A Review of the Hosman and Van der Vaart Tracking Experiment

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One of the first large research projects on human control behavior performed at Delft University of Technology is the work of Hosman and Van der Vaart. In their tracking experiment, Hosman and Van der Vaart investigated the influence of visual and vestibular motion cues on human control behavior in a situation similar to manual control of an aircraft. In these compensatory tracking tasks, subjects were asked to follow or counteract a signal presented on a central (foveal) display. The changes in performance and control behavior were investigated for the addition of peripheral visual and vestibular motion cues.

Both disturbance and target following tasks were performed with exactly the same forcing function signal realization. This resulted in a target following and disturbance task which were both thought to be representative for manual control in actual flight, but yielded a significant difference in task difficulty between both types of task. Because of this discrepancy in task difficulty, it is unsure to what extent the differences between the two types of tracking task observed by Hosman and Van der Vaart actually result from their inherent differences, or are caused by the different levels of task difficulty.

This paper describes the results of a recent experiment, highly similar to the tracking experiment of Hosman and Van der Vaart, that was performed in the SIMONA Research Simulator at Delft University of Technology. The goal of this experiment was to measure the effect of different visual and vestibular motion cues on control behavior in compensatory target following and disturbance tasks of equal difficulty, thereby allowing for clear comparison of use of motion cues in both types of tasks. The results of this experiment indicate that the main trends in tracking performance and control behavior reported by Hosman and Van der Vaart for their target following and disturbance tasks can still be seen as representative for both types of classical compensatory tracking task.

I. Introduction

Nowadays, simulators seem to be available for nearly every possible existing system, phenomenon or product. Especially in the aerospace field, simulators have proven to be highly useful and versatile tools for a whole range of purposes. However, in recent years a heated discussion has developed regarding the effectiveness of simulators for pilot training. In some instances, the inaccuracy of the vestibular and visual motion cues generated in simulator environments was found to actually have an adverse effect on pilot control in actual flight.1

At the start of 2005 a large research project was started at Delft University of Technology (DUT) in which flight simulator fidelity would be investigated in detail.2 The main goal of this research project is “to develop a method to objectively and quantifiably assess the extent to which a flight simulator supports real-flight pilot behavior and, when discrepancies occur, to trace them back to the way the multimodal stimuli are presented in the simulator.”

DUT’s simulator fidelity research project adopts a cybernetic (control theoretic) approach to compare measured pilot control behavior during tracking tasks, both in a simulator environment and in actual flight. By varying the mechanisms for generating motion cues in the simulator environment and evaluating their influence on control behavior it is hoped that optimal rules for simulator motion cueing can be formulated.

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This approach requires a high level of knowledge on human control behavior and a large tracking experiment data base for reference.

One of the first large research projects performed on human control behavior at DUT is the work of Hosman and Van der Vaart.\textsuperscript{3,4} During the 1980s, they performed extensive research on this subject through a large number of stimulus-response and tracking experiments in the University’s (previous) simulators. The results of their research have been used as references for all later research performed in this field at DUT. Especially the methods developed by Hosman and Van der Vaart to model human motion perception and control behavior are still applied today.

In his thesis, Van der Vaart\textsuperscript{4} already points out that due to the use of exactly the same forcing function signal in the target following and disturbance tasks of their tracking experiment, two tasks of different baseline difficulty were performed. One of the goals of the Hosman and Van der Vaart was to compare the use of motion cues in both types of compensatory tracking task. It is not known to what extent the differences observed from their tracking experiment measurement data are caused by the inherent differences between target following and disturbance tasks, or by the discrepancy in basic task difficulty between both tasks. In the light of the simulator fidelity research performed at Delft University of Technology today, specifically because of the detailed understanding of human control behavior required for its approach, a review of the Hosman and Van der Vaart is found to be required.

In this paper, first a short overview of the goals and results of the Hosman and Van der Vaart tracking experiment will be given. Also, the exact reasons for reviewing and redoing the experiment will be pointed out in detail. Second, the tracking experiment that was performed in DUT’s SIMONA Research Simulator (SRS) to verify the conclusions of Hosman and Van der Vaart will be described and finally the results of this experiment will be analyzed in detail and compared to the findings of the original experiment. The goal of this paper is to indicate to what extent the conclusions drawn on human control behavior in laboratory tracking tasks by Hosman and Van der Vaart still stand today.

II. The Hosman and Van der Vaart tracking experiment

II.A. Main experimental variables

In research on human control behavior performed prior to the work of Hosman and Van der Vaart, it was found that the addition of extra peripheral visual or vestibular motion cues affected control behavior differently in tracking tasks configured as a target following task or as a disturbance task.\textsuperscript{5–7} Nearly all these experiments used different controlled elements and forcing function signals, ranging from relatively simple to extremely difficult combinations. These large differences in the setup of these tracking experiments made it hard to compare results. For this reason, Hosman and Van der Vaart devised their grand experiment, which would yield a large data base for human control behavior for a single combination of controlled system, forcing function signal and motion cue variations.

II.A.1. Compensatory target following and disturbance tasks

In their tracking experiment, Hosman and Van der Vaart wanted to investigate the use of visual and vestibular motion cues in compensatory tracking tasks. In a compensatory tracking task only the error to be compensated by the human operator is shown to him. Classically, two different types of compensatory tracking tasks are generally considered in tracking experiments: target following and disturbance tasks, whose general structures are depicted in Figure 1(a) and (b) respectively. Note that the block diagrams in Figure 1 show target following and disturbance tasks with a compensatory display only, where the human controller $H_p$ only perceives the tracking error $e$.

The target following and disturbance tasks with only a central compensatory display shown in Figure 1 are in fact equivalent: if the forcing function signals $f_t$ and $f_d$ are chosen accordingly, the error signal $e$ and therefore also the human control action will be exactly the same in both tasks. The previously measured differences between target following and disturbance tasks occurred when extra motion cues were made available. The fact that there are indeed some inherent differences between target following and disturbance tasks when extra motion cues are made available is illustrated in Figure 2.

Note that the lumped human operator response $H_p$ is split into two parts in Figure 2: a response to the compensatory error signal $e$ and an additional response to the response of the controlled system $y$ (depicted with the symbols $H_{pc}$ and $H_{py}$ respectively). As will be explained in the next section of this paper, peripheral...
visual and vestibular motion cues give access to the controlled system state \( y \). Verify from Figure 2 that in target following tasks, the inputs to the responses \( H_p e \) and \( H_p y \) are different, while for the disturbance task both are equal to the (negative) system state \( y \). This difference is also reflected in the expressions for the lumped operator response \( H_p \) that can be determined from Figure 2 for both types of task:

\[
\text{Target following : } H_p(j\omega) = \frac{U(j\omega)}{E(j\omega)} = \frac{H_{p_e}(j\omega)}{1 + H_{p_y}(j\omega)H_c(j\omega)} \\
\text{Disturbance : } H_p(j\omega) = \frac{U(j\omega)}{E(j\omega)} = H_{p_e}(j\omega) + H_{p_y}(j\omega)
\]

From their tracking experiment, Hosman and Van der Vaart measured the lumped operator frequency response \( H_p \). The inherent differences between target following and disturbance tasks illustrated by Figure 2 and Equations (1) and (2) inevitably lead to differences in measured lumped control behavior in both tasks.

II.A.2. Variation of motion cues

The ultimate goal of performing tracking experiments is to be able to draw conclusions on the behavior of human operators in actual manual control tasks, in the case of Hosman and Van der Vaart the manual control of aircraft around the roll axis. The system state \( y \) defined in the previous section therefore was in fact the roll angle \( \phi \). In this sense, Hosman and Van der Vaart hypothesized that in actual flight human pilots use motion information from three different sources to aid them in their control task:

- Perception of attitude and rate from a central (compensatory) instrument display
- Perception of rate from the peripheral visual field
- Perception of acceleration and specific force from simulator motion

For this reason, Hosman and Van der Vaart performed a tracking experiment in which the availability of these three sets of motion cues was varied. The central (foveal) visual cues were presented in the form of a
simplified artificial horizon instrument display as shown in Figure 3(a), which was displayed on a 105 x 132 mm CRT monitor. The artificial horizon image was generated on an analog computer, yielding an update rate of 250 Hz. Note that since compensatory target following and disturbance tasks were performed, the error signal $e$ was depicted on the foveal display.

(a) Central display  
(b) Peripheral display

Figure 3: The displays used for generation of central and peripheral visual motion cues in the Hosman and Van der Vaart tracking experiment: a simple artificial horizon image (a) and a moving checkerboard pattern (b) respectively.

For the generation of peripheral visual cues, Hosman and Van der Vaart used two TV-monitors displaying a checkerboard pattern (see Figure 3(b)), which were mounted outside the two simulator side windows. As shown in Figure 3(b) the checkerboard patterns spanned 9.5 x 7.5 blocks; the size of each block was 50 mm. These checkerboard patterns moved in vertical direction with a velocity equivalent to the simulated controlled system roll rate. The refresh rate of the TV-monitors was 30 Hz. The reason for using these moving checkerboard patterns to provide peripheral visual cues instead of a more realistic out-of-the-window visual scene was that such a checkerboard pattern does not provide any information on the system attitude (i.e. no “horizon”).

Vestibular motion cues were provided by the three degree-of-freedom motion base (pitch, roll and heave) of the simulator available at Delft University of Technology at the time. Note that Hosman and Van der Vaart only performed the conditions of their experiment where vestibular motion cues were provided in this moving-base simulator: all conditions without vestibular motion cues were performed in a different fixed-base simulator setup. The fact that different simulators were used was shown to not have affected the results.

II.A.3. Forcing function and controlled system dynamics

Previous experiments that investigated the influence of the addition of extra motion cues on control behavior and tracking performance used a whole range of different forcing function signals ($f_t$ and $f_d$ in Figures 1 and 2) and controlled system dynamics $H_c$. The forcing function signal and the controlled system dynamics largely define the level of tracking task difficulty and therefore have a large influence on the achievable level of tracking performance and on the control behavior that will be adopted. Differences in these experimental variables increase the difficulty in comparing results. For their forcing function signal, Hosman and Van der Vaart used a sum of ten individual sinusoids:

$$f(t) = \sum_{i=1}^{10} A_i \sin (\omega_i t + \phi_i) \quad (3)$$

The forcing function frequencies $\omega_i$ were chosen highly similar to the values used by McRuer in his classical tracking experiments, i.e. more or less evenly distributed over the range of 0.153 to 13.576 rad/s. For the amplitude distribution of their forcing function signal $A_i$, Hosman and Van der Vaart defined a first order low-pass filter, whose magnitude at a forcing function sinusoid frequency determines the amplitude of this sinusoid:

$$A_i(\omega_i) = \frac{K_f}{1 + \tau_f j\omega_i} \quad (4)$$
The values of the filter gain $K_f$ and lag constant $\tau_f$ were chosen at $1.11^\circ$ and 0.6 seconds respectively. This low-pass shape of the sinusoid amplitude distribution ensures that the higher frequency sinusoids in the forcing function signal have reduced power. Finally, for the sinusoid phases $\phi_i$ in Equation (3), one random set of phases was chosen.

This choice of forcing function parameters gave Hosman and Van der Vaart one forcing function signal, referred to as $f_0$ in this paper. This one forcing function realization was used for all tracking experiment runs and was applied as both the target following as well as the disturbance task forcing function ($f_t$ and $f_d$ in Figure 2).

The controlled system in the Hosman and Van der Vaart tracking experiment was chosen to be a second-order double integrator:

$$H_c(j\omega) = \frac{K_c}{(j\omega)^2}$$

(5)

The dynamics gain constant $K_c$ was chosen at 4 by Hosman and Van der Vaart.

II.A.4. Side stick manipulator

In the Hosman and Van der Vaart tracking experiment, subjects used a spring-centered side stick for generating their control inputs. The documented force-displacement characteristic of this manipulator is shown in Figure 4.3

![Figure 4](image)

Figure 4: Exerted force-displacement characteristic of the side stick used in the Hosman and Van der Vaart tracking experiment.

This side stick was mounted at the right pilot station of the moving base simulator where the experiment was performed.

II.A.5. Subjects and experimental procedure

Three employees of Delft University of Technology volunteered for the tracking experiment of Hosman and Van der Vaart. All three were trained jet aircraft pilots in addition to their work as University staff members. Each of these three subjects performed the complete experiment.

Each individual run of the tracking experiment lasted 104 seconds, of the first 22 were considered as run-in time. The recorded data over the last 82 seconds of each run were considered as the measurement data. As stated above, the tracking experiment of Hosman and Van der Vaart was split into two separate parts: in the first part all runs without vestibular motion cues were completed in a separate fixed-base simulator setup, the second part consisted of all runs with simulator motion. Before starting the measurement runs of the first part of their experiments, Hosman and Van der Vaart let their three subjects perform a combined total of 350 training runs. For the second part of the experiment, an additional 110 training runs were performed before starting the measurements. The final measurement data consisted of five replications of each of the experimental conditions per subject.

During each part of their tracking experiment, the experimental conditions (target following or disturbance tasks and motion cue variations) were presented in random order. Hosman and Van der Vaart considered all possible variations of the three motion cues in their tracking experiment. In this paper, only the results for the conditions with the central display only (C), added peripheral visual (CP) or vestibular motion cues (CM) and the combination of all three (CPM) are considered.
The subjects that performed the Hosman and Van der Vaart tracking experiment showed significant increases in performance level in both target following and disturbance tasks when extra peripheral and vestibular motion cues were made available. The measured Root Mean Square values of the error and control signals $e$ and $u$ shown in Figure 5 clearly indicate this.

![Figure 5: Error signal (a) and control signal (b) Root Mean Square (RMS) values measured by Hosman and Van der Vaart for their target following and disturbance tasks.](image_url)

Figure 5 clearly shows that each addition of extra motion cues was measured to improve the tracking performance expressed as the RMS of the error signal $\sigma_e$. The RMS of the control signal showed a similarly decreasing trend, indicating more precise control behavior with a lower magnitude when extra motion cues were available. From their measured performance data, Hosman and Van der Vaart concluded that the addition of peripheral visual cues showed a greater increase in performance in target following than in disturbance tasks. Compared to the peripheral visual cues, the addition of vestibular motion cues was found to result in a much greater increase in performance, especially in the disturbance tasks.

While Hosman and Van der Vaart found similar trends in tracking performance variations with the addition of extra motion cues in target following and disturbance tasks, the observed trends in the measured control behavior for both tasks differed considerably. The main bulk of the measurement data of the Hosman and Van der Vaart tracking experiment consisted of measured lumped operator frequency response function magnitudes $|H_p|$ and phases $\angle H_p$, of which an example is shown in Figure 6 for the target following tasks of the baseline condition.

The frequency responses shown in Figure 6 were obtained by averaging the frequency response of all experiment subjects. The variance bars indicate the spread of the frequency response data at each frequency prime. For their evaluation of control behavior in target following and disturbance tasks, Hosman and Van der Vaart considered the crossover frequency $\omega_c$ and phase margin $\varphi_m$ corresponding to these average lumped frequency responses. In Figure 7 these crossover frequency and phase margin data as documented in Van der Vaart’s thesis are depicted.

Figure 7 shows clear differences in the changes in $\omega_c$ and $\varphi_m$ with the addition of extra motion cues for target following and disturbance tasks. In target following tasks Hosman and Van der Vaart found a slight decrease in crossover frequency when peripheral visual and vestibular cues were made available, accompanied by a significant increase in phase margin. In disturbance tasks the crossover frequency was found to show a significant increase, whereas $\varphi_m$ remained relatively constant.

Note from Figure 7(a) that the disturbance task crossover frequencies were found to be significantly higher than for the equivalent target following tasks by Hosman and Van der Vaart, even for the condition with a central display only (C). The control strategies subjects of tracking experiments adopt for a certain task are highly dependent on the nature of this task. One of the landmark works on this subject is the work of McRuer et al., who investigated the changes in control behavior for different forcing functions and controlled dynamics. From comparison with the work of McRuer, the differences in target following and disturbance task crossover frequency and phase margin found by Hosman and Van der Vaart are thought to be a result of the different level of difficulty of both tasks.
Figure 6: Lumped operator frequency response magnitude (a) and phase (b) measured by Hosman and Van der Vaart for their target following and disturbance tasks for the condition with a central display only.

Figure 7: Crossover frequency (a) and phase margin (b) from Hosman and Van der Vaart measurement data for different sets of motion cues.
McRuer et al. evaluated manual control behavior for three different forcing function settings and for controlled system dynamics of $K_c$, $K_c/j\omega$ and $K_c/(j\omega)^2$. Forcing function difficulty was increased by increasing the bandwidth of the forcing function spectrum. The results of this experiment showed that for the combination of the most difficult controlled dynamics (double integrator) and the most difficult forcing function, subjects adopted a different control strategy than for all other experimental conditions. This change in control behavior, named crossover regression by McRuer, is characterized by a drop in unit-gain crossover frequency $\omega_c$ and a corresponding increase of the subject’s phase margin $\phi_m$.

From his tracking experiment measurement data, McRuer formulated a set of simple calculations that could predict the measured crossover frequencies and phase margins based on the forcing function bandwidth. These calculations are known as the Verbal Adjustment Rules (VAR). In Figure 7 the crossover frequency and phase margin calculated for McRuer’s easiest forcing function spectrum, referred to as “6-4” in this paper, using these VAR are shown as white diamonds. Note that the disturbance task data found by Hosman and Van der Vaart correspond reasonably well with these theoretical values, while the measured target following task crossover frequency is significantly lower and the phase margin higher. These observations clearly correspond with the phenomenon of crossover regression and their origin can be traced back to the difficulty of the target following and disturbance tasks of the Hosman and Van der Vaart tracking experiment.

II.C. Target following and disturbance task difficulty

As stated earlier in this paper, Hosman and Van der Vaart used one forcing function signal $f$ for both their target following and disturbance tasks. Note from Figure 1(b) that in the disturbance tasks, the forcing function was injected as a disturbance on the subject’s control signal, i.e. before the system dynamics $H_c$. In this disturbance task configuration the forcing function signal is filtered by the system dynamics before it is perceived by the controller in the form of the error signal $e$. Compare this to the error signal for the target following task in Figure 1(a), where the forcing function signal is transferred into $e$ directly.

The spectrum of the error signal $e$ shown on the compensatory display is a clear indication of the difficulty of a compensatory tracking task. Generally it can be said that increased high frequency power in the signal that has to be tracked yields a more difficult tracking task. For the tracking experiment of Hosman and Van der Vaart, where the goal was to investigate the effect of extra motion cues in both target following and disturbance tasks, it would have been ideal if both task types were equivalent, i.e. of the same level of difficulty. In Figure 8, the effective error signal spectra for both task types as defined in Figure 1 are shown.

Figure 8 clearly shows that the signal that was effectively controlled in the disturbance tasks of the Hosman and Van der Vaart tracking experiment had significantly reduced high-frequency power compared to the target following tasks. The difference in error signal spectra shown in Figure 8 shows that the basic

![Figure 8: Comparison of the spectra of the effective error signal $e$ that were controlled in the Hosman and Van der Vaart target following and disturbance tasks.](attachment:image.png)

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level of difficulty of the target following and disturbance tasks in this experiment was not equal. The spectra suggest that the disturbance tasks were relatively easier; this is also reflected in the tracking performance data documented by Hosman and Van der Vaart. This discrepancy in task difficulty was known to Hosman and Van der Vaart at the time they wrote their respective theses and in his thesis Van der Vaart proposed alternative experimental setups to equalize the target following and disturbance task effective error spectra.

In the previous section it was concluded that the relatively low value of the measured crossover frequency \( \omega_c \) for the target following tasks might well be caused by the occurrence of crossover regression in these tasks of the Hosman and Van der Vaart tracking experiment. In fact, a comparison of the effective error signal spectrum shown in Figure 8 for this task with the forcing function spectra used by McRuer et al.\(^{11}\) shows a high-frequency content very similar to what would result from McRuer’s most difficult forcing function. In contrast, the effective disturbance task error signal spectrum in Figure 8 is even less high-pass than McRuer’s easiest forcing function, for which the VAR data are shown.

The net result of these observations and the comparison to the work of McRuer et al. is that it is unknown to what extent the differences in tracking performance and control behavior found by Hosman and Van der Vaart between target following and disturbance tasks can in fact be attributed to their inherent differences. Part of the changes in tracking performance and control behavior could well be a result of the significantly different level of difficulty of both tasks in the Hosman and Van der Vaart tracking experiment and the different control strategies that may have been adopted because of this.

### III. Reviewing experiment

To investigate to what extent this discrepancy in baseline task difficulty has affected the conclusions on human tracking performance and control behavior drawn from the Hosman and Van der Vaart tracking experiment, a similar experiment has been performed in the SIMONA Research Simulator at Delft University of Technology. For this experiment, a lot of effort was put into making most experimental variables as equal as possible to those of the original experiment, in order to be able to validly compare the results. In the following sections the most important deviations from the tracking experiment performed by Hosman and Van der Vaart will be described and motivated.

#### III.A. Layout of control tasks

As stated earlier in this paper, in theory compensatory target following and disturbance tasks with a central display only (Figure 1) are equivalent. The key to achieving equivalent target following and disturbance tasks of equal difficulty is to ensure equal spectra of the error signal \( e \) in both tasks. For this Van der Vaart indicates two options, which would result in two tracking tasks at the difficulty level of either the Hosman and Van der Vaart target following or disturbance tasks.

Analysis of these two options proposed by Van der Vaart showed that the first would result in a target following task forcing function amplitude distribution equal to the disturbance task effective error spectrum shown in Figure 8. The use of this amplitude distribution for would imply excursions of extremely high magnitude (see the lowest frequency amplitudes in Figure 8) would have to be followed, which means that for conditions with simulator motion the motion system would actually have to achieve these extreme attitudes.

The second option results in a disturbance task which is much more high-pass than the one performed by Hosman and Van der Vaart. This greatly increases the accelerations that would have to be produced by the simulator motion system for conditions with vestibular motion cues, but these proved to remain well within the limits of the SIMONA motion base. Therefore it was decided to perform exactly the same target following and disturbance task structures as those of the original experiment, combined with a modified or pre-filtered disturbance task. The resulting target following and disturbance task structures are shown in Figure 9(b).

In the experiment, the pre-filtered disturbance task structure depicted in Figure 9 was in fact implemented by adapting the amplitude distribution of the forcing function signal \( f_d \). For compensation with the inverse of the system dynamics, as shown in Figure 9, the pre-filtered amplitude corresponding to a sinusoid with frequency \( \omega_i \) can be calculated from the corresponding target following amplitude \( A_{f_t}(\omega_i) \) as follows:

\[
A_{f_d}(\omega_i) = \left| \frac{1}{H_c(\omega_i)} \right| A_{f_t}(\omega_i) = \frac{\omega_i^2}{K_c} A_{f_t}(\omega_i)
\]  

(6)

This modification of the individual sinusoid amplitudes in the disturbance task forcing function signal
ensures equal error spectra and therefore equal baseline difficulty in the target following and disturbance tasks.

### III.B. Forcing functions

To ensure results of the review experiment could be validly compared to the experiment of Hosman and Van der Vaart, exactly the same forcing function signal would have to be used. However, because of the hypothesis that the subjects adopted “normal” control behavior in the disturbance task runs of the Hosman and Van der Vaart experiment, while they displayed crossover regression for the target following task, it was decided to also attempt to measure both these control strategies in the experiment in the SIMONA Research Simulator (now for tasks of equal difficulty). To achieve this, it was decided that the complete experiment would be performed with two forcing function signals. The only difference between these two was in the distribution of their sinusoid amplitudes $A_f$, which can be verified from Figure 10.

![Figure 10: The amplitude distribution of both experiment forcing function signals: the spectrum selected by Hosman and Van der Vaart for their forcing function $f$ and a block-shaped McRuer 6-4 spectrum scaled to the same time history RMS. Note the decreased high frequency content for this second forcing function signal.](image)

The amplitude distribution shown in white circles in Figure 10 depicts the first-order low-pass filter used by Hosman and Van der Vaart for the calculation of their forcing function amplitudes (Equation (4)). The second, indicated with black triangles, indicates a block-shaped amplitude distribution like those used by McRuer. In fact, McRuer’s easiest (6-4) spectrum was selected, because in McRuer’s experiments subjects did not show crossover regression for this forcing function in combination with double integrator dynamics. This second experiment forcing function will be referred to as $f_{6-4}$ in the remainder of this paper.
III.C. Simulator environment and motion cue variations

In their tracking experiment, Hosman and Van der Vaart used TV-monitors for displaying the peripheral checkerboard patterns. In both simulator setups used in their experiment, these monitors were mounted at some distance to the left and right of the pilot station. The reviewing experiment was performed in the SIMONA Research Simulator, Delft University of Technology’s high-fidelity six degree-of-freedom simulator, shown in Figure 11(a).

![Figure 11(a)](image)

Figure 11: The six degree-of-freedom SIMONA Research Simulator (a) and a view of the right pilot station during the replication of the Hosman and Van der Vaart tracking experiment in this simulator (b), showing the checkerboard pattern projected on the outside visual system.

Instead of using TV-monitors to generate the peripheral visual cues in the SRS, it was decided to project moving checkerboard patterns on SIMONA’s outside visual display system. In Figure 11(b) a view of the right pilot station, showing the right-hand side checkerboard pattern, is depicted. For these projected checkerboard patterns it was ensured that their positions in the subjects’ fields of view when seated at the right pilot station were approximately equal to the those of the TV-monitors in the Hosman and Van der Vaart experiment. The update rate of the checkerboard pattern was 60 Hz; the time delay of the generation of the outside visual scene (including the projection) was measured to be in the order of 25-30 ms using a newly developed visual delay measurement system.12

Figure 11(b) also shows the compensatory artificial horizon image, shown on a LCD monitor that is used as a Primary Flight Display (PFD) in SIMONA. The update rate of the PFD was 60 Hz and the time delay associated with the central artificial horizon display was determined to be in the order of 20-25 ms.

Finally, Figure 11(b) also shows the electronic side stick that is mounted at the right pilot station of the SIMONA Research Simulator. For the experiment described here, this side stick was calibrated to have exactly the same force-displacement characteristic as documented for the Hosman and Van der Vaart tracking experiment (Figure 4).

For generating the roll-axis vestibular motion cues, SIMONA’s six degree-of-freedom motion system was used. In the simulator used by Hosman and Van der Vaart for their tracking experiment, the roll axis was located slightly closer to the right pilot station than is the case in SIMONA (70 mm horizontally; 87.5 mm vertically). In order to generate pilot head accelerations that were as similar as possible to the original experiment, extra heave and sway motion was implemented to effectively move SIMONA’s roll axis to the desired position. The delay of motion cues generated with the motion system of the SIMONA Research Simulator has been determined at around 30 ms.13

III.D. Experimental measurement conditions and dependent variables

Reviewing the Hosman and Van der Vaart tracking experiment with two forcing function signals yielded an experiment of considerable size in terms of the number of experimental measurement conditions. In total there were sixteen:

- Two forcing function signals: Hosman and Van der Vaart \((f)\) and McRuer 6-4 \((f_{6-4})\) spectra
- Two types of tracking task: target following and (pre-filtered) disturbance
• Four motion cue variations: conditions C, CP, CM and CPM

For comparison with the experimental results of Hosman and Van der Vaart it was decided to use the same dependent measures to evaluate tracking performance and control behavior for this experiment. In this paper the RMS of the error and control signals will be used as a measure of tracking performance. For evaluating control behavior, the crossover frequencies and phase margins of the measured lumped operator responses were selected as depend measures. The values of these dependent measures found for the tasks of the condition with a central display only (C) are used as the baseline.

III.E. Subjects and experimental procedure

Hosman and Van der Vaart had three subjects perform their tracking experiment. All three were University employees and trained jet aircraft pilots. For the current experiment five subjects were selected. The level of experience in performing manual control tasks among these five subjects was not as homogeneous as in the original experiment: experience ranged from pilot-equivalent to none at all. The reason for not using actual pilots as tracking experiment subjects lies in tight scheduling of the available simulator time for completing this experiment.

In contrast with the experiment of Hosman and Van der Vaart, the experimental conditions with and without vestibular motion cues were not performed separately. The experiment however did consist of two separate parts, since it was decided best that each subject would finish the experiment with the Hosman and Van der Vaart forcing function before redoing it with the second forcing function signal.

Experimental conditions were gathered in sets of eight runs (target following/disturbance tasks and four motion cue variations for each). Within each set of eight runs the order of presentation was random. For each of the two forcing functions, each subject performed each condition around 8 to 10 times. From evaluation of the measured performance it was found that the performance had stabilized enough to use the final five sets of all eight conditions performed by each subject as the measurement data (five replications per subject).

IV. Results and Discussion

In this section the results of the experiment in the SIMONA Research Simulator will be described and compared to the measurements of Hosman and Van der Vaart. First the measured performance and control behavior in the target following and pre-filtered disturbance tasks performed with the same forcing function signal as used by Hosman and Van der Vaart will be evaluated. Then, these results will be compared to the measurement data from the second half of the experiment, where a less high-pass forcing function signal was used. Finally, some general trends in target following and disturbance task performance and control behavior will be summarized.

IV.A. Pilot performance and control activity in tracking tasks of equal difficulty

In Figure 5 the measured target following and disturbance task error and control signal RMS found by Hosman and Van der Vaart are depicted. In Figure 12, the measured values of the same two parameters for the target following and pre-filtered disturbance tasks performed in the SRS are depicted.

First of all, note that the target following task error signal RMS data shown as white circles in Figure 12(a) are very close to the values found by Hosman and Van der Vaart for this exact same task. Also note that the measured performance for the target following and disturbance tasks of the baseline condition with a central display only (C) show very little difference. Statistically this slight difference is found to be insignificant ($p = 0.2526$), illustrating that the desired equivalence of basic task difficulty was achieved.

Finally, from comparison with Figure 5 it can be concluded that the trends in error RMS shown in Figure 12(a) are highly similar to those found by Hosman and Van der Vaart for both types of tracking task. The minor influence of peripheral visual cues compared to the addition of vestibular motion is clearly observable. Also the reduced increase in disturbance task performance compared to the target following task data when peripheral cues are added is reflected by the SIMONA measurement data.

The error signal RMS data shown in Figure 12(a) have been obtained by averaging over the five replications performed by each subject as well as the five individual subjects themselves. This implies each data point in Figure 12 indicates the average of 25 measurement values (compared to 15 for the Hosman and
Figure 12: Measured target following and pre-filtered disturbance task error signal (a) and control signal RMS (b). The values measured by Hosman and Van der Vaart for the same target following task are depicted with gray rectangles for reference.

Van der Vaart data). For the error signal RMS, it is clear that a slightly higher spread is present in the measurement data compared to Hosman and Van der Vaart.

Figure 12(b) clearly shows a significantly higher spread in the measurement data for the control signal RMS. Evaluation of the performance data for each of the individual subjects showed that these differences can be attributed to the relative inhomogeneity of the subject pool: the less experienced subjects showed control with a significantly increased magnitude compared to those with more manual control experience.

In Table 1(a) the results of an Analysis of Variance (ANOVA) performed on the target following task data shown in Figure 12 are summarized. The fixed ANOVA factors were chosen to be the availability of peripheral visual and vestibular motion cues ("P" and "M" respectively). The differences between individual subjects were modeled with the random influence “subject”.

Table 1: Two-way ANOVA results for target following (a) and pre-filtered disturbance task (a) tracking performance data.

<table>
<thead>
<tr>
<th>(a) Target following</th>
<th>Source</th>
<th>$\sigma_e$</th>
<th>$\sigma_u$</th>
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<tr>
<td>P</td>
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<td>M</td>
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<td></td>
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<tr>
<td>subject</td>
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<tr>
<td>P*M</td>
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<td>P*subject</td>
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<td>M*subject</td>
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</table>

<table>
<thead>
<tr>
<th>(b) Pre-filtered disturbance</th>
<th>Source</th>
<th>$\sigma_e$</th>
<th>$\sigma_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
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<tr>
<td>M</td>
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<td>subject</td>
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<td>P*M</td>
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<tr>
<td>P*subject</td>
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<tr>
<td>M*subject</td>
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<td>**</td>
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</tbody>
</table>

** = significant ($p < 0.01$)
* = significant ($0.01 < p < 0.05$)
- = not significant

As is clear from Table 1(a) both the addition of peripheral and vestibular motion cues has a significant effect on both $\sigma_e$ and $\sigma_u$. As expected from the observed inter-subject differences in performance and control strategy, also the measured differences between subjects are found to be significant.

The fact that the interaction P*M is also found to be significant for the target following task error RMS data is caused by the fact that when peripheral cues are added to the condition where vestibular cues are already present (from CM to CPM), the observed change in $\sigma_e$ is much lower than when peripheral cues are added to the baseline condition (from C to CP). This fact can be observed clearly from Figure 12(a).
In addition, also one of the interactions with the “subject” influence shows some significant effect on the control RMS $\sigma_u$. This indicates that in fact there were significant differences between subjects in the changes caused by the addition of simulator motion. From analysis of the individual subject performance data it was found that indeed the changes in control signal RMS for the addition of vestibular motion cues were not all of the same magnitude for the five subjects; the observed trends in the performance data however were all found to be highly similar.

The performance data shown in Figure 12 do not seem to show very large differences with the target following and disturbance task performance data of Hosman and Van der Vaart (Figure 5), except for the disturbance task control signal RMS. Where Hosman and Van der Vaart found a decreasing trend in disturbance task $\sigma_u$ with the addition of extra motion cues, Figure 12(a) clearly shows an increase for the pre-filtered disturbance task performed in SIMONA.

Compared to the Hosman and Van der Vaart disturbance task, the pre-filtered task performed in the SRS was much more high-pass, resulting in more violent simulator motion. The subjects that performed this disturbance task reported they actually had difficulty keeping their gaze focused on the instrument display at times because of the relatively large accelerations on their heads caused by the simulator motion. In addition to the movement of their heads, some subjects also reported really bracing themselves, and specifically their arm holding the side stick, when performing these disturbance tasks with vestibular motion cues.

### IV.B. Measured trends in pilot control behavior

In Figure 6 the lumped frequency responses measured by Hosman and Van der Vaart for their target following and disturbance tasks for the baseline condition are depicted. In Figure 13 the average lumped frequency responses measured for the equivalent target following and disturbance tasks in the SRS are shown and compared to the target following task data from the Hosman and Van der Vaart tracking experiment, shown in gray. Sample standard deviations are again indicated with variance bars.

From a comparison of Figures 13(a) and 13(b) it is clear that the measured baseline target following and disturbance task frequency responses are almost equal. Note that the low-frequency magnitude behavior found by Hosman and Van der Vaart for their disturbance task is not visible in Figure 13(b).

In addition to the differences in the measured frequency response for target following and disturbance tasks, Hosman and Van der Vaart also found opposite trends in the measured crossover frequencies and phase margins for both tasks (see Figure 7). In Figure 14 their average values for $\omega_c$ and $\varphi_m$ are compared with those determined for the target following and disturbance tasks performed in the SIMONA Research Simulator.

First of all note that for the baseline condition (C), the measured target following and disturbance task crossover frequencies and phase margins are nearly equal (compare with the difference for the Hosman and Van der Vaart data). Again the differences in the measured values for $\omega_c$ and $\varphi_m$ for the condition with a central display only are not statistically significant ($p = 0.1503$ and 0.7027 respectively).

Figure 14 shows that the discrepancy in task difficulty in the Hosman and Van der Vaart tracking experiment did not really affect their observed trends in crossover frequency and phase margin. As can be verified from Figure 14, the progression of $\omega_c$ and $\varphi_m$ with added motion cues is very similar for both sets of disturbance task data. Addition of vestibular motion cues results in a significant increase in crossover frequency, while the phase margin remains almost constant. The results of an ANOVA shown in Table 2 show that the slight variations in the disturbance task values of $\varphi_m$ are in fact not statistically significant, as was also found by Hosman and Van der Vaart.

Also note from Table 2 that both the changes in crossover frequency for both types of task and the increase in target following task $\varphi_m$ for addition of vestibular motion cues are statistically significant.

### IV.C. The effects of forcing function bandwidth reduction

The results of the first half of the reviewing experiment, performed with the Hosman and Van der Vaart forcing function $f$, showed results that are highly similar to those documented by Hosman and Van der Vaart. For the second half of the experiment, where the forcing function signal high-frequency power was reduced, significantly higher tracking performance was measured as can be observed from comparing Figures 12 and 15.

As is clear from Figure 15(a), the baseline magnitude of the tracking errors measured for both target following and disturbance tasks was significantly reduced for the tasks performed with $f_{0.4}$. An unexpected
Figure 13: Average measured target following (a) and disturbance task (b) frequency response functions for the baseline condition with a central display only (C). The frequency response measured by Hosman and Van der Vaart for the same target following task is shown in gray.

Figure 14: Average measured crossover frequencies (a) and phase margins (b) for the target following and pre-filtered disturbance tasks performed with the Hosman and Van der Vaart forcing function. Hosman and Van der Vaart target following and disturbance task data are depicted with gray and black rectangles for reference.
Table 2: 2-Way ANOVA results for target following (a) and disturbance task (b) values of $\omega_c$ and $\varphi_m$.

(a) Target following

<table>
<thead>
<tr>
<th>Source</th>
<th>$\omega_c$</th>
<th>$\varphi_m$</th>
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<td>P</td>
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<td>P*subject</td>
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<td>M*subject</td>
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</table>

(b) Pre-filtered disturbance

<table>
<thead>
<tr>
<th>Source</th>
<th>$\omega_c$</th>
<th>$\varphi_m$</th>
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</table>

** = significant ($p < 0.01$)
* = significant ($0.01 < p < 0.05$)
- = not significant

Figure 15: Measured tracking performance in terms of error signal (a) and control signal RMS (b) for target following and disturbance tasks performed with the McRuer 6-4 forcing function signal $f_{6-4}$. 
result was that the disturbance task error signal RMS for conditions with vestibular motion cues was found to be significantly lower than for the equivalent target following tasks. Note from Figure 12 that this difference in performance was not found for the tasks performed with the Hosman and Van der Vaart forcing function.

The control signal RMS $\sigma_u$ follows trends highly similar to those measured in the first part of the experiment. Again the large spread in the data is caused by the large differences in control magnitude between the five tracking experiment subjects. Note a slightly reduced increase in control RMS for the reduced forcing function bandwidth disturbance tasks compared to Figure 12(b). The statistical significance of the performance data in Figure 15 was found to highly similar to what is documented for the Hosman and Van der Vaart forcing function performance data in Table 1.

Lumped operator response crossover frequencies and phase margins have also been calculated for target following and disturbance tasks performed with $f_{6-4}$. These are depicted in Figure 16.

![Figure 16: Average measured crossover frequencies (a) and phase margins (b) for target following tasks performed with a forcing function with reduced high-frequency power compared to Hosman and Van der Vaart.](image)

Note from comparison with Figure 14(a) that the trends in the crossover frequency of the lumped response $H_p$ are found to be highly similar for both forcing functions. Note however that the baseline value of $\omega_c$ is higher compared to what was found for the more high-pass forcing function $f$, as would be expected for an easier task.

For the measured phase margin data in Figure 16(b) the observed trends are also similar. Note however that the target following task phase margin shows a significantly reduced increase with the addition of vestibular motion cues compared to what was found in Figure 14(a).

In Figure 16 again the crossover frequency and phase margin that result from application of McRuer’s Verbal Adjustment Rules to his easiest (6-4) forcing function bandwidth are depicted. Note that the experimental data measured with $f_{6-4}$, which in theory should yield results similar to those found with the VAR, are slightly off: the measured crossover frequencies are lower and the phase margins slightly higher, indicating a relatively more difficult task. This increased difficulty is thought to lie in the combination of the forcing function amplitude and the presentation of the error signal on compensatory display. During experimental runs with $f_{6-4}$, which has a maximum amplitude around 5°, the errors shown on the artificial horizon image were found to be very small (see Figure 15(a)) and therefore difficult to perceive.

In this section it was shown that performing the experiment with a forcing function signal of comparatively lower bandwidth resulted in highly similar trends in measured tracking performance and control behavior. Only a reduced decrease in error RMS $\sigma_e$ and reduced increase in phase margin $\varphi_m$ were observed for the target following tasks performed with $f_{6-4}$.

IV.D. Influence of extra cues on target following and disturbance task control behavior

The measured crossover frequencies and phase margins for the target following and disturbance tasks evaluated in this paper clearly show opposite trends of development for the addition of motion cues. This can be observed even more clearly when depicting phase margin as a function of crossover frequency, as is done for the Hosman and Van der Vaart tasks in Figure 17.
Figure 17: Lumped operator response phase margin as a function of crossover frequency for the target following and disturbance task measurement data documented by Hosman and Van der Vaart.

Note that the target following task curve clearly progresses to the top-left of Figure 17, while the corresponding disturbance task data points move almost straight to the right, to the higher crossover frequencies. In Figure 18, also the measured data for both forcing function signals obtained for the target following and disturbance tasks performed in SIMONA are depicted in the same manner.

From Figure 18 it is clear that the relative difficulty of disturbance tasks appears to have little effect on the observed changes in control behavior. For decreasing forcing function bandwidth ($f$ to $f_{6-4}$ to the Hosman and Van der Vaart disturbance task data), the baseline crossover frequency is increased and the corresponding phase margin decreased significantly. The addition of vestibular motion cues is seen to cause changes of similar magnitude in $\omega_c$ and $\phi_m$ for all three disturbance tasks.

For the three sets of target following task data shown in Figure 18, the same influence of baseline difficulty level can be observed. Since the Hosman and Van der Vaart target following task was replicated exactly, only two distinctly different target following task difficulties have been considered, but the increasing trend in $\omega_c$ and decreasing trend in $\phi_m$ is also visible here. Figure 18 also clearly shows the reduced effect of vestibular motion cues in the target following task with the forcing function with the reduced high-frequency content...
In disturbance tasks central visual, peripheral visual and vestibular motion cues all give the same information: the system response \( y \). The fact that the addition of extra cues to the baseline condition with a central display only leads to a measured increase in crossover frequency in combination with a nearly constant phase margin indicates that the enhanced perception of the state \( y \) (and especially its rate) through these extra cues appears to allow for control with a higher gain without loss of stability. Why a similar reasoning does not seem to apply to the target following task data may perhaps be explained by evaluating the slightly modified target following task structure shown in Figure 19.

![Figure 19: Modified target following task structure, which indicates how the response to the system state \( H_{ps} \) may allow for an effective reduction of the order of the system dynamics \( H_c \) by forming an inner-loop.](image)

The only difference with Figure 2(a) is how the response to the system state \( y \) is depicted. The target following task structure of Figure 19 indicates that the peripheral visual and vestibular motion cues in target following tasks may be used to form an inner stabilizing loop, effectively simplifying the dynamics of the controlled system \( H_c \). Subjects performing target following tasks with vestibular motion cues in SIMONA stated that for these specific tasks they felt they were making conscious use of the vestibular motion for deciding on when to start decelerating the system moving in a certain direction, which is in line with the target following task representation of Figure 19. This hypothesis of use of motion cues in target following tasks has also been used by Hosman and Van der Vaart and in later research to explain these changes in target following task control behavior.\(^3, 14, 15\)

Using simple models of the operator responses to the error signal \( H_{pe} \) and system state \( H_{py} \), the exact same trends in the crossover frequency and phase margin of the lumped target following task operator response \( H_p \) can be easily reproduced. For the response to the error signal \( e \), generally a model that includes both proportional and rate control is supposed:\(^3, 4\)

\[
H_{pe}(j\omega) = K_{pe}(1 + T_L j\omega)e^{-j\omega \tau_e} \tag{7}
\]

Realistic parameter values, taken from Van der Vaart’s thesis,\(^4\) will be used for this example: \( K_{pe} = 0.07 \), \( T_L = 5 \text{ s} \) and \( \tau_e = 0.35 \text{ s} \). It is generally supposed that the use of peripheral visual and vestibular motion cues lies in the fact that they may be used for estimating the system rate. This would suggest that the response to the system state \( H_{ps} \) can be modeled as a simple differentiator.\(^3\) This gives the following simple model:

\[
H_{ps}(j\omega) = K_{ps} j\omega \tag{8}
\]

Equations (7) and (8) can be combined with Equation (1) to calculate the corresponding lumped operator response \( H_p \). For three settings of the gain \( K_{ps} \), the resulting lumped frequency responses and corresponding crossover frequencies and phase margins are shown in Figure 20 and Table 3 respectively.

\[
\begin{array}{c|c|c|c}
K_{ps} [-] & \omega_c \text{ [rad/s]} & \phi_m \text{ [°]} \\
0.0 & 1.41 & 49.5 \\
0.1 & 1.36 & 66.9 \\
0.2 & 1.17 & 87.7 \\
\end{array}
\]

Table 3: Lumped model crossover frequency and phase margin variations with the gain \( K_{ps} \).

Note that the trends in lumped response crossover frequency and phase margin are highly similar to those observed in the target following task measurement data (Figures 14 and 16) and are only caused by variations in the inner-loop gain \( K_{ps} \).
The fact that the measured increase in target following task phase margin and resulting performance for the forcing function with reduced bandwidth was found to significantly lower than for the Hosman and Van der Vaart forcing function may perhaps also be explained with the hypothesis of this inner-loop. The reduced high-frequency content in the forcing function signal resulted in significantly reduced and less high-frequency simulator movement. This lower system rate would have rendered a less effective inner-loop and an effectively lower value of $K_{py}$.

V. Conclusions and Recommendations

Summarizing, it can be stated that the trends in target following and disturbance task tracking performance and control behavior with variations of available motion cues as reported by Hosman and Van der Vaart still largely stand today. The results of the experiment performed in the SIMONA Research Simulator indicate that even the large discrepancy in baseline difficulty of both types of tasks in the Hosman and Van der Vaart tracking experiment has not resulted in invalidation of the main trends they have reported:

- For both types of tracking task, the addition of peripheral visual and vestibular motion cues yields an increase in tracking performance in terms of the error signal RMS.

- The positive effects of peripheral visual cues are larger in target following than in disturbance tasks.

- Addition of peripheral visual cues when vestibular motion cues are already provided yields only a very slight increase in performance.

- In disturbance tasks, the addition of extra motion cues allows for an increase in operator crossover frequency $\omega_c$, while the phase margin is found to remain constant. This suggests that the extra motion cues allow for more higher gain control without loss of stability.

- In target following tasks the addition of extra motion cues results in a slight reduction in the crossover frequency of the lumped response and a significant increase in phase margin. These effects are consistent with an increase in the gain of the rate perception path provided by peripheral visual and vestibular motion cues in these tasks.

The only real deviation from the results of Hosman and Van der Vaart is found in the disturbance task control signal RMS. Hosman and Van der Vaart found that the control magnitudes decreased in their disturbance task when vestibular motion cues were available. Both the pre-filtered disturbance tasks performed in
SIMONA show an increase. This variation in $\sigma_u$ is found to be dependent on the forcing function bandwidth, as a reduced increase was found with the McRuer 6-4 forcing function.

In addition, some extra conclusions on the effect of visual and vestibular motion cues in target following and disturbance tasks can be drawn from the current research:

- The effects of extra visual and vestibular motion cues on tracking performance and control behavior proves to be more dependent on the forcing function signal bandwidth for target following tasks than for disturbance tasks. A reduction in high-frequency power clearly increases the crossover frequency and decreases the phase margin for the baseline condition (C) of both types of task. For disturbance tasks the relative effects of additional motion cues compared to this baseline appear independent of the forcing function bandwidth. For target following tasks, the benevolent effects (increase in performance) are found to be reduced for a forcing function with a reduced bandwidth.

- Despite the fact that less experienced subjects were used than in the original experiment, the results were still found to correspond well with those measured by Hosman and Van der Vaart. Relatively large differences in control strategies were observed between subjects, but were hardly reflected in the resulting level of performance.

In addition to the findings of the research described in this paper, some recommendations for future research will be put forward:

- For future research it is highly recommended to perform a similar tracking experiment with peripheral visual cues that more resemble those experienced during actual aircraft control. Perhaps the effects of peripheral visual cues that are generated by an actual out-of-the-window view are much stronger than those found for the moving checkerboards from the current research.

- For disturbance tasks it would be worthwhile to investigate to what extent the same trends in performance and control behavior for tasks with real aircraft dynamics and disturbance forcing function signals that are more representative of actual turbulence. In addition, an important subject for further research is thought to be the extent to which actual full-frequency range turbulence spectra can in fact be approximated by disturbance task forcing function signals consisting of a limited number of sinusoids.

- In the Hosman and Van der Vaart experiment, it was only possible to generate motion cues around the simulator’s own roll axis. From the current research, it is unknown to what extent subjects use the actual roll cues for their control action. The linear accelerations at the subjects’ heads resulting from simulator roll could perhaps be more important than the angular roll accelerations. Using more advanced motion systems like available in the SIMONA Research Simulator, it is possible to verify the influence of these individual vestibular motion cues on control behavior.

- The crossover frequencies and phase margins measured with a forcing function signal that has the same theoretical bandwidth as McRuer’s easiest forcing function signal were found to differ from those measured by McRuer. A variation of some key experimental variables (i.e. central compensatory display geometry and scaling, side stick dynamics) might give an explanation for this deviation from McRuer’s results.

References


