral displays were used, subjects were instructed to fixate their eyes, after responding, on the blank central display, until the next response. Apart from the immediate feedback of the error after each keyboard response, subjects were informed of the total rate error standard deviation after a run.
The experiment was run during a number of morning sessions in which subjects completed series of the 9 types of different runs, presented in random order. After a series of 9 runs, which took around 45 minutes to complete, subjects

were always allowed a break of at least 15 minutes. A total of 9x5x2 = 40 runs were completed. Different random number sequences setting the order of 105 presentations within a run, were used for successive runs and the random number sequences themselves were frequently refreshed in order to prevent subjects becoming familiar with particular random sequences. Because of the equal probability of occurrence, more stimuli at larger rates occurred than with the gaussian probability density function in the earlier rate experiments. This made the present task a more difficult one. However, a sufficiently large number of runs was made during preliminary evaluation to assure a steady level of performance.

RESULTS

The overall results for the 9 combinations of exposition time and display configurations have been summarized in Table 1. Figure 5 shows the standard deviation of the total error (relative to zero mean). For $\Delta t_{exp} = 0.3$ the decrease in total error standard deviation due to addition of peripheral displays (configuration CP compared to configuration C) is just significant ($\alpha < 0.10$). The changes due to peripheral displays for $\Delta t_{exp} = 0.1$ sec are highly significant ($\alpha < 0.01$).

Also shown for comparison (solid symbols in Fig. 5) are the corresponding values obtained in the experiments of Ref. 3. Figure 6 shows the error scores. It can be seen that although standard deviations are larger throughout for the present experiment, the error scores are lower than for the earlier tests. The effects due to exposition time and display configuration are quite similar. For example, addition of peripheral displays to the central display at 0.1 sec exposition time, decreases the total error standard deviation by around 65% in both experiments.

Mean reacton times and standard deviations have also been summarized in Table 1. For all exposition times, mean reaction times for peripheral displays only and for central and peripheral displays are significantly ($\alpha < 0.01$) smaller than those for the central display alone, confirming the earlier findings of Ref. 3. In Figs 7 and 8 mean perception errors, standard deviation and standard deviation of total error have been plotted as a function of stimulus rate magnitude for $\Delta t_{exp} = 0.3$ and 0.1 sec respectively.

With decreasing exposure time, a tendency for overestimating low rates and underestimating higher rates can be observed and addition of peripheral displays to the central display is seen to suppress this range effect. Also, an apparent tendency to more underestimating the larger rates than to overestimating the smaller rates, can be observed.

An interesting feature is the increase of standard deviation of the mean error as a function of rate. It follows from Figs 7 and 8 that the increase of total error standard deviation, for rates up to around 20 deg/sec, is largely caused by the increase in random error, except for the case of $\Delta t_{exp} = 0.1$ sec in the configuration C. Although the overall effect of peripheral displays for $\Delta t_{exp} = 0.3$ sec is small, it is remarkable to see that for zero rate, a highly significant ($\alpha < 0.01$) decrease in error standard deviation occurs.

In order to put the present results into the proper perspective, mean perceived rates and standard deviations have been plotted as a function of stimulus rate magnitude in Figs 9 and 10.

DISCUSSION AND CONCLUDING REMARKS

A comparison of overall results for the 9 combinations of exposure times and display configurations shows that the results as obtained are dependent on the probability density function of the rate stimulus magnitude. Since results are apparently task-dependent, some care should be taken when extrapolating them to other tasks, for instance tracking tasks. On the other hand, relative changes due to display configurations or exposition times seem to have rather constant magnitudes.

As concerned individual differences, it should be remarked that, as far as total rate error standard deviation is concerned, subjects showed only significant differences in the case of all displays (configuration CP) for exposition times of 0.1 and 0.3 seconds.

Subjects showed consistent and highly significant ($\alpha < 0.01$) differences in mean reaction times (around 0.11 sec) but both showed a decrease in mean RT and standard deviation at $\Delta t_{exp} = 0.1$ sec between the C and the P configuration.

The 'slower' subject seemed to profit more from the peripheral displays, both in terms of lower mean RT, lower RT standard deviation and decrease in total rate error standard deviation. An illustration of individual differences is given in Fig. 11 where total error standard deviation is plotted as a function of mean RT for both subjects, for $\Delta t_{exp} = 0.1$ sec.

It would appear from the data of subject 2 that a decrease in mean RT is consistent with a decrease in rate error standard deviation. A larger number of subjects would be necessary to see whether this is a general trend.

Apart for the case of zero rate magnitude, where RT mean and standard deviations are slightly smaller, mean reaction time and standard deviation are fairly constant over stimulus rates.

A range effect is evident in the present results and more so if task difficulty increases (shorter Δt_{exp}). This probably reflects a strategy, adapted by subjects in difficult perception tasks, to guess for the mean absolute stimulus rate to be expected.

The gross underestimation of large rates in the present experiment might be due to the fact that pilots, experienced in closed loop control, are reluctant to overcontrol in the case of large deviations.

When the present data are to be applied to closed-loop control, however, it appears that this phenomenon would be of relatively little importance when very few excursions greater than 5 to 10 degr/sec would occur, for instance in the case of the roll control of a jet transport in mild turbulence.

TABLE 1: Results for 2 subjects, 5 replications each.

Conf.*)	Δt_{exp} (sec)	Reaction Time (sec)	Perceived rate error (deg/sec)	Stand deviation total error (degr/sec)	Score**)
C	= RT	0.832±0.103	-0.24±3.59	3.60	0.0532
P	= RT	0.816±0.123	-0.54±3.55	3.59	0.0539
CP	= RT	0.805±0.098	-0.11±3.49	3.49	0.0501
C	0.3	0.824±0.095	-0.62±3.51	3.57	0.0525
P	0.3	0.794±0.105	-1.28±3.39	3.58	0.0540
CP	0.3	0.800±0.091	-0.22±3.20	3.21	0.0449
C	0.1	0.898±0.198	-3.60±7.48	8.30	0.2564
P	0.1	0.792±0.126	-1.11±5.61	5.72	0.1269
CP	0.1	0.812±0.116	-1.57±5.59	5.80	0.1300

*) C central display only
P peripheral displays only
CP central and peripheral displays

**) Error score parameter, defined by:

$$S_c = \frac{\sigma^2_{\Delta\dot{\varphi}_t}}{\sigma^2_{\dot{\varphi}_{st}}}$$

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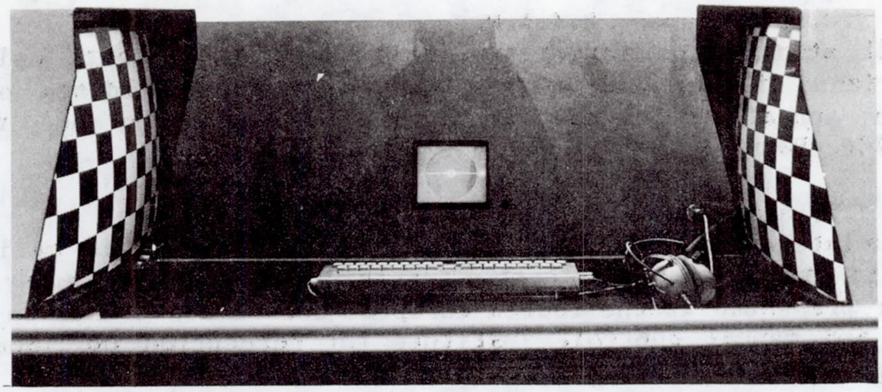

Fig. 1. Overview of test facility showing central display, the perihperal displays and the digital keyboard.

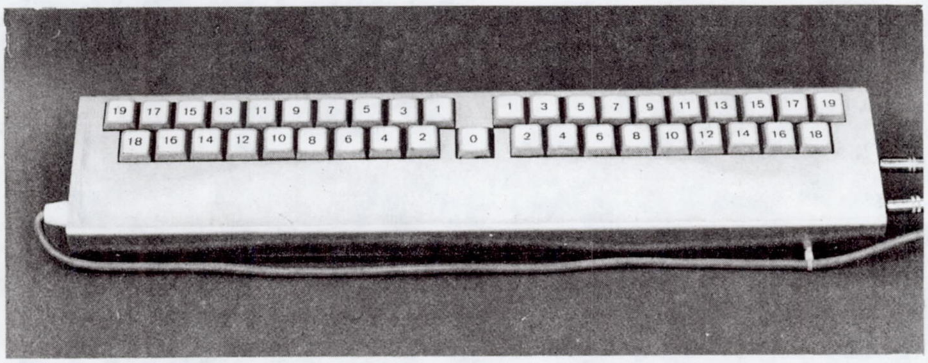

Fig. 2. Digital keyboard device.

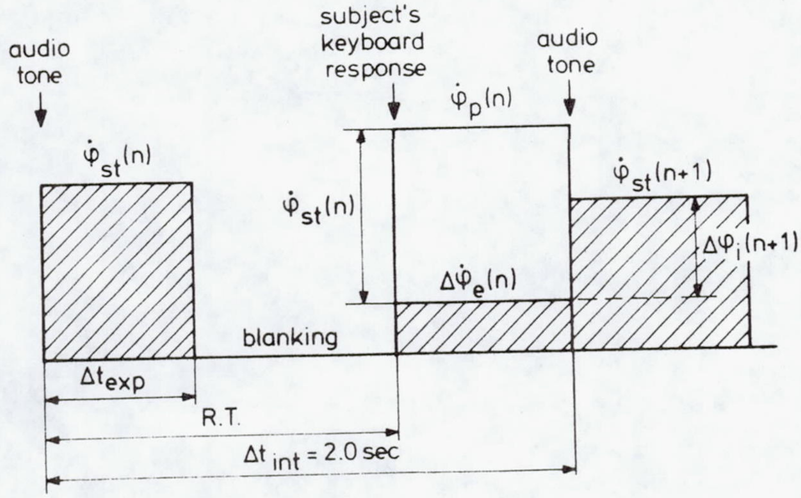

Fig. 3. Sequence during one interval of a test run. Shaded areas represent rate magnitude as displayed.

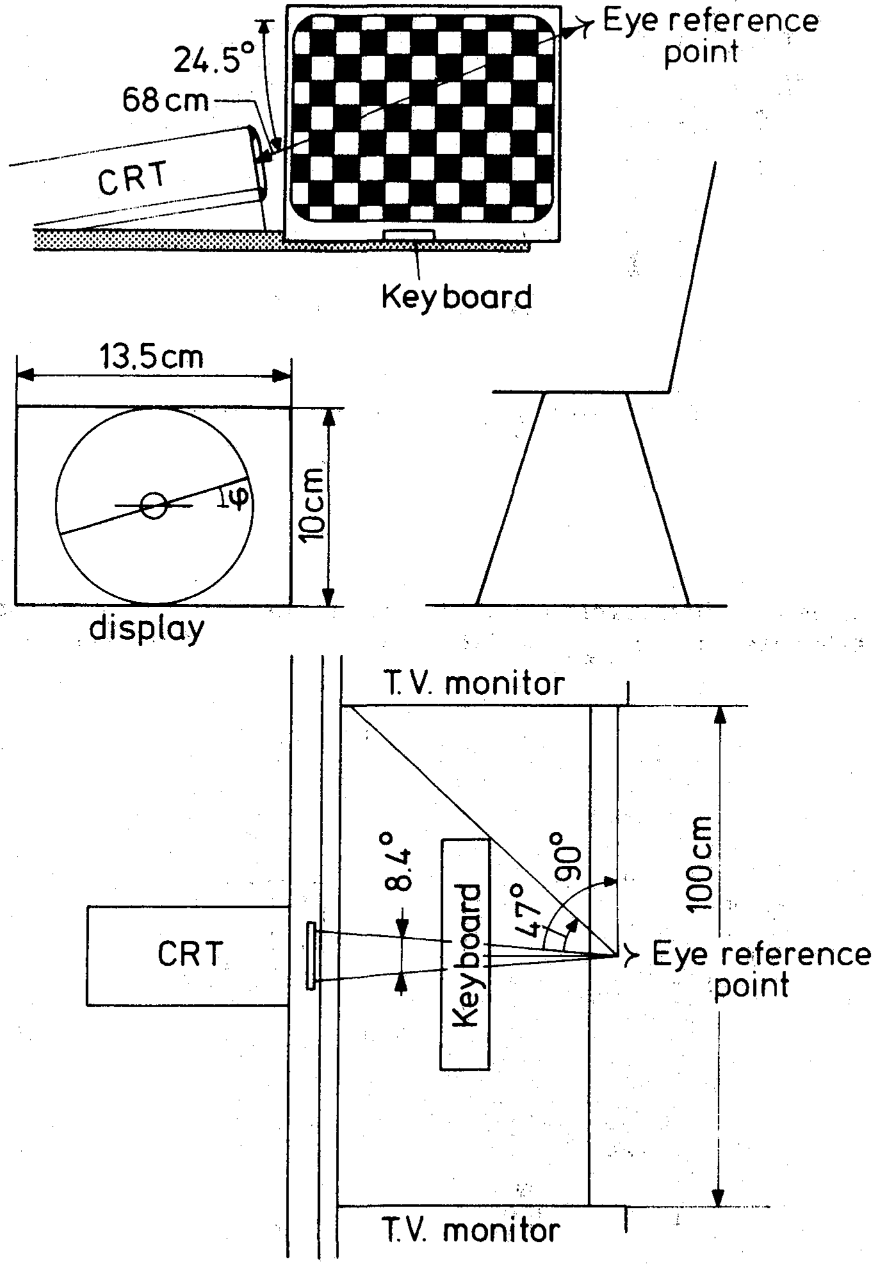

Fig. 4. Positions of displays relative to the subject's eye reference point. Central display image and dimensions.

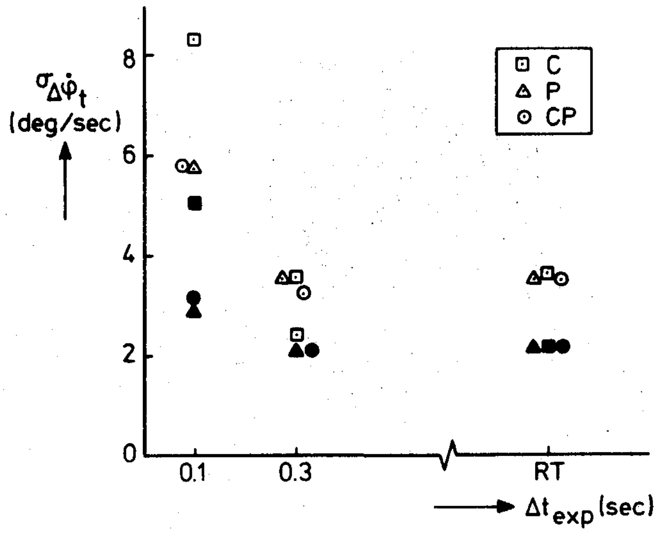

Fig. 5. Standard deviation of total rate perception error as a function of exposure time Δt_{exp}. Solid symbols: data from Ref. 3.

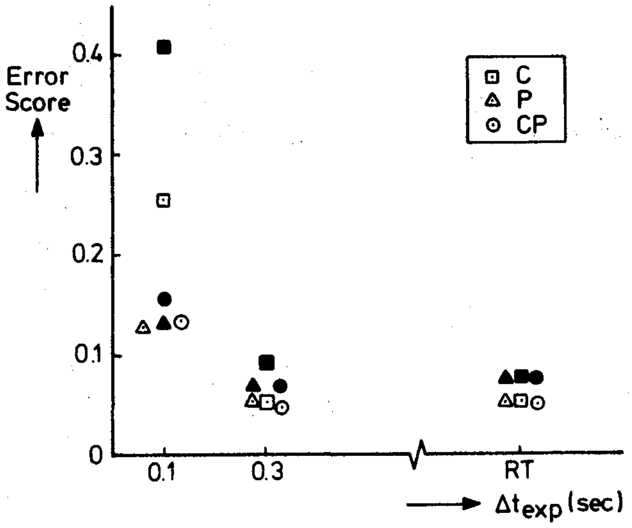

Fig. 6. Error score as a function of exposure time Δt_{exp}. Solid symbols: data from Ref. 3.

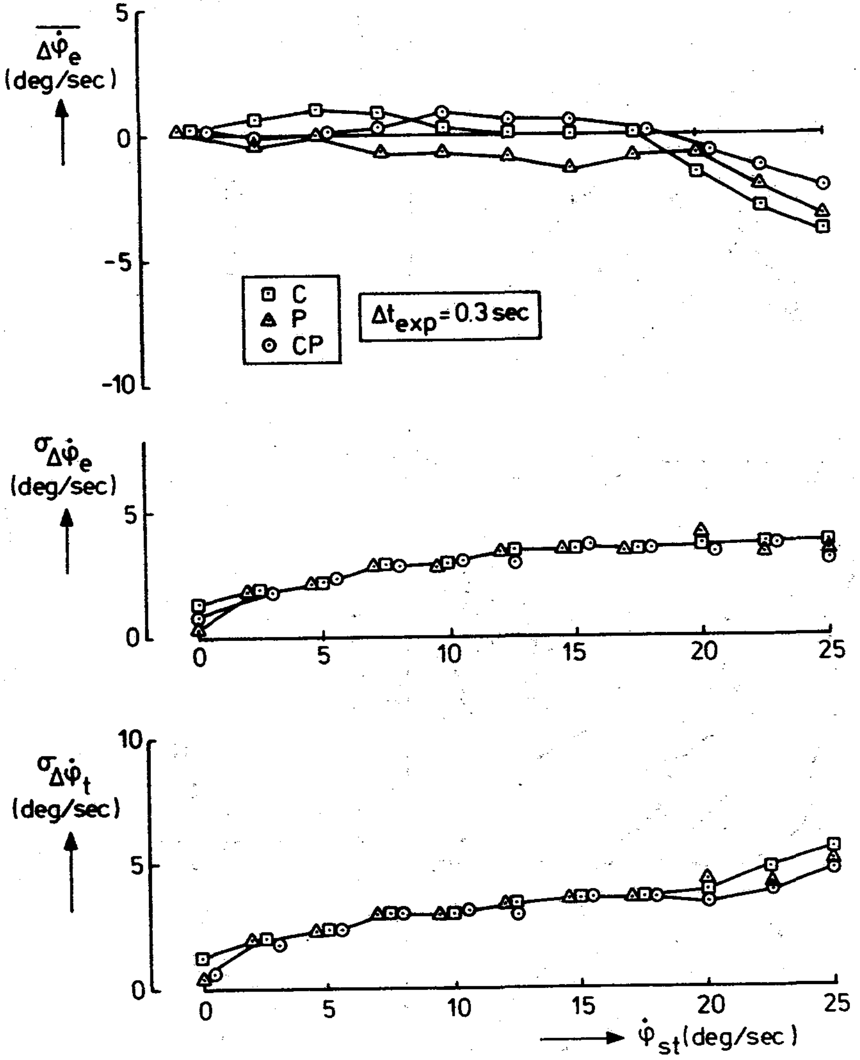

Fig. 7. Mean rate perception error, standard deviations of mean error and total error as a function of stimulus rate magnitude, $\Delta t_{exp} = 0.3$ sec.

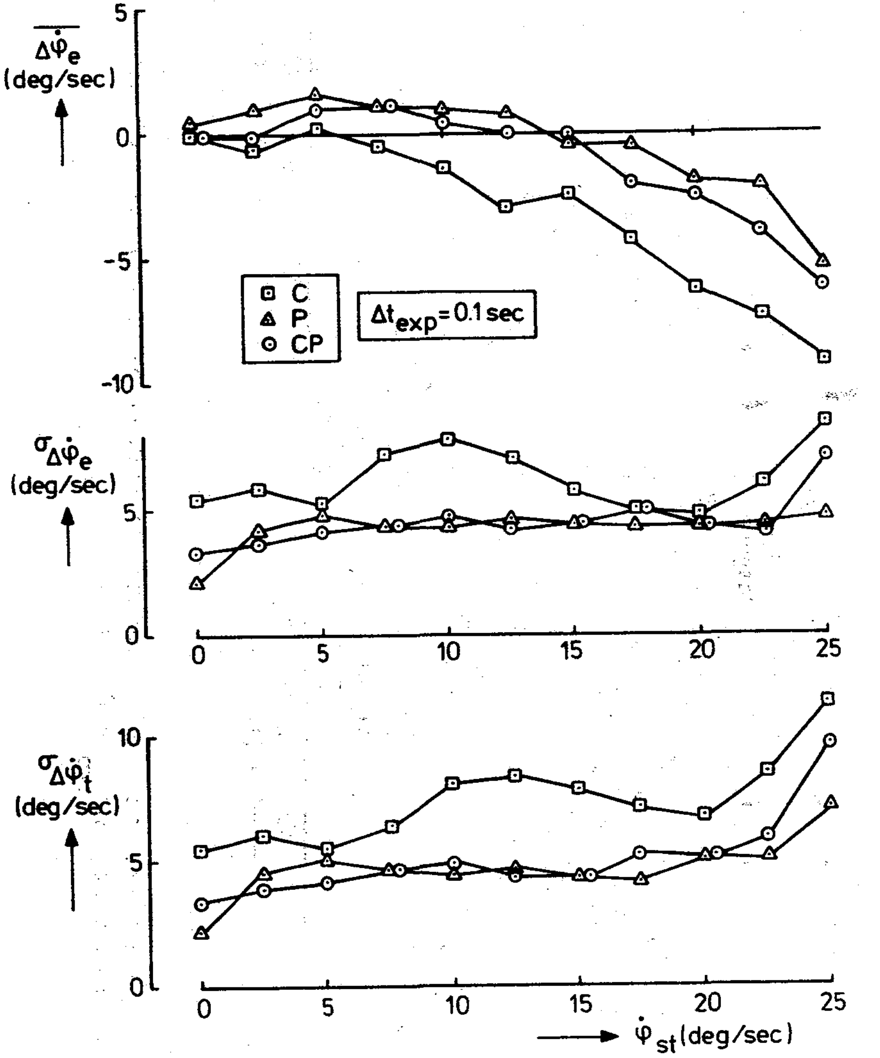

Fig. 8. Mean rate perception error, standard deviations of mean error and total error as a function of stimulus rate magnitude, $\Delta t_{exp} = 0.1$ sec.

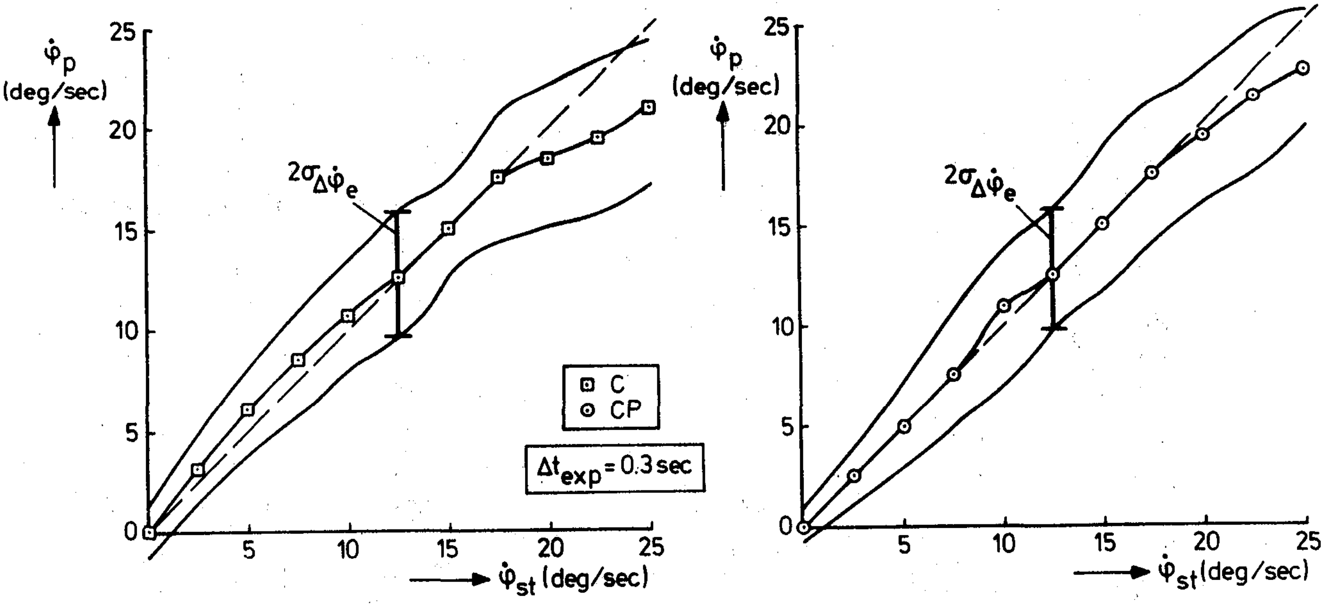

Fig. 9. Mean perceived rate and standard deviation as a function of stimulus rate magnitude, Δt_{exp} = 0.3 sec.

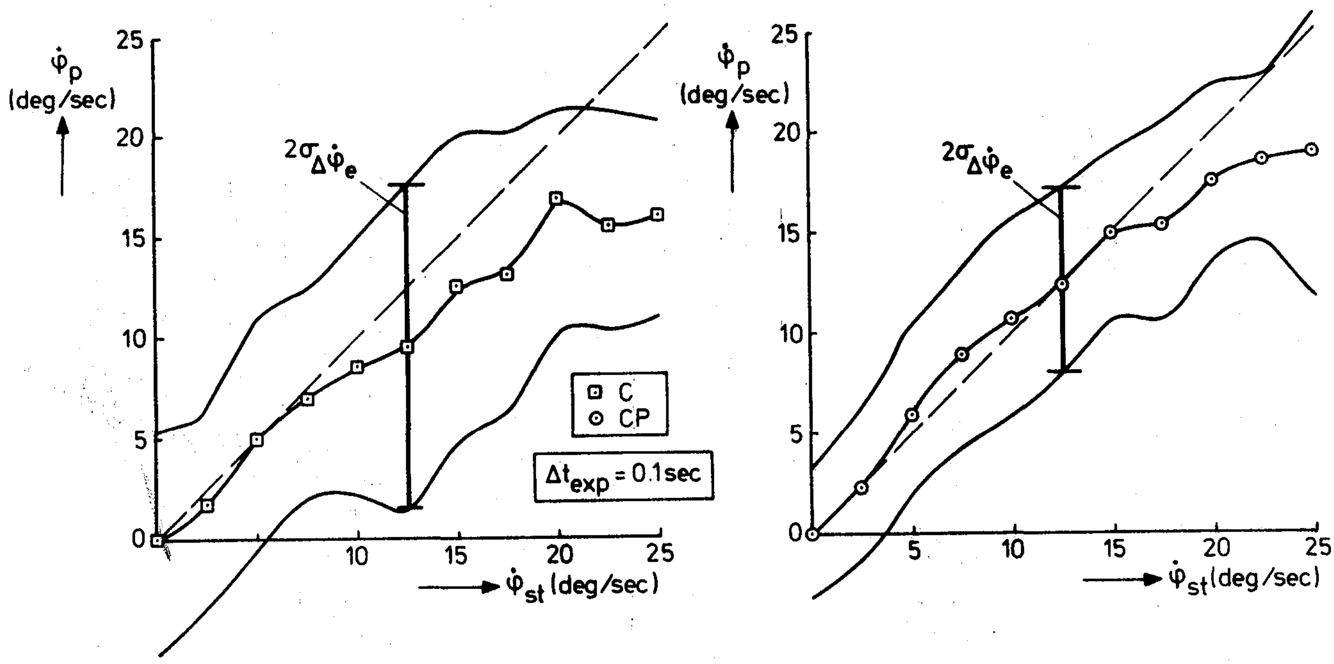

Fig. 10. Mean perceived rate and standard deviation as a function of stimulus rate magnitude, Δt_{exp} = 0.1 sec.

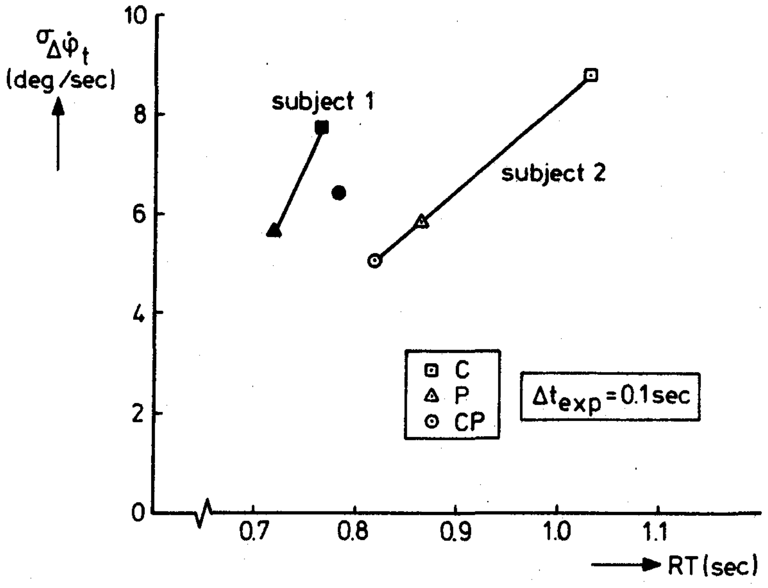

Fig. 11. Total error standard deviation as a function of reaction time RT for the two subjects, $\Delta t_{exp} = 0.1$ sec.