# EFFECTS OF VISUAL AND VESTIBULAR MOTION PERCEPTION ON CONTROL TASK PERFORMANCE

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## Abstract

The influence of visual and vestibular motion perception on pilot's behaviour in a control task has aroused many discussions during the last decades which have not yet come to an end. This influence is of direct relevance to the modelling of pilot control behaviour and to flight simulation.
Results of experiments in this field as reported in the literature appeared to be somewhat different from the experience gained in the research flight simulator of the Department of Aerospace Engineering of the Delft University of Technology. The aim of the experiment described in the present Paper was to obtain a data base on pilot's behaviour using central and peripheral visual and motion cues.
In a following task (or compensatory tracking task) and in a disturbance task (both roll tasks) using a double integrator as the controlled element, all possible combinations of central visual, peripheral visual and vestibular motion cues were presented to the subjects.
The results show significant influence of the peripheral visual and vestibular cues on subject's performance and dynamic behaviour in both control tasks.

## 1. INTRODUCTION

Theories of control behaviour of a pilot or a human controller are generally based on the concept of a controller as a processor of information. In these theories as well as in quite a number of mathematical models of human control behaviour three main features are usually distinguished: observation, decision making and output generation.
The perception of position and motion by way of visual, vestibular, tactile and proprioceptive cues can be considered as a first stage in the observation process. Research in the field of control behaviour at the Aerospace Department of Delft University is mainly concerned with motion perception. An example of earlier work are the experiments (reported in Ref. 1) on vestibular thresholds of motion perception. In these tests, subjects were passive and were only required to give verbal responses to selected motion stimuli in a typical flight deck situation.
Of course motion perception by a pilot in a situation where he actively controls an aeroplane is quite different from that of a passive observer. The work reported in the present Paper was undertaken to gather more insight into the motion perception in a control situation.
In this area especially there is a considerable lack of knowledge. Very little is known in fact, about exactly what are the most vital senses for an aircraft control task and on how the information processing takes places.

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Knowledge of all these aspects is essential for formulating the mathematical models that are not only to be tools for aircraft development but also for motion simulation.
It is conceivable that much of the present motion versus non-motion controversy in the field of flight simulation partly springs from a general lack of knowledge about the rôle of motion perception in the control of aircraft.
It is obvious that there is a certain degree of overlapping (redundancy) in sensory information. Furthermore it is clear that the amount and quality of sensory information needed depend on the nature and difficulty of the control task, although quantitative data are again either scarce or lacking altogether.
An ideal tool in the quest for answers to the questions posed above is a modern moving base flight simulator in which it is possible to simulate a wide variety of system characteristics, to delete or alter different sensory cues and to vary systematically the nature and difficulty of a control task. In this way the information processing task of the pilot can be influenced and studied.

In the literature a number of experiments on the influence of motion in control tasks is reported, see Refs. 2 through 7. The results of these experiments are not always consistent, however. Differences in the reported results can be attributed to differences in the dynamic characteristics of systems to be controlled, in the characteristics of the motion simulation systems and in the experimental set-ups. Experiments on the influence of peripheral visual cues on pilot control behaviour are reported in Refs. 8 through 10. It is reported there that, under certain circumstances, peripheral visual cues can partially substitute for vestibular motion cues.

Because no work has been reported covering systematic variation of available sensory cues, it was decided to do an experiment in the Aerospace Department's moving base flight simulator, in which a simple roll control task and the various 'sensory displays' - i.e. central CRT-display, peripheral field display and simulator cockpit motion - were systematically varied. Two different control tasks (see Section 4) were used, the controlled element characteristics being the same in both cases (see Section 3).

Although the basic physical quantity to be controlled in a roll control task is the roll angle, the quantities perceived through the different displays will differ due to the different characteristics of the sensory organs involved and the particular way in which the sensory information is processed. For instance, it is usually assumed that a human controller is able to derive, from a central visual display, some measure of rate of change (roll rate) from the basic roll angle information. A far better impression of roll rate may be obtained, however, from the peripheral visual field, which is known to yield mainly velocity information (Ref. 11).
Furthermore, the otoliths in the vestibular system are also sensitive to the simulator roll angle, due to the gravitational influences, while the semicircular canal organs are sensitive to roll acceleration.

## 2. INSTRUMENTATION AND DATA REDUCTION

All measurements with motion were carried out in the Delft University of Technology Department of Aerospace Engineering flight simulator (see Fig. 1). The three degrees of freedom motion system of this simulator has unique high fidelity motion characteristics, making the simulator a very suitable tool for the present experiments. The application, in this motion system, of so called 'hydrostatic' bearings in the hydraulic servo actuators results in very smooth and almost rumble free simulator motions, see Ref. 12. Under normal operating conditions motion noise is well below the thresholds of motion perception, as determined by the tests reported in Ref. 1. For the present roll axis control task, a central (foveal) CRT display (simulating an artificial horizon) was installed in the instrument panel in front of the subject's seat in the simulator cockpit, as shown in Fig. 2. Peripheral visual motion cues were provided by two T.V. monitors mounted against the side windows of the simulator cockpit (Figs. 2 and 3). These monitors displayed a moveable checkerboard pattern. The relative positions of the displays and test subject's eye position are given in Fig. 3, the technical details of which are described in Ref. 13.

Subjects used a spring centered side-arm controller to control the dynamics of the system (see Section 3). Details of the side-arm controller can be found in Ref. 14. The dynamics of the controlled system were simulated on a hybrid computer that also generated the quasi-random disturbances acting on the system (see Section 4), as well as the signals controlling the displays and the simulator motion system. The computer algorithms driving the visual displays and the motion system were implemented such that time delays between these systems were smaller than 0.01 second.
During test runs measurements were taken at a rate of 25 per second. In the case of the 'disturbance task' the roll angle $\varphi$, the roll rate $\dot{\varphi}$ and the control stick deflection $\delta_a$ were recorded. In the so-called 'following task' (see Section 4) the roll angle error $e_\varphi$ was recorded in addition to $\varphi$, $\dot{\varphi}$ and $\delta_a$.

Shortly after the end of a test run, data analysis was completed by a digital program yielding standard deviations of the recorded variables. Simultaneously Bode plots of the human operator transfer functions were obtained by using a Fast Fourier Transform (F.F.T.) routine ,Ref. 15.

All combinations of display configurations used in the experiment, are shown in Table 1. Due to limited availability of the flight simulator, all non-motion conditions were run in a similar fixed base experimental set-up in an acoustically isolated room. An analysis of variance revealed no significant differences when a number of these non-motion conditions were replicated in the flight simulator.

## 3. ROLL CONTROL TASK DYNAMICS

The roll control task was chosen because it was felt that any influence of the peripheral displays would be more dramatic in comparison with the other possible modes of the flight simulator - i.e. pitch and heave. The dynamics of the controlled system were those of a double integrator having the transfer function

$$H(s) = \frac{K}{s^2} \qquad (1)$$

where K was set to a value of 4.

The dynamics of eq. (1) are roughly similar to the roll control of a slowly responding aircraft, such as a medium to large sized jet transport flying at low speeds. There is, however, a minor difference between the motion to be sensed in an aircraft and in the simulator. When the simulator in the present experimental set-up is made to roll by a control stick deflection, the subject senses, in addition to the rotational roll acceleration, a lateral force component due to the simulator tilt. Due to the particular dynamics of an aircraft and its larger number of degrees of freedom, this lateral force component is virtually absent in actual flight.

## 4. DISTURBANCE AND FOLLOWING TASK

It is known that human control behaviour is also influenced by the manner in which disturbances act on the controlled loop, see Ref. 6. Therefore two distinct control tasks were used in the present experiments.

In the first one, the disturbance task, the disturbing signal was made to act on the controlled system, as shown in Fig. 4a. In this situation, which is quite comparable to the case in which a pilot stabilizes an aircraft in rough air, the roll angle, or attitude, perceived through the peripheral display by the cockpit motion exactly corresponds to the roll attitude presented on the central display. All 'sensory displays' therefore yield attitude relative to the outside world.

In the second control task, the following, or tracking task, the displayed signal on the central display, $e_\varphi$, is the difference between the disturbance signal, i, and the roll angle, $\varphi$, of the controlled system, see Fig. 4b. The peripheral display and the motion system, however, correspond with the roll angle $\varphi$ of the controlled system. The motion of the system in this case depends on the subject's control action only and there is no direct simple relationship between roll angle error $e_\varphi$ as presented by the central display and roll angle and roll rate as presented by the motion system and peripheral displays.

If only one of the controlled variables $\varphi$ or $e_\varphi$ is presented on the central display, a well trained subject is able to discriminate between a disturbance and a following task, even though the task goal, which is to keep the displayed variable as small as possible, is the same. The addition of peripheral visual and motion cues serves to amplify the difference between the two tasks. In the disturbance task, the task goal can be achieved by keeping the motion of the controlled system as small as possible. This can be achieved by avoiding high roll rates, as would be caused by quick and large control stick deflections. This is contrary to the situation in the following task, where the subject is free to induce large changes in roll attitude and roll rate in order to minimize the displayed error magnitude.

The disturbing signal used in all tasks was a quasi-random one, consisting of the sum of 10 sinusoids whose frequency, amplitude and phase are given in Table 2. The standard deviation of the disturbing signal was $\sigma_i = 1.875$ degrees.

## 5. SUBJECTS AND TEST PROCEDURE

Three subjects, all university staff members and qualified jet transport pilots, volunteered for the experiments. Extensive training was done until stable performance, as expressed by roll angle or roll angle error standard deviation, was reached.
As the non-motion test runs were performed outside the simulator in a separate experimental set-up, the actual experiments were run in two parts. Within each part, control tasks and display configurations were presented in random order. The duration of a single test run (one particular task under one configuration) was 110 seconds. Measurements were taken only during the last 82 seconds of a run. Five replications were performed, resulting in a total of 4 x 3 x 5 = 60 test runs for the following task and 7 x 3 x 5 = 105 for the disturbance task.
Each series of test runs presented to a subject (6 or 7 runs) lasted approximately 20 to 25 minutes. For the purpose of training alone, 420 test runs were completed among the three subjects before starting the main test program.

## 6. RESULTS

Two distinct aspects of the control task are considered here: Task performance and control behaviour. Task performance is expressed by the standard deviation of the controlled variables. Control behaviour is assessed by using the computed human controller Bode plots.

### Performance

#### Disturbance task

From Fig. 5 an impression can be obtained of the performance as expressed by the relevant standard deviation $\sigma_\varphi$ as a function of display configuration. Adding the peripheral displays to the central display (Configuration 2) is seen to have a beneficial effect on the performance of the disturbance task, but the influence of motion is seen to be most dramatic (Configurations 4, 5, 6 and 7). Quite remarkable is the performance for the case of motion alone (Configuration 7). Once motion is present little appears to be gained by adding peripheral displays (Configurations 4 and 5). Addition of the central display in the case of motion (Configurations 5 and 6) gives a small but significant improvement. The standard deviations of the angular rate $\dot{\varphi}$ and the control output $\delta_a$ also demonstrate the considerable influence of motion. In summary it can be observed that addition of the peripheral displays in the disturbance task improves the performance of the subjects just as motion does, the influence of motion begin stronger. No further improvement can be obtained by adding the peripheral displays once motion is present.

#### Following task

A similar decrease of $\sigma_{e_\varphi}$ - i.e. improved performance - is seen for the following task due to the addition of either the peripheral displays, motion or both, see Fig. 5. In this task the peripheral visual and motion cues are not in correspondence with the centrally displayed error signal $e_\varphi$. However, the same trend of decreasing standard deviations is found for both $\varphi$ and $\dot{\varphi}$ although these variables are not the directly controlled ones, see Fig. 5.

The standard deviations for $\delta_a$ follow a similar trend. From these data it appears that the influence of the peripheral displays is stronger than in the case of the disturbance task whereas the influence of motion is slightly less.

Analysis of variance on the measured variables of the 105 testruns for the disturbance task and the 60 test runs for the following task are summarized in Table 3. These analyses show that the changes in performance, as expressed by $\sigma_\varphi$ and $\sigma_{e\varphi}$, due to changes of the display configurations, are significant for both tasks.
This also holds for the standard deviations of $\dot{\varphi}$ and $\delta_a$ for the disturbance task and $\varphi$, $\mathring{\varphi}$ and $\delta_a$ for the following task. In addition a significant influence of the subjects and the interaction between subjects and configurations is demonstrated for these variables. This indicates that subjects, while obtaining approximately equal performance, used different control stategies and reacted differently on the changes of the display configurations.

The mean effects of adding peripheral displays or motion can be summarized by the following relative decreases in standard deviations of the controlled variables $\sigma_\varphi$ and $\sigma_{e\varphi}$.

| Task | Peripheral display | Motion |
|---|---|---|
| Disturbance task | 12% | 59% |
| Following task | 16% | 32% |

Control behaviour

Bode plots of the transfer function $H_p(\omega)$ relating the subject's input $\varphi$ or $e_\varphi$ to the subject's output $\delta_a$ were calculated for all combinations of display configurations and control tasks tested.

Disturbance task

The bode plots of the transfer function $H_p(\omega)$ for the disturbance task are presented in Figs. 6 and 7. Due to the addition of peripheral visual and motion cues the modulus of the transfer function is seen to increase at low frequencies. As could be expected from the performance data, the influence of motion on the transfer function is the strongest. Of all the configurations without central display (Configurations 3, 6 and 7), Configuration 3 (peripheral display only) shows a drecrease of the modulus at the low frequencies. This can be explained by the fact that in this configuration, subjects could hardly derive any roll attitude information from these displays, especially at the low frequencies. In the Configurations 6 and 7 however, the subjects can perceive the side force due to the bank angle $\varphi$. From these data it follows that the side force is a good substitute for the central visual display. In Fig. 8 the crossover frequency and the phase margin $\varphi_m$ have been plotted as a function of the seven configurations. As could be expected, the crossover frequency is increased when the peripheral displays and motion are added to the central display. The phase margin remains approximately constant.

Following task

For the following task, see Fig. 9 the changes due to addition of peripheral visual and motion cues are opposite to the ones in the disturbance task. The modulus decreases especially at the low frequencies, the phase angle increases at low frequencies and decreases at high frequencies.
In Fig. 8 the crossover frequency $\omega_c$ and the phase marging $\varphi_m$ have been presented as a function of the four display configurations. In this case $\omega_c$ is hardly influenced by the addition of the peripheral displays or motion. However, the phase margin is seen to increase. Finally, Figs. 10 and 11 may serve to stress the differences in the changes of the subject's control behaviour. In these Figures the open loop transfer functions $H_p(\omega).H_c(\omega)$ for two display configurations are plotted for both the disturbance and the following task.

Summarizing the results concerning the control behaviour in both tasks it can be concluded that the performance improvement due to the addition of peripheral displays and/or motion, coincides with changes in the subject's transfer function in both tasks.
For the disturbance task the performance improvement can easily be explained by the increase of $\omega_c$ at nearly constant $\varphi_m$.
For the following task, however, the performance improvement is seen to be accompanied by an increase in phase margin, the crossover frequency remaining nearly constant.

## 7. DISCUSSION AND CONCLUSIONS

That motion as well as peripheral visual cues should, in general, have a considerable influence on subject's control performance and control behaviour could be expected considering the results reported in the literature (Refs. 2 through 10). In the present experiment, however, the disturbance signal was small, resulting in very low values of the standard deviation of the roll angle and roll angle rate ($\sigma_\varphi$ = 1-3 degrees, $\sigma_{\dot\varphi}$= 1,5 - 5 degrees/sec). In spite of these low values, a considerable influence, especially of motion, was found on performance and control behaviour.

Ref. 6 describes disturbance and following tasks using configurations similar to no's 1 and 4 (central display only and central display with motion). The results are quite comparable to the present ones: a performance improvement and a considerable increase of the crossover frequency for the disturbance task. The following task of Ref. 6 showed a slight improvement of the performance together with a large increase of the phase lead at low frequencies due to the addition of motion.
Another experiment with a following task only, see Ref. 9, showed the same trend as the present one although the controlled system of Ref. 9 was a much more difficult one to control.
The remarkable difference between the changes of control behaviour for both control tasks brought about by the addition of peripheral visual and motion cues can probably be explained in terms of a difference in the subjective cost function that the subjects tried to minimize. If the subject tries to maintain the roll angle $\varphi$ on the central display in the disturbance task as

small as possible, the peripheral displayed roll rate $\dot{\varphi}$ and the simulator motion will also be small. In the case of the following task, however, relatively large roll angles and roll rates will occur, when the subject minimizes the centrally displayed roll angle error. From the present experiment it turns out that for the following task, the subjects developed a control strategy that resulted not only in a decrease in roll angle error $e_\varphi$ but also in an accurate control of the roll angle $\varphi$ and roll angle rate $\dot{\varphi}$, if peripheral visual and motion cues were present. Apparently, subjects tended to keep the roll angle and roll angle rate at relatively low values. This means that they somehow included these variables in their subjective cost function.

Summarizing the resuls of the present experiments it can be concluded that:

1. Performance is improved significantly in both disturbance and following task by adding peripheral visual cues and/or motion cues.

2. Control behaviour as expressed by human operator transfer functions is influenced by adding peripheral visual cues and/or motion cues in both disturbance and following task.

3. In the disturbance task the increase in performance due to the addition of peripheral visual and/or motion cues is readily interpreted by the increase in the crossover frequency.

4. In the following or tracking task the influence of peripheral and/or motion cues on the human operator transfer function shows a trend opposite to the one in the disturbance task. As a consequence improvements in performance cannot readily be interpreted in terms of human operator transfer functions.

Although improvements in performance and changes in dynamic behaviour were definitely demonstrated as a result of the addition of peripheral visual cues and motion cues, it is not clear what exactly are the causes for these improvements and changes.
Motion perception may have been improved in either of two ways.
Firstly it may be that by addition of peripheral visual and/or motion cues, redundant information is made available to the subject thus improving the accuracy of the motion perception process.
Another possibility is that due to differences in the dynamic characteristics of the vestibular system and the peripheral visual system on the one hand, and those of the foveal visual system on the other, a subject receives additional information that enables him to improve motion perception.
Further research into the motion perception process in particular into the separate aspects of central visual, peripheral visual and vestibular motion perception and their interactions is called for.

## 8. REFERENCES

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Table 1: Display configurations

| Configuration no/code | Central display | Peripheral display | Motion | task Disturbance Following |
|---|---|---|---|---|
| 1 C | x | | | D, F |
| 2 CP | x | x | | D, F |
| 3 P | | x | | D |
| 4 CM | x | | x | D, F |
| 5 CPM | x | x | x | D, F |
| 6 PM | | x | x | D |
| 7 M | | | x | D |

Table 2: Frequency, amplitude and phase of the sinusoids used to generate the quasi-random disturbance signal

| Frequency $\omega$ (rad/sec) | Amplitude (degrees) | Phase (degrees) |
|---|---|---|
| 0.153 | 1.106 | 4 |
| 0.230 | 1.099 | 151 |
| 0.383 | 1.083 | 43 |
| 0.537 | 1.058 | 122 |
| 0.997 | 0.957 | 324 |
| 1.457 | 0.842 | 184 |
| 2.378 | 0.646 | 281 |
| 4.065 | 0.428 | 194 |
| 7.440 | 0.247 | 162 |
| 13.576 | 0.136 | 43 |

Table 3: Results of the analysis of variance on the standard deviation of the measured variables

| Disturbance task | $\sigma_{\varphi}$ | $\sigma_{\dot{\varphi}}$ | $\sigma_{\delta_a}$ |
|---|---|---|---|
| 1 Configurations | **** | **** | **** |
| 2 Subjects | - | **** | **** |
| 3 Interaction subjects-configurations | - | **** | **** |
| 4 Replications | - | * | * |

| Following task | $\sigma_{e_{\varphi}}$ | $\sigma_{\varphi}$ | $\sigma_{\dot{\varphi}}$ | $\sigma_{\delta_a}$ |
|---|---|---|---|---|
| 1 Configurations | **** | **** | **** | **** |
| 2 Subjects | - | **** | **** | **** |
| 3 Interaction subjects-configurations | - | - | *** | **** |
| 4 Replications | ** | ** | - | *** |

$\alpha < 0.01$ ****
$\alpha < 0.05$ ***
$\alpha < 0.1$ **
$\alpha < 0.25$ *

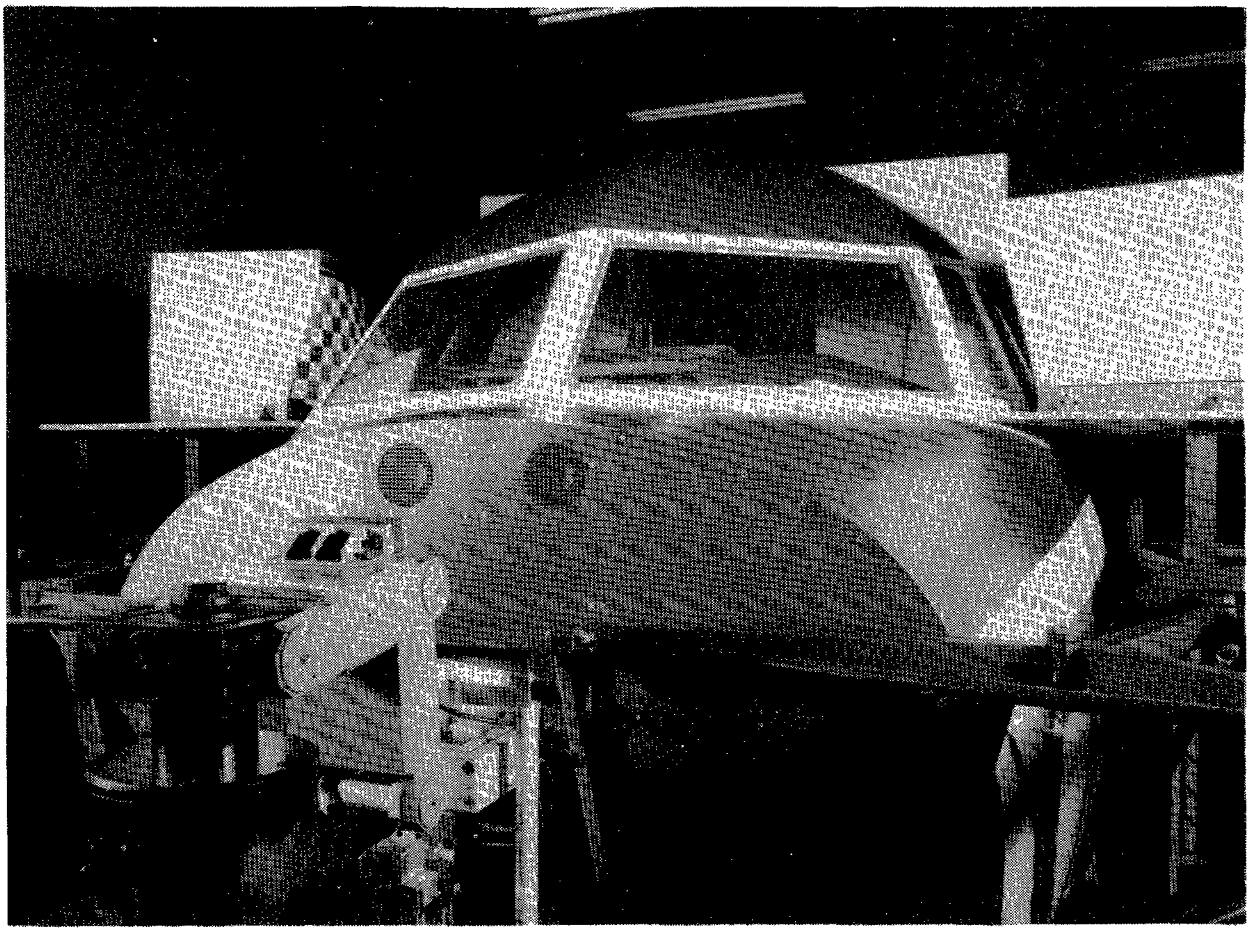


Fig. 1: The flight simulator cab with peripheral displays.

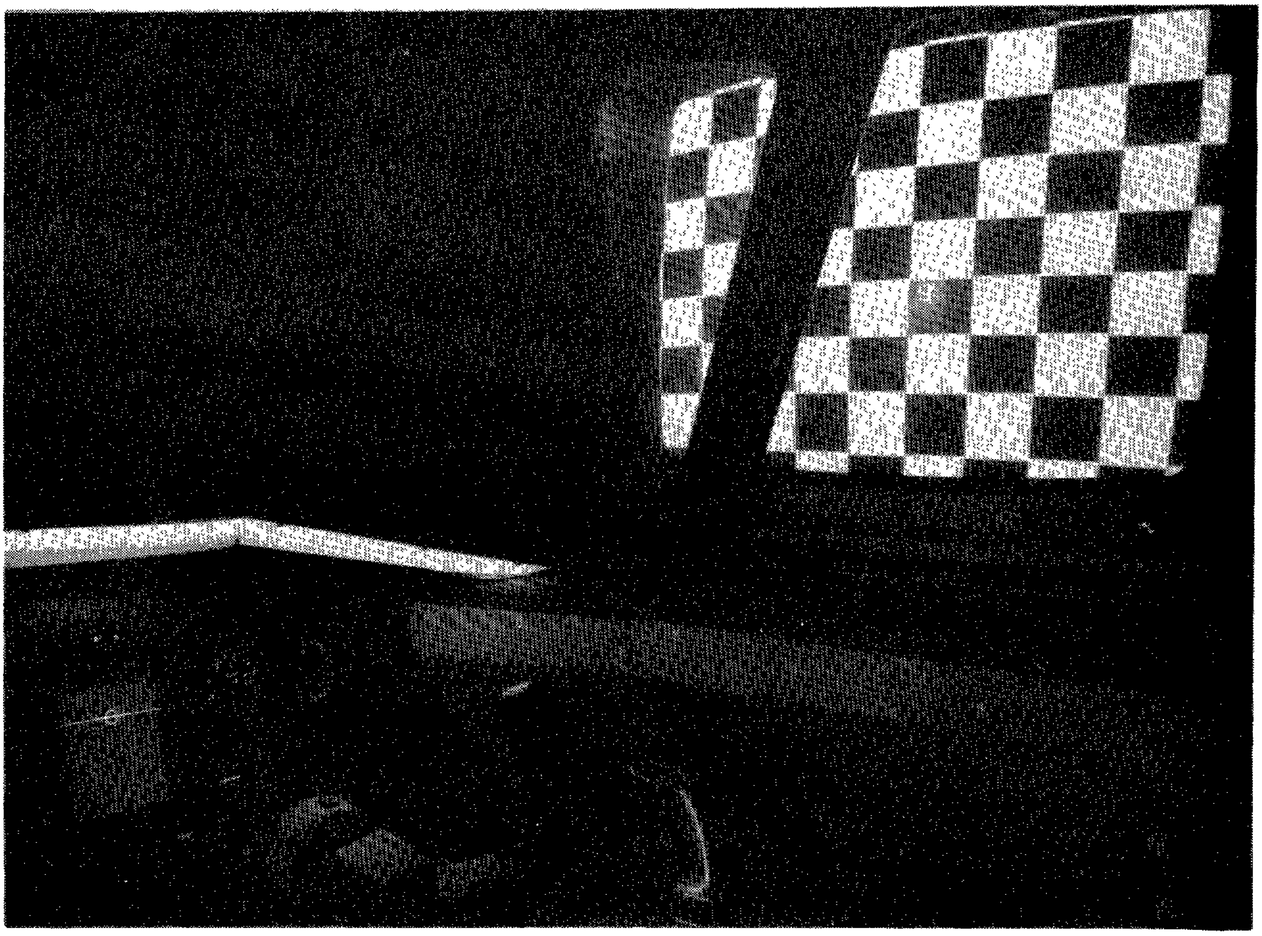


Fig. 2: Simulator cockpit with central C.R.T. display, peripheral display and side arm controller.

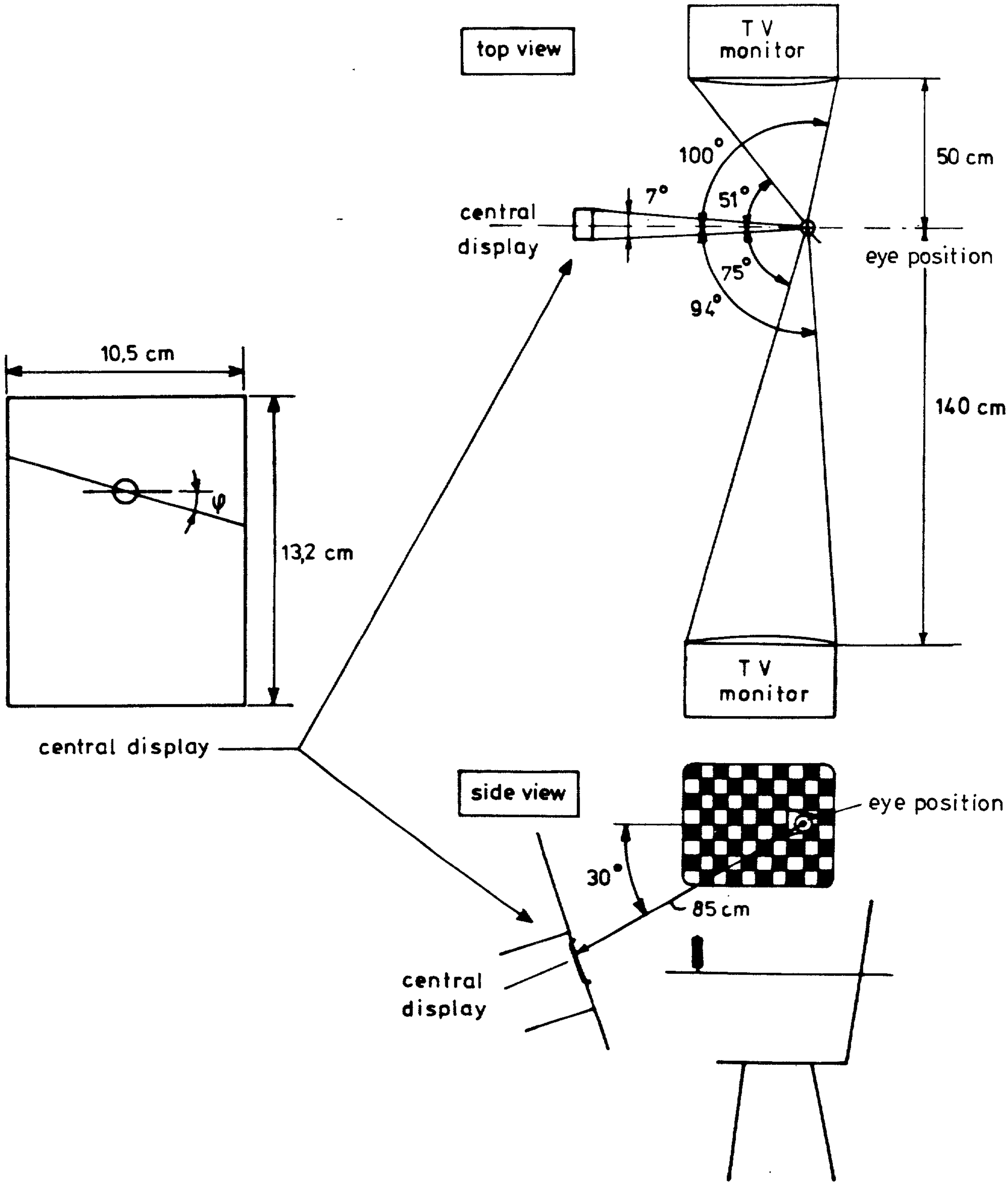
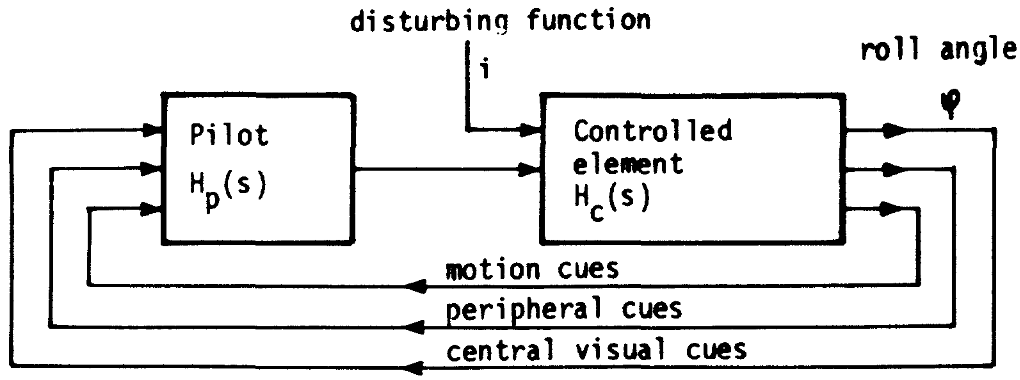
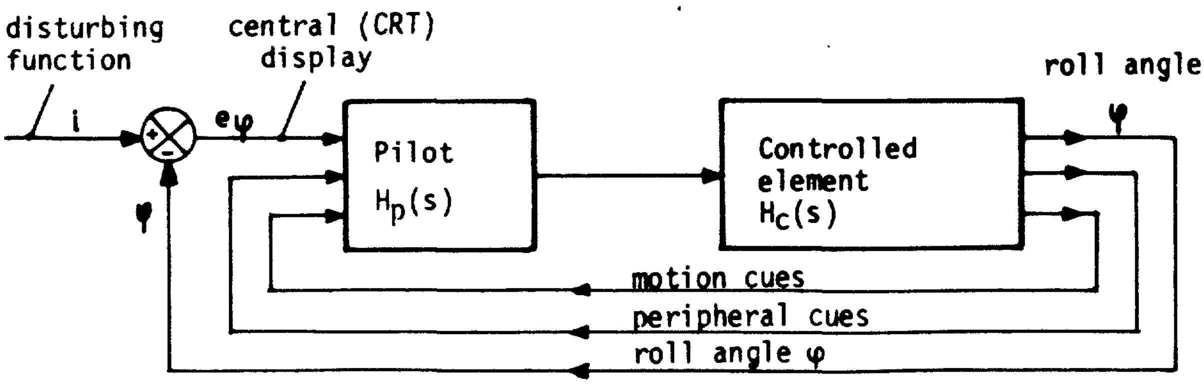



Fig. 3 . Positions of displays relative to the test subject's eye position. Central display image.




(a) Disturbance task




(b) Following task

Fig. 4: Block diagram of controller and controlled element for the disturbance task and the following task.

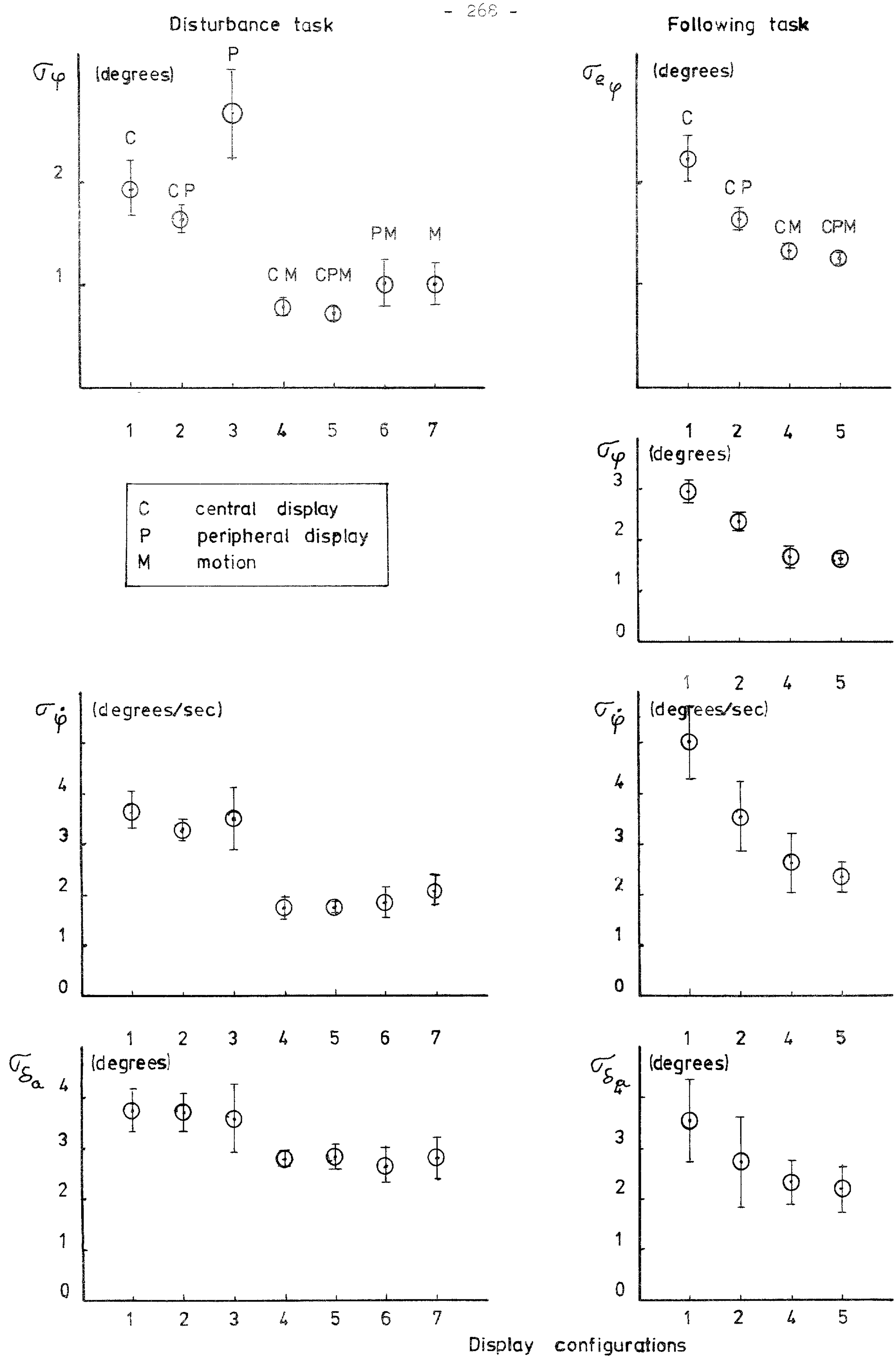



Fig. 5: Standard deviations of controlled variables and control deflections as a function of display configuration.

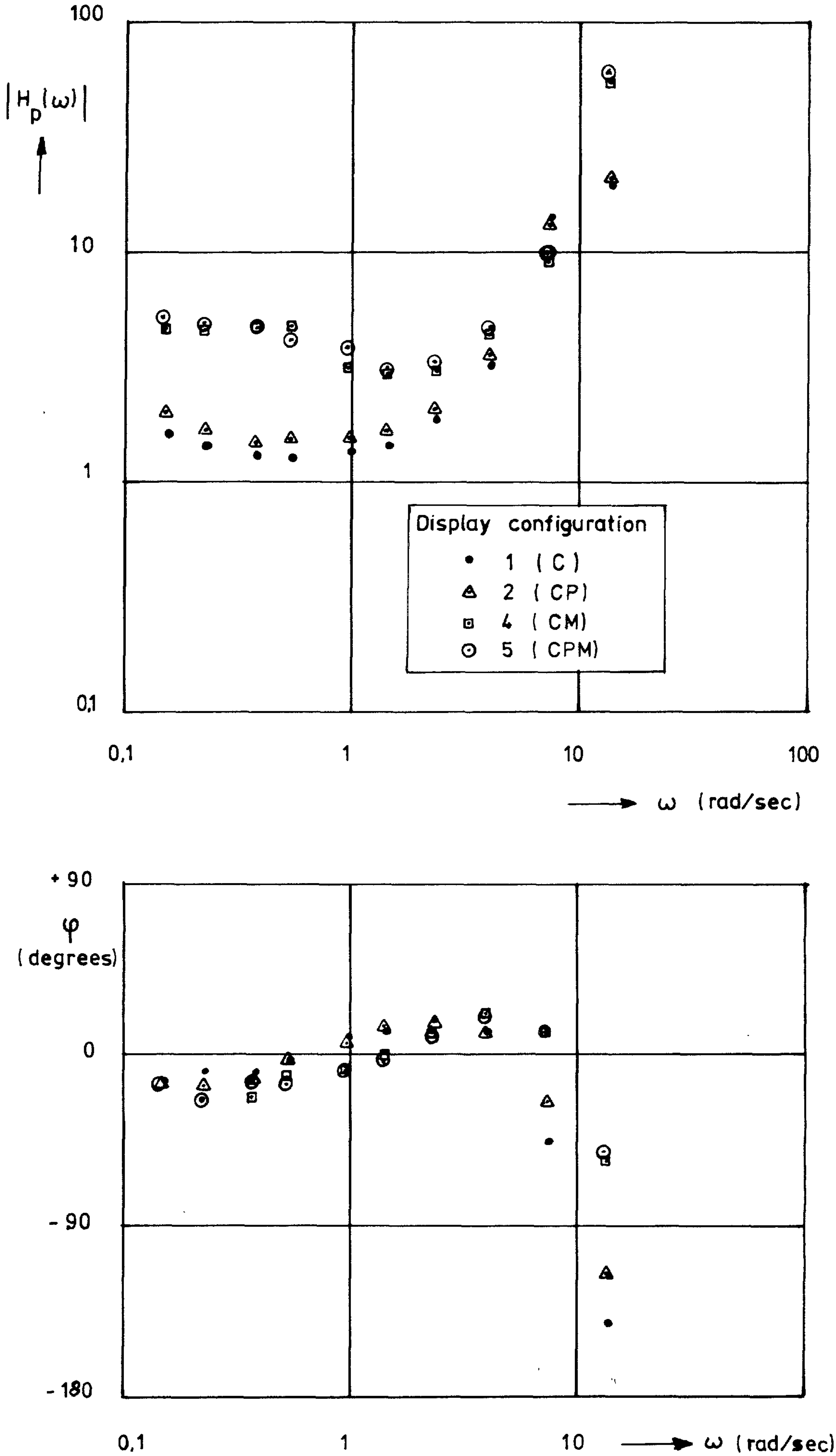



Fig. 6: Bode plots of the transfer function $H_p(\omega)$ of the test subjects in the disturbance task.
Display configurations 1, 2 , 4 and 5.

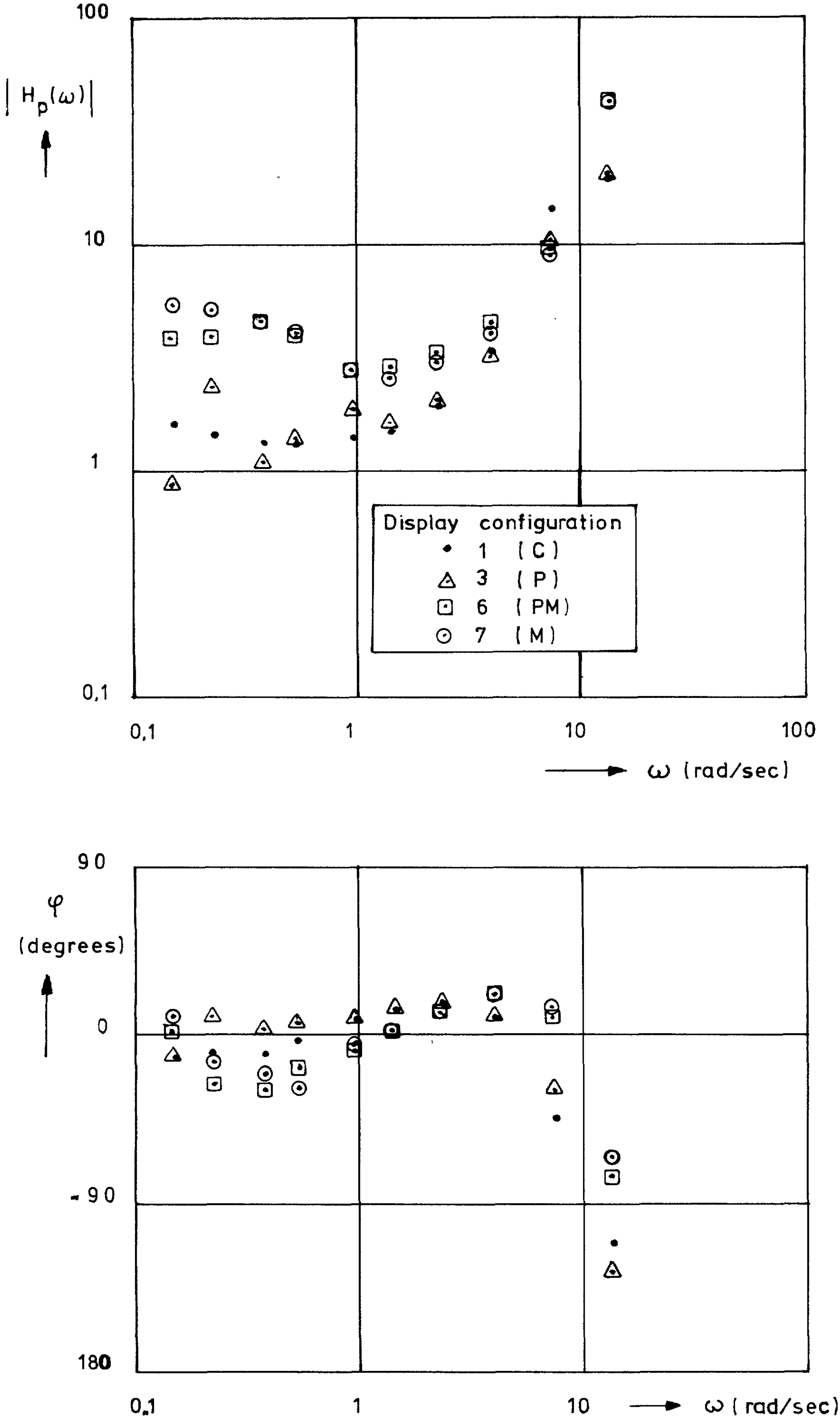



Fig. 7: Bode plots of the transfer function $H_p(\omega)$ of the test subjects in the disturbance task.
Display configurations 1, 3, 6 and 7.

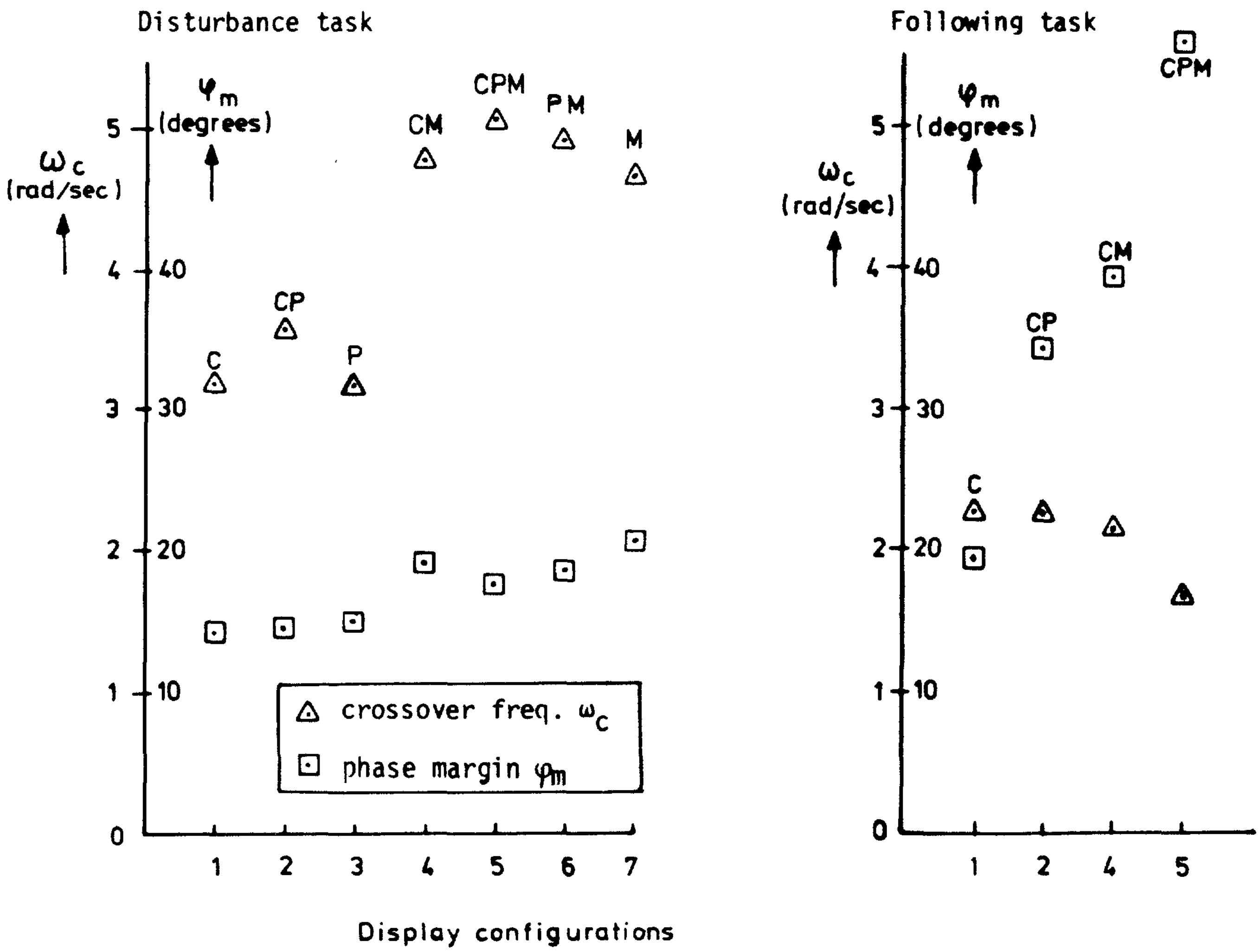



Fig. 8: Phase margins and crossover frequencies of $H_p(s).H_c(s)$ as a function of display configuration.

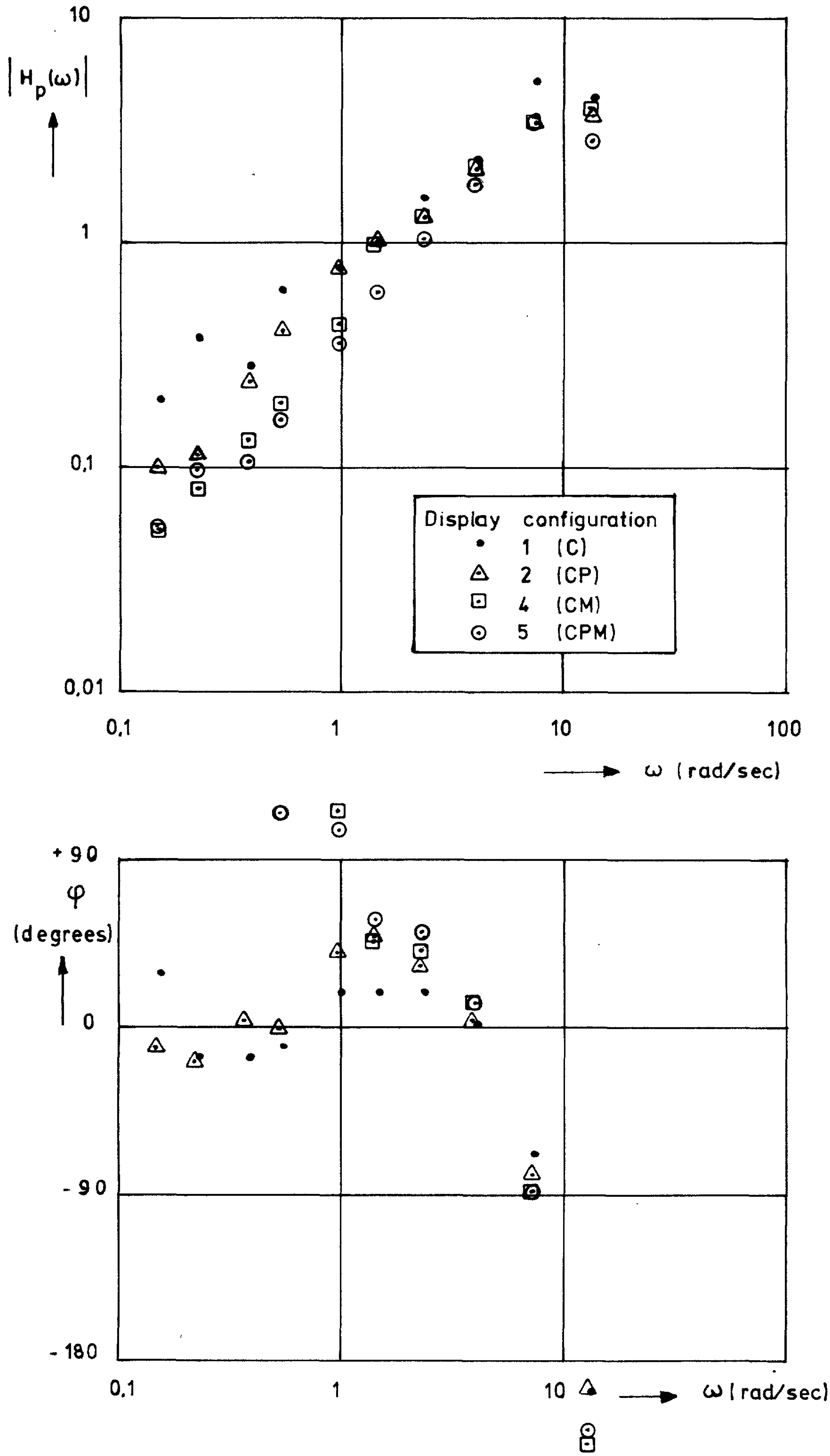



Fig. 9: Bode plots of the transfer function $H_p(\omega)$ of the test subjects in the following task.

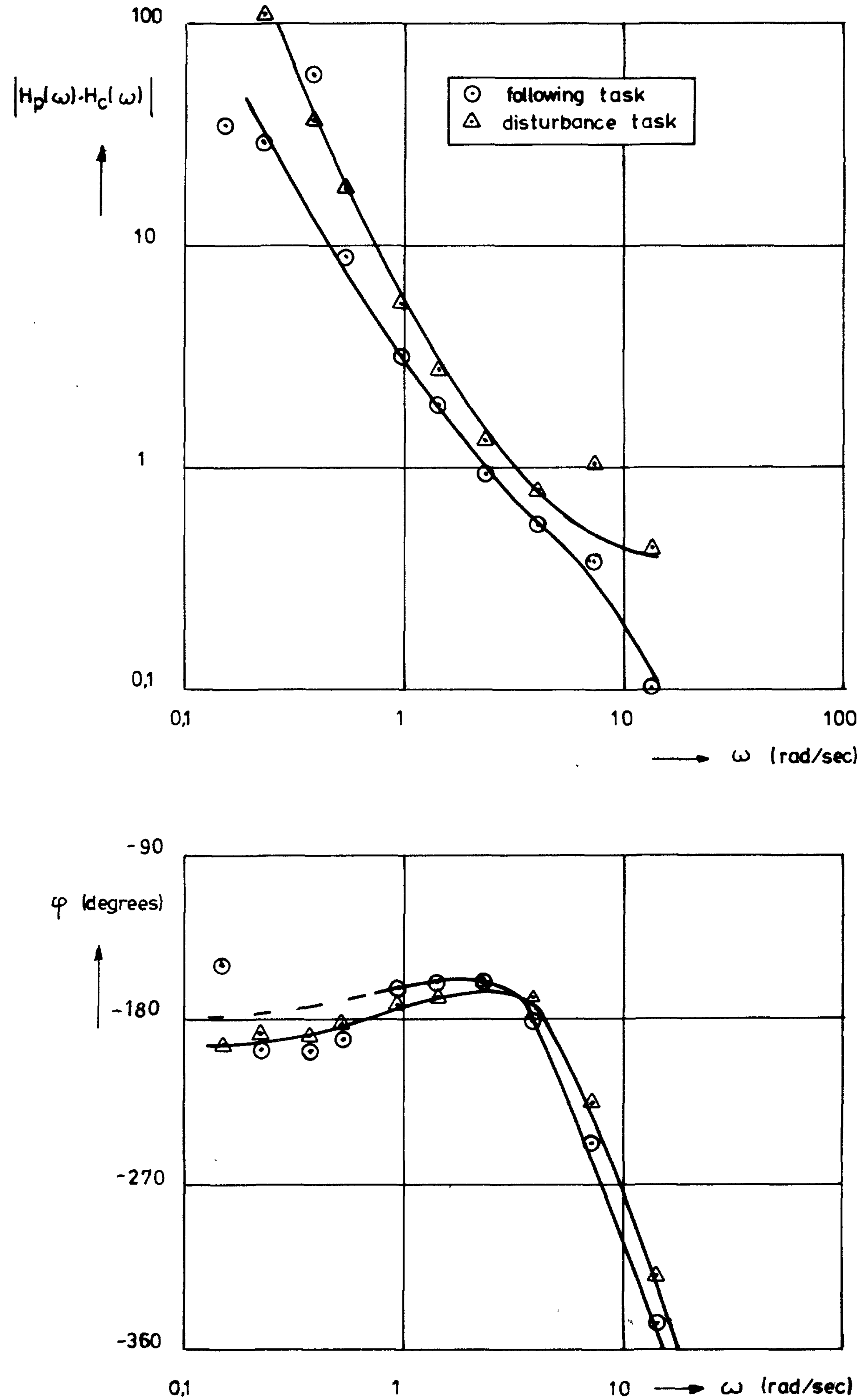



Fig. 10: Typical examples of measured transfer characteristics or controller and controlled element $H_p(\omega).H_c(\omega)$. Display configuration 1 (C).

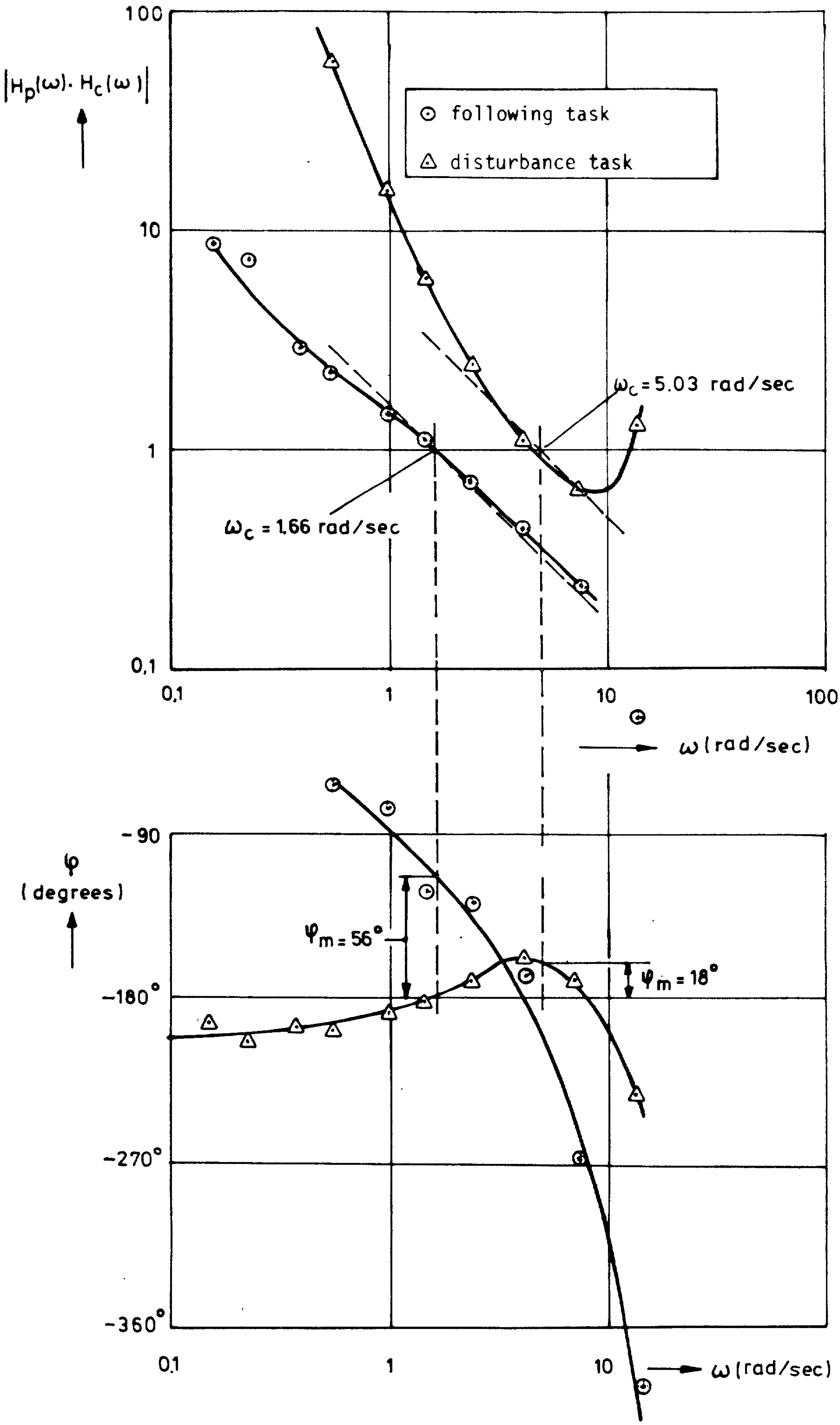



Fig. 11: Typical examples of measured transfer characteristics of controller and controlled element, $H_p(\omega).H_c(\omega)$. Display configuration 5 (CPM).