The Role of Motion Feedback in Manual Preview Tracking Tasks

João Luís Alexandre Costa de Morais e Almeida

Thesis to obtain the Master of Science Degree in Aerospace Engineering

Supervisor: Prof. Agostinho Rui Alves da Fonseca

Examination Committee

Chairperson: Prof. João Manuel Lage de Miranda Lemos
Supervisor: Prof. Agostinho Rui Alves da Fonseca
Member of the Committee: Prof. José Raúl Carreira Azinheira

October 2016
Acknowledgments

Over the past ten months of work, a lot of people helped me in this investigation and in writing this master thesis. Some of them helped directly, by lending their expertise and knowledge, while others were just as important with their support throughout these months.

I would like to thank my daily supervisors, Daan and Kasper, for all the time, patience and effort they put into this project. It was a pleasure to work with both of you, and the challenges and comments you made about my work made me strive to be the best I could. I learned a lot from both of you in these seven months. I would also like to thank Max and Rene, for making time when it was needed for my project and for their interest on it.

For all the time spent in the simulator, getting me the data I needed for the experiment, I need to thank David, Dirk, Filipe, Isaac, Ivan, Laurens, Martijn, Matej, Rick, Tao and Wei. Thank you for taking the time to be inside a simulator for a few hours.

I also need to thank all the people that worked alongside me almost every day: Diogo, Joao Paulo, Joao, Miguel, Pedro, Ricardo and Tomas.

Last but not the least, I need to thank all the people back home, who may not have been physically present, but were indeed present through this project. First, my family, for giving me the wonderful opportunity of studying here, and for being present to hear all my complaints and cheer my victories. Second, all the friends who helped me be at my best every day, and whom I thank from the bottom of my heart, a list too long to be written here. Thanks to all of you I felt close to home, even being this far away. You certainly know who you are, and this project is also a bit from each and every one of you. Thank you.
Resumo

O efeito do movimento é importante em muitas tarefas efectuadas por humanos. Neste trabalho, a infulência do movimento é investigada para tarefas de seguimento com dinâmica de duplo integrador, usando resultados de uma experiência no SIMONA Research Simulator na Universidade Técnica de Delft. Oito participantes realizaram uma tarefa de seguimento em guinada com dois tipos de apresentação diferentes: compensatory e preview, com e sem movimento. Técnicas de identificação em frequência e modelos quasi-lineares para controlo manual foram utilizados para explicar o comportamento humano nestas tarefas. Uma extensão a um modelo existente foi proposta, para modelar o efeito do movimento numa tarefa com preview. É descoberto que, quando o movimento está presente, os controladores humanos adaptam o seu comportamento de um modo semelhante ao registado em tarefas com um compensatory display. A presença de movimento permite aos humanos melhorarem a sua estratégia de controlo utilizando um preview display. Este trabalho mostra pela primeira vez que o movimento tem um efeito importante no controlo manual, mesmo utilizando informação visual mais complexa.

Palavras-Chave: efeito do movimento, controlo manual, simuladores de voo, seguimento de guinada
Abstract

Motion feedback has an important effect in many tasks performed by humans. In this research, we aim to investigate the role of motion feedback in preview tracking tasks with double integrator dynamics, using results from a human-in-the-loop experiment performed in the SIMONA Research Simulator of the Delft University of Technology. Eight subjects performed the same yaw tracking task with a compensatory and preview display, both with and without motion feedback. System identification techniques and quasi-linear human controller models for preview and motion feedback are used to explain human controller’s behavior in tracking tasks. An extension to an existing human preview control model is proposed, in order to model the human in a preview task using motion feedback. It is found that, when motion feedback is available, human controllers adapt their behavior in a similar way for compensatory and preview tasks. Motion feedback allows human controllers to further improve their performance in preview tracking. This research shows for the first time that motion feedback still has an important effect on the human controller behavior, even if visual preview is available.

**Keywords:** motion feedback, manual control, flight simulators, yaw tracking
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Acronyms

**ANOVA**  Analysis of Variance  
**FC**      Fourier Coefficients  
**NVP**     Near-Viewpoint Response  
**SRS**     SIMONA Research Simulator  
**TX**      Target-Feedthrough and State-Feedback  
**VAF**     Variance Accounted For
List of Symbols

Greek Symbols

Γ coherence
ω radial frequency
φ phase angle
σ standard deviation
τ time shift
Θ parameter vector
ζ damping ratio

Roman Symbols

A amplitude
E Fourier transform of the error
e error
F Fourier transform of the forcing function
f forcing function
List of Symbols

\( H \)  
frequency response function

\( j \)  
imaginary unit

\( K \)  
gain

\( N \)  
Fourier transform of the remnant

\( n \)  
remnant

\( P \)  
periodogram

\( S \)  
power spectral density function

\( T \)  
time constant

\( t \)  
time

\( U \)  
Fourier transform of the control input

\( u \)  
control input

\( X \)  
Fourier transform of the output

\( x \)  
output

**Subscripts**

\( b \)  
base

\( c \)  
crossover

\( ce \)  
controlled element

\( d \)  
disturbance

\( e \)  
error

\( e^* \)  
internal-error response

\( f \)  
far-viewpoint

\( i \)  
input

\( L \)  
lead

\( l \)  
lag

\( m \)  
motion
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<tr>
<td>$nms$</td>
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<td>$ol$</td>
<td>open-loop</td>
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<td>$p$</td>
<td>preview</td>
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<td>$scc$</td>
<td>semi-circular canals</td>
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<td>$t$</td>
<td>target</td>
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Chapter 1

Introduction

The topic of manual control has been widely studied in the scientific community. McRuer and his colleagues [1] developed the widely known "crossover model", which models how humans perform a task using a compensatory display. This enables obtaining a mathematical model for humans in a very simple task, where only the error is displayed. Obtaining such a model for more realistic tasks, where more information is present (more visual feedbacks, motion feedback) would allow for a more complete understanding of manual control.

Research has previously been conducted on the role of motion feedback in compensatory tasks ([2...9]). Not only was motion feedback found to result in improved tracking performance, but also extensions to the crossover model including motion feedback were proposed. The main drawback of the compensatory task is that it translates poorly to real-life tasks. The preview task, in which the future movement of the target is also shown to the human, is closer to what can be seen in the real world, in tasks such as driving a vehicle along a road. A number of preview models have been proposed throughout the years, based on optimal control ([10], [11], [12]) or driving models ([13], [14], [15]), among others. Recent research at the Delft University of Technology proposed a new empirical model for this kind of task ([16], [17]). This model allows to understand how humans use preview, by using both feedforward and feedback control.
It is still not clear if human controllers use preview similarly in tasks using motion feedback, and if motion feedback is still beneficial in preview tracking tasks. This project investigates the role of motion feedback in preview tracking tasks, by analyzing how both feedbacks affect performance, and human tracking behavior.

The main objective of the project is to understand what is the effect of motion feedback, and if we are able to model the human response to it. In order to do this, an experiment will be conducted in the SIMONA Research Simulator (SRS) at the Delft University of Technology. Subjects perform a yaw tracking task using a double integrator controlled element, with compensatory and preview displays, both with and without motion feedback. Offline model simulations will also be performed in order to predict what the effect of the motion feedback would be in preview tracking tasks. A number of parametric and non-parametric measures will be calculated in order to understand the influence of motion feedback on preview tasks. Coherence will be calculated as a measure of linearity of the human controller. Error and control output variances will be obtained, and system identification methods will be used to identify the pilot response. The van der El et. al model [16] will be tested to the experimental data, with an extension for the case of preview with motion feedback. The Variance Accounted For (VAF) will be calculated as a measure of the quality of the model fit.

This dissertation is structured in seven chapters. The second chapter contains the description of the control task to be performed, while the third contains the details of the computer simulations performed. The fourth chapter contains the experimental method and the fifth the experimental results. Chapters six and seven contain the discussion and conclusions of the work. Seven appendices are included, containing the experiment briefing, the experimental design, the choice of control variables, variance results per subject, model parameters per subject, and comparison of models with near-viewpoint response (NVP) and with the motion feedback channel.
This chapter focuses on previous research on the control task that will be studied in this research. In the first section, the task characteristics are outlined. In the following sections, previous work related to the task to be studied is detailed: human controller modeling in compensatory and preview tasks. In the final section, the proposed model for preview with motion feedback is presented.

2-1 Task Characteristics

The control task considered in this research is a combined target-tracking and disturbance-rejection task. In a target-tracking task, the human controller is asked to track a target signal, designated by $f_t(t)$, minimizing the error $e(t)$ between the output $x(t)$ and the current target [1]. This output can also be perturbed by a disturbance signal $f_d(t)$, which constitutes the disturbance-rejection part of the task.

In this project, control tasks performed with compensatory and preview displays are investigated. In the compensatory task, only the error is displayed. In the preview task, the human controller can see the future target signal up to $\tau_p$ seconds ahead. These displays can be seen in Figure 2-1. Both displays were chosen to have an "inside-out" representation, with a static
output marker (a circle) and a moving target. In the compensatory case (Figure 2-1 (a)), the target is represented by a cross. In the preview case (Figure 2-1 (b)) the current target is the bottom ($\tau_p = 0$) of the preview line.

![Figure 2-1: The compensatory (a) and preview display (b)](image)

The controlled element used in these tracking tasks can take a different number of forms, including models that approach aircraft dynamics to simpler systems such as gain, single integrator and double integrator. In this project, the focus will be on the double integrator controlled element, since it is the case in which the motion feedback is found to have a larger effect on performance and the highest motion use, according to [8]. The frequency response function of the controlled element used in this control task was given by:

$$H_{ce}(j\omega) = \frac{5}{(j\omega)^2} \quad (2-1)$$

2-2 Human Controller Modeling in Compensatory Tasks

A compensatory tracking task is defined as a task in which only the current error, $e(t)$, is presented to the human controller. For this type of task, an empirical model has been derived by McRuer $et$ $al.$ in [1]. McRuer proposed a quasi-linear model to explain the behavior of the human controller in such a task, in which the operator is described by a linear frequency response function $H_{oe}(j\omega)$, and a non-linear part $n(t)$, the remnant signal. This model is illustrated in the control diagram in Figure 2-2, for a target-tracking task.

The proposed model states that humans adapt their control dynamics so that, in the crossover
region (around a crossover frequency $\omega_c$), the open-loop describing function approximates a single integrator with a time delay, as in Equation (2-2) [1].

$$H_{ol}(j\omega) = H_{oe}(j\omega)H_{ce}(j\omega) = \frac{\omega_c}{j\omega}e^{-j\omega \tau_v}$$ \hspace{1cm} (2-2)

The operator frequency response function $H_{oe}(j\omega)$ is modeled for a double integrator as in Equation (2-3).

$$H_{oe}(j\omega) = K_e(1 + T_{Le}j\omega)e^{-\tau_v j\omega}H_{nms}(j\omega)$$ \hspace{1cm} (2-3)

In this model, $K_e$ represents the human controller response gain, $T_{Le}$ the lead time constant, $\tau_v$ the visual time delay and $H_{nms}$ the neuromuscular dynamics. The neuromuscular dynamics are typically modeled ([5], [8]), as seen in Equation (2-4), with $\omega_{nms}$ the natural frequency of the neuromuscular system and $\zeta_{nms}$ the damping ratio.

$$H_{nms}(j\omega) = \frac{\omega_{nms}^2}{(j\omega)^2 + 2\zeta_{nms}\omega_{nms}j\omega + \omega_{nms}^2}$$ \hspace{1cm} (2-4)

2-3 Role of Motion Feedback in Compensatory Tasks

The effect of motion feedback in compensatory tracking tasks is well documented in literature ([2], [3], [4], [5], [6], [7], [8], [9]). Hosman and Van der Vaart [2] found that motion cues significantly improved performance. For the target-following task, a reduction in the target crossover frequency $\omega_{ct}$ and an increase in the target phase margin $\phi_{mt}$ are found. Regarding disturbance rejection, the study found an increase in the disturbance phase margin $\phi_{md}$ and in the disturbance crossover frequency $\omega_{cd}$. Schroeder [3] and Pool et. al [5] later confirmed
these findings. In [7], a compilation of a large number of research studies on the field was obtained, and these findings were found to be a general trend, apart from the phase margins. For both the target and disturbance phase margins, motion was found not to have an effect in this research. According to Hosman [4], the motion feedback is modeled as an extra feedback path, with a frequency response function including the semi-circular canal dynamics:

\[ H_{om}(j\omega) = (j\omega)^2 H_{sc}(j\omega) K_m e^{-\tau_m j\omega} \] (2-5)

The most remarkable effect of motion feedback in compensatory tasks is an increase in performance. With motion feedback, human controllers adapt their control strategy, by increasing the error response gain \( K_e \). The lead generated by the motion feedback channel allows human controllers to generate less visual lead, which is shown by the decrease in the lead time constant \( T_{L,e} \). The task then becomes easier for the human controller, which is shown by an increase in the disturbance crossover frequency ([5], [7], [8]).

The complete control diagram including this motion feedback can be seen in Figure 2-3.

![Figure 2-3: Compensatory model with motion feedback proposed by Hosman [4]](image)

2-4 Human Controller Modeling in Preview Tasks

A number of different models have been developed for preview tracking ([10], [11], [12], [16], [17]). In this project, the model from van der El et. al ([16], [17]) will be used.

Van der El et. al [16] proposed a model for preview tracking in which the response of the human controller to a previewed target trajectory is captured by a response to two different points ahead: the near-viewpoint \( f_{t,n} \) and the far-viewpoint \( f_{t,f} \):
The near-viewpoint will not be included in this project, since in previous studies it is found to be difficult to determine whether it is actually being used by the human controller [17] and its contribution to the human controller’s output is generally small for a double integrator controlled element. This allows to reduce the number of parameters to estimate, yielding lower estimation uncertainties in the remaining parameters, as used in [18].

The far-viewpoint response is modeled as a low-pass filter, as the human controller uses it to track the low frequencies of the target signal:

$$H_{of}(j\omega) = K_f \frac{1}{1 + T_{l,f}j\omega}$$ \hspace{1cm} (2-7)

in which $K_f$ is the far-viewpoint gain and $T_{l,f}$ is the far-viewpoint lag time constant.

The human controller responds to an error $e^\star$, defined as the difference between the target filtered by the far-viewpoint dynamics and the controlled element output:

$$E^\star(j\omega) = F_{l,f}^\star(j\omega) - X(j\omega) = H_{of} F_l(j\omega) - X(j\omega)$$ \hspace{1cm} (2-8)

The dynamics of the internal-error response resemble the equalization term of compensatory tracking, as can be seen in Equation (2-9) for a double integrator controlled element.

$$H_{oe^\star}(j\omega) = K_{e^\star} (1 + T_{L,e^\star}j\omega)$$ \hspace{1cm} (2-9)

in which $K_{e^\star}$ is the error response gain, $T_{L,e^\star}$ is the lead time constant.
The human controller can respond to the output, the target and the error, in a total of three describing functions. Using two external signals, the target and the disturbance, only two operator describing functions can be identified. The model is then typically restructured to a a two-channel model, with $H_{ot}$ representing the response to the target and $H_{ox}$ the response to the controlled element output \[16\], \[17\], \[18\], see Figure 2-5. These lumped dynamics are defined as:

\[
H_{ot}(j\omega) = [H_{otf}(j\omega)H_{ot\star}(j\omega)e^{\tau_f j\omega} + H_{on}(j\omega)e^{\tau_n j\omega}]H_{nms}(j\omega)e^{-\tau_v j\omega} \quad (2-10)
\]

\[
H_{ox}(j\omega) = H_{ox\star}(j\omega)H_{nms}(j\omega)e^{-\tau_v j\omega} \quad (2-11)
\]

![Figure 2-5: Model with lumped dynamics in TX (target and output response) form, as in Van der El et. al [16]](image)

### 2-5 Proposed model

For preview with motion feedback, a new model is proposed which combines the previous research on compensatory tasks with the van der El et. al \[16\] model for preview tasks. The extension adds an extra feedback path to the preview model, as can be seen in Figure 2-6.

The proposed model for preview tracking accounting for motion feedback can be converted to the same lumped structure of Figure 2-5 by adding the $H_{on}$ frequency response function to Equation (2-11), while there is no change in Equation (2-10).

\[
H_{ox}(j\omega) = H_{ox\star}(j\omega)H_{nms}(j\omega)e^{-\tau_v j\omega} + H_{om}(j\omega)H_{nms}(j\omega) \quad (2-12)
\]
In this equation, $H_{om}$ uses the same structure as Equation (2-5). The normalized semi-circular canals model was used, as in [19]. This model includes a gain which ensures the model has an unitary absolute value at 1 rad/s.

$$H_{scc}(j\omega) = \frac{5.97(0.11j\omega + 1)}{(5.9j\omega + 1)(0.005j\omega + 1)} \quad (2-13)$$

It should be noted that the proposed model doesn’t introduce a large change in the existing preview model: in fact, the $H_{om}$ equation can be simplified over a range of frequencies to:

$$H_{om}(j\omega) = |(j\omega)|K_m e^{-\tau_m j\omega} \quad (2-14)$$

On the other hand, for a double integrator, $H_{oe^*}$ including the visual time delay is given by:

$$H_{oe^*} = K_{e^*} e^{-\tau_v j\omega} + K_{e^*} T_{Le^*} j\omega e^{-\tau_v j\omega} \quad (2-15)$$

It can be seen that the second term of Equation (2-15) has the same structure of the additional $H_{om}$ path in the proposed model. It can then be expected there is undesired redundancy in the proposed model, which may lead to problems in the identification of its parameters.
Offline human control model simulations were performed using the proposed model (Figure 2-6) to predict the possible benefit of motion feedback and using an $H_{om}$ response in preview tracking tasks. The simulation settings and its findings are presented in this chapter.

3-1 Simulation settings

In order to predict the human controller’s adaptation to motion feedback, the response of the proposed model is simulated for increasing values of the motion gain $K_m$, while all other model parameters (e.g., $H_{oe}$, $H_{of}$) are kept constant. This simulation was performed both for compensatory and preview tasks.

The proposed model includes two motion parameters: the gain $K_m$ and the and the motion delay $\tau_m$. Since the motion time delay $\tau_m$ is consistently found around 0.2 in literature [8], it was fixed at that value. The gain $K_m$ was changed from 0 (no motion) to 0.25 in increments of 0.05. This maximum gain was defined as further increase in the motion gain causes instability for the preview condition.
3-2 Model settings

The settings used for the offline model simulations can be seen in Table 3-1. The controlled element was a double integrator given by $5/(j\omega)^2$. The compensatory parameters were based on the results of [8] and the preview model parameters were taken from the results of [16].

<table>
<thead>
<tr>
<th>Conditions</th>
<th>$K_e^*, -$</th>
<th>$T_{L,e^*}, s$</th>
<th>$\omega_{nms}, rad/s$</th>
<th>$\zeta_{nms}, -$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compensatory</td>
<td>0.20</td>
<td>1.70</td>
<td>12</td>
<td>0.40</td>
</tr>
<tr>
<td>Preview</td>
<td>0.20</td>
<td>2</td>
<td>6</td>
<td>0.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conditions</th>
<th>$\tau_v, s$</th>
<th>$K_f, -$</th>
<th>$T_{l,f}, s$</th>
<th>$\tau_f, s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compensatory</td>
<td>0.30</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Preview</td>
<td>0.30</td>
<td>0.9</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

3-3 Results

The error and control output variances were calculated to quantify performance and control output, respectively. Open-loop describing functions were also used to calculate the crossover frequency and phase margin for each value of $K_m$.

3-3-1 Tracking Performance and Control Activity

In Figure 3-1 the variance of the error and control output are displayed.

When no motion feedback is available, there is a clear increase in performance when preview is used, with a total decrease in the variance of the error of 64%. It should be noted that this increase in performance is largely due to the target frequencies, in which there is an 84% decrease in the variance of the error.

Regarding the motion feedback in the compensatory case, a performance improvement is found as $K_m$ increases. Even without any adaptation in the other parameters, the use of motion feedback improves performance in compensatory tracking, as found in previous experiments ([2], [3], [5], [6], [7], [8]).
For the preview case, there is an increase in the error when motion feedback is used. However, it can be seen that there is a better tracking of the disturbance frequencies, with the increase in error caused by the target frequencies.

**3-3-2 Crossover Frequency and Phase Margin**

In Figures 3-2 and 3-3, the crossover frequency and phase margin of the offline model simulations are displayed.

For the crossover frequency, the same trend is found for the compensatory and preview simulations. The target crossover frequency $\omega_{ct}$ decreases when motion is added, and the disturbance crossover frequency $\omega_{cd}$ increases. These results are in line with previous results in literature ([2], [3], [5], [7], [8]).
Regarding the phase margin, it can be seen that the target phase margin $\phi_m$ increases when motion is added, mostly on the preview case. On the disturbance phase margin $\phi_d$, however, the compensatory and preview tasks show a substantial difference: while there is only a modest increase in the compensatory case (as found in [2], [3], [5], [8]), for the preview case it decreases and eventually becomes negative, indicating the closed-loop becomes unstable.
Figure 3-3: Target (a) and disturbance (b) phase margin for increasing magnitude of the motion feedback channel
Chapter 4

Experimental Method

This chapter details the experimental method used in the project. In the first section, the experimental hypothesis to be tested are presented. In the following sections, the independent variables, experimental apparatus, control variables and forcing functions of the experiment are detailed. This is followed by the description of the experimental procedure and dependent variables. The chapter is concluded by the description of the data analysis techniques that were used in the project.

4-1 Hypotheses

Regarding the effect of motion feedback, and the previous research summarized in Section 2-3, it is known that motion has a marked effect on tracking performance and human control behavior in tracking tasks with double integrator dynamics. It is thus hypothesized that:

I When motion feedback is added, there will be an increase in performance for compensatory tasks and human controller adaptation. The human adaptation will be clear by an increase in the error response gain $K_e$, a decrease in the lead time constant $T_{L_e}$ and a non-zero gain $K_m$. 
When a human controller is provided with preview, he has the ability to look ahead and respond not only to the error, but also to the future target, which allows for better performance [17]. Therefore, in accordance with the findings in [17], the following hypothesis is drawn:

II Availability of preview information allows human controllers to improve their target-tracking performance. by responding to . The use of preview introduces a negative time delay $\tau_f$ in the system, which allows the human controller to respond to an internal-error $e^*$, filtered by the far-viewpoint response $H_{of}$.

On the one hand, the offline model simulations predicted a degradation in performance when motion feedback is included in the preview task. The disturbance-rejection, however, is improved in the simulations. On the other hand, compensatory tracking literature finds a significant improvement in performance when motion feedback is added. It is also known that human controllers adapt their behavior when motion feedback is available, which was not considered in the offline model simulations, and may influence target-tracking behavior. It is then hypothesized that:

III For preview tracking, the tracking performance will be improved on the disturbance frequencies when motion feedback is available. Using motion feedback, the human controller is able to close an additional motion channel $H_{om}$, and it is expected that the human controller adaptation will be similar to what was compensatory tracking tasks, with an increase in the error response gain $K_e$ and a decrease in the lead time constant $T_{Le}$.

### 4-2 Independent Variables

The experiment considered two independent variables: the display type and the presence of motion feedback. The displays had either compensatory or preview configuration, see Figure 2-1. The motion feedback was either off or on. A full-factorial design was used, so all combinations of the independent variables were tested by each participant. This yields a total of four conditions, as it can be seen in Table 4-1.
4-3 Apparatus

The experiment was conducted in the SIMONA Research Simulator (SRS) at the Delft University of Technology (see Figure 4-1). The subjects were seated in the right seat of the simulator, using an electric sidestick to give an input to the system. The stick was fixed in the pitch axis and could only rotate around its roll axis.

The displays were presented on the primary flight display of the simulator, directly in front of the subjects, with green lines and indicators on a black background. These displays were either compensatory or preview, as can be seen in Figure 2-1.

4-4 Control Variables

Two seconds of preview are displayed on the screen, well above the critical preview time found in [18]. The critical preview time is defined as the length of preview above which there is no improvement in the tracking performance.

The motion cue used in the experiment was the yaw rotation of the simulator, and was the

<table>
<thead>
<tr>
<th>Compensatory</th>
<th>Motion off</th>
<th>Motion on</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>CM</td>
<td></td>
</tr>
<tr>
<td>Preview</td>
<td>P</td>
<td>PM</td>
</tr>
</tbody>
</table>

Table 4-1: Experimental conditions definition
same for all the conditions including motion feedback. The yaw rotation was corrected so that the motion axis was centered in the right seat of the simulator and not on the centroid of the simulator. Motion was presented one to one, with no washout.

### 4-5 Forcing Functions

To facilitate the use of system identification methods described in Section 4-8, the forcing functions in the experiment were defined as a sum of sinusoids given by Equation (4-1). The same expression was used for the disturbance and target forcing functions.

\[ f_{t,d}(t) = \sum_{k=1}^{20} A_{t,d}[i] \sin(\omega_{t,d}[i]t + \phi_{t,d}[i]) \quad (4-1) \]

In this expression, \( f \) stands for the forcing function signal, and \( A, \omega \) and \( \phi \) for the sinusoid amplitude, frequency and phase, respectively.

Both target and disturbance amplitudes were defined using a second-order low-pass filter, as used in [5] and [6]. The absolute value of the filter at a given frequency yields the sinusoid amplitude. This filter is defined in Equation (4-2).

\[ H_A(j\omega) = \frac{(1 + 0.1j\omega)^2}{(1 + 0.8j\omega)^2} \quad (4-2) \]

This amplitude distribution results in a realistic and not too difficult task for the subjects [6]. This is also the same amplitude distribution used in previous yaw motion experiments, such as [8]. In order to avoid leakage and allow the use of spectral analysis, the frequencies used were integer multiples of the base frequency \( \omega_b \). Each run consisted of a measurement time of 120 seconds, which yields a base frequency \( \omega_b = \frac{2\pi}{120} = 0.0524 \text{ rad/s} \). To allow for the calculation of coherence, double bands of frequencies were used [16]. The frequencies used were the same as in [16] and [17], in a total of 20 sinusoids.

Five different target signals were used, different only on the phases \( \phi_t \), to avoid memorization of the signal by the subjects. For the disturbance signal only one realization was used, as it is unlikely the subjects would memorize it since it is not directly displayed. Given that in the SRS the disturbance is inserted before the controlled element, it was pre-filtered with
4-6 Experimental Procedure

The experiment was performed by eight male volunteers aged between 22 and 32 years old. Their experience in tracking tasks ranged from little practice to extensive experience. All the subjects were briefed before participating, and given all necessary instructions to perform the experiment.

For each subject, a task familiarization was performed before the actual experiment, in which each condition was tried at least once. After this phase, the measurement phase begun. The order of the conditions was randomized using a balanced Latin-Square distribution among the subjects. For each condition, each subject performed three training runs, and an extra five to twelve runs, until stable performance was achieved. Only the last five runs of each condition for each subject were used for data analysis.

After every run, the experimenter reported the score to the subjects, using the root-meansquare of the error. Each run lasted for 132 seconds, of which the first eight seconds were

\[ S_{ff}(j\omega) \]

\[ S_{fd}(j\omega) \]

Figure 4-2: Single-sided Power Spectral Density of the forcing function signals
run-in time and the last four were fade-out time, with 120 seconds being used as measurement time. Breaks were taken between every two conditions. The total experiment time, breaks included, was around three hours per subject.

### 4-7 Dependent Variables

In this experiment, the variances of the error and control output are used quantify performance and control activity. Coherence is calculated to validate the use of a quasi-linear model for the human controller. Open-loop describing functions are calculated in order to obtain crossover frequencies and phase margins to quantify performance in the frequency domain and closed-loop stability. Black-box identification and parameter estimation are used to obtain the frequency response of the human controller. Model parameters are obtained based on the proposed model in order to understand the human behavior in the control task. Model VAFs are obtained in order to quantify the ability of the model to describe the output.

<table>
<thead>
<tr>
<th>k</th>
<th>( n_d )</th>
<th>( A_d )</th>
<th>( \omega_d )</th>
<th>( \phi_{d,1} )</th>
<th>( \phi_{d,2} )</th>
<th>( \phi_{d,3} )</th>
<th>( \phi_{d,4} )</th>
<th>( \phi_{d,5} )</th>
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<td>0.028</td>
<td>1.156</td>
<td>1.278</td>
<td>4.752</td>
<td>5.105</td>
</tr>
<tr>
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<td>3</td>
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<td>0.157</td>
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<td>1.783</td>
<td>2.651</td>
<td>5.326</td>
<td>5.492</td>
</tr>
<tr>
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<td>0.419</td>
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<td>3.655</td>
<td>2.051</td>
<td>6.104</td>
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<td>3.364</td>
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<td>3.549</td>
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<td>0.713</td>
<td>3.805</td>
<td>3.827</td>
<td>1.411</td>
<td>2.490</td>
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</table>

---

Table 4-2: Parameters of the target and disturbance forcing function signals
4-8 Data Analysis

4-8-1 Coherence

The coherence is a measure for the linear relationship between two signals. It can range from 0 to 1, where 0 means no linear relation and 1 means completely linear relation. The coherence is calculated to verify the linearity of the human controller’s inputs in response to the applied forcing functions. A high coherence shows that the relation is close to linear, which means that quasi-linear models can be applied to model the human controller dynamics. Equation (4-3) shows how coherence is estimated for the target signal. Calculation for the disturbance signal is analogous.

\[
\Gamma_{f_t,u}(\tilde{\omega}_t) = \sqrt{\frac{|\hat{P}_{f_t,u}(\tilde{\omega}_t)|^2}{\hat{P}_{f_t,f_t}(\tilde{\omega}_t)\hat{P}_{u u}(\tilde{\omega}_t)}}, \tag{4-3}
\]

In this equation, \(\tilde{\omega}\) is the average frequency between two frequencies in a double band, and \(\hat{P}\) is the average periodogram of the respective subscripted signals at that average frequency.

4-8-2 Open-loop Describing Functions

Open-loop describing functions allow to further understand the performance and the stability of the system. The measures used are the crossover frequency \(\omega_c\), which corresponds to the frequency at which \(|H_{ol}(j\omega)| = 1\), and the phase margin \(\phi_m\) defined by \(180 + \angle H_{ol}(j\omega_c)\). The open-loop describing functions are defined, for a combined target-tracking and disturbance-rejection tracking tasks, as in [20]:

\[
H_{ol,t}(j\omega_t) = \frac{X(j\omega_t)}{E(j\omega_t)} = \frac{H_{ot}(j\omega_t)H_{ce}(j\omega_t)}{1 + [H_{ot}(j\omega_t) - H_{oz}(j\omega_t)]H_{ce}(j\omega_t)} \tag{4-4}
\]

\[
H_{ol,d}(j\omega_t) = \frac{X(j\omega_d) - F_d(j\omega_t)}{X(j\omega_d)} = H_{ce}(j\omega_d)H_{oz}(j\omega_d) \tag{4-5}
\]
4-8-3 Black-Box Multiloop System Identification

For system identification, a black-box, Fourier Coefficient (FC) based method is used, as described in [21]. For the introduced two-channel model (see Figure 2-5), Equation (4-6) can be obtained, in which $U$, $F_t$ and $X$ are the Fourier transforms of the control output, the target forcing function and the controlled element output, respectively. This equation excludes the remnant, as it is considered small at the input frequencies [21].

$$U(j\omega) = H_{ot}(j\omega)F_t(j\omega) - H_{ox}(j\omega)X(j\omega)$$  \hspace{1cm} (4-6)

This equation contains two different describing functions, $H_{ot}$ and $H_{ox}$. In order to solve for both describing functions, a second equation is required. This equation can be obtained by evaluating Equation (4-6) only at the signal input frequencies, while also interpolating the Fourier transforms at the disturbance frequencies to the target frequencies, yielding the signals $\tilde{U}$, $\tilde{F}_t$ and $\tilde{X}$. This yields a system of two equations and two unknowns, given by Equation (4-7), which can be solved for $H_{ot}$ and $H_{ox}$. The same process is performed for the disturbance frequencies, so that $H_{ot}$ and $H_{ox}$ estimates are obtained at all excited frequencies.

$$
\begin{bmatrix}
U(j\omega_l) \\
\tilde{U}(j\omega_l)
\end{bmatrix} =
\begin{bmatrix}
F_t(j\omega_l) & -X(j\omega_l) \\
\tilde{F}_t(j\omega_l) & -\tilde{X}(j\omega_l)
\end{bmatrix}
\begin{bmatrix}
H_{ot}(j\omega_l) \\
H_{ox}(j\omega_l)
\end{bmatrix}
$$  \hspace{1cm} (4-7)

4-8-4 Parameter Estimation

The model parameters were obtained by minimization of a cost function $J$, given in Equation (4-8).

$$J(\Theta) = \sum_{i=1}^{N_t} |U(j\omega_l) - \hat{U}(j\omega_l|\Theta)|^2$$  \hspace{1cm} (4-8)

with

$$\hat{U}(j\omega_l|\Theta) = \hat{H}_{ot}(j\omega_l|\Theta)F_t(j\omega_l) - \hat{H}_{ox}(j\omega_l|\Theta)X(j\omega_l)$$  \hspace{1cm} (4-9)
This cost function is the difference between the measured and modeled control output, at a number \( N_t \) of \( \omega_i \) frequencies below a cut-off frequency, chosen at 25 rad/s. The parameter vector \( \Theta \) is defined as \([K_e, T_{L,e}, \tau_v, \omega_{nms}, \zeta_{nms}, K_f, T_{l,f}, \tau_f, K_m, \tau_m]^T\).

In order to minimize \( J \), a Nelder-Mead algorithm was used, with the MATLAB function \texttt{fminsearch()}\). It was constrained to discard only negative parameters. 10,000 initial parameter sets are randomly generated and the 100 with the lowest cost function are used as starting points for the optimization. The solution with the lowest cost is considered the best solution.

### 4-8-5 Variance Accounted For

The Variance Accounted For (VAF) is used as a measure of the similarity of two signals. A maximum value of 100% means that the signals are identical. It can then be used to compare the modeled and measured control output, to quantify how well the model represents the human controller behavior. The VAF is given by:

\[
VAF = \left( 1 - \frac{\sum_{k=1}^{N_s} P_{\epsilon u}(k\omega_k)}{\sum_{k=1}^{N_s} P_{uu}(k\omega_k)} \right) \times 100\%,
\]

(4-10)

with \( \epsilon_u \) the modeling error \( (U(j\omega_k) - \hat{U}(j\omega_k|\Theta)) \) and \( N_s \) is the total number of samples.

### 4-8-6 Data Processing

Coherence was calculated per subject and per run. The results were averaged over five runs and then averaged over the eight subjects, for each condition. The variances of the error and control output were calculated for individual runs and averaged for each subject. These variances were calculated by integration of power spectral densities, in order to allow separation of the contributions of target, disturbance and remnant frequencies [20]. The frequency response functions were estimated using the frequency-domain average of the five measurement runs for each subject, in order to reduce noise. The phase margins and crossover frequencies were calculated using the estimated frequency response functions, using Equation (4-4) and (4-5). The Variance Accounted For is calculated per subject, based on the obtained models.
A two-way repeated measures Analysis of Variance (ANOVA) was applied to test for significant changes in tracking performance, control activity, crossover frequency and phase margin. 95% confidence intervals of the variances, crossover frequencies, phase margins and model parameters were corrected for between-subject variability.
Chapter 5

Obtained Results

This chapter contains the experimental results. First, the non-parametric measures are presented, including tracking performance, control activity, coherence, crossover frequency and phase margin. Second, the human controller describing functions are presented for the eight experimental subjects, along with the model comparison for the condition of preview with motion feedback. Fourth, the human controller model parameters are presented and the Variance Accounted For is calculated as a measure of the quality of the model fit.

5-1 Tracking Performance and Control Activity

Figure 5-1 shows the average variances of the tracking error $e$ and the control output $u$, for each condition. Each bar also shows the contributions of the target, disturbance and remnant frequencies. The 95% confidence intervals of the means of the total $\sigma^2_e$ and $\sigma^2_u$ are also depicted.

To quantitatively compare the change in the target, disturbance and remnant contributions due to preview and motion feedback, the percentage change in variance is presented in Tables 5-1 and 5-2.
Obtained Results

Figure 5-1: Variance of the error (a) and control output (b)

Table 5-1: Motion and preview effects on the error variance

<table>
<thead>
<tr>
<th>Frequencies</th>
<th>Motion Effect</th>
<th>Preview Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compensatory</td>
<td>Preview</td>
</tr>
<tr>
<td>Total</td>
<td>-49%</td>
<td>-26%</td>
</tr>
<tr>
<td>Remnant</td>
<td>-62%</td>
<td>-19%</td>
</tr>
<tr>
<td>Disturbance</td>
<td>-54%</td>
<td>-25%</td>
</tr>
<tr>
<td>Target</td>
<td>-39%</td>
<td>-39%</td>
</tr>
</tbody>
</table>

Table 5-2: Motion and preview effects on the control output variance

<table>
<thead>
<tr>
<th>Frequencies</th>
<th>Motion Effect</th>
<th>Preview Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compensatory</td>
<td>Preview</td>
</tr>
<tr>
<td>Total</td>
<td>+4%</td>
<td>+22%</td>
</tr>
<tr>
<td>Remnant</td>
<td>+9%</td>
<td>+28%</td>
</tr>
<tr>
<td>Disturbance</td>
<td>+42%</td>
<td>+9%</td>
</tr>
<tr>
<td>Target</td>
<td>-13%</td>
<td>+29%</td>
</tr>
</tbody>
</table>
A statistical test is performed in order to further understand how significant are the effects of the different displays and motion feedback for the error and control output variance.

<table>
<thead>
<tr>
<th>Table 5-3: Tracking performance and control activity ANOVA results ¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>error, <em>e</em></td>
</tr>
<tr>
<td>control output, <em>u</em></td>
</tr>
<tr>
<td>df</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>motion</td>
</tr>
<tr>
<td>σ²</td>
</tr>
<tr>
<td>mot.*disp.</td>
</tr>
<tr>
<td>motion</td>
</tr>
<tr>
<td>σ²</td>
</tr>
<tr>
<td>mot.*disp.</td>
</tr>
<tr>
<td>motion</td>
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<td>σ²</td>
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<td>mot.*disp.</td>
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<tr>
<td>motion</td>
</tr>
<tr>
<td>σ²</td>
</tr>
<tr>
<td>mot.*disp.</td>
</tr>
</tbody>
</table>

¹The symbol - stands for not significant result (p<0.05), * for significant result (p<0.05) and ** for highly significant result (p<0.01)

When analyzing the error variances, there is a significant difference in performance for the target, remnant and disturbance contributions, both for motion and displays. This suggests that the extra information provided to the human controller effectively allows to control the system with a smaller error.

Preview yields a significant improvement in target performance, see Table 5-3. This is most visible in the target frequencies, with a reduction in the error of 92%. With preview, humans can see the future target and anticipate its upcoming changes. There is a significant effect of the applied display variation for the target, disturbance and remnant frequencies on the tracking performance, which shows that preview information allows the human controller to improve both its target-tracking and disturbance-rejection performance.

Motion feedback also has a significant effect on tracking performance, which can be seen for all frequencies. This effect can be seen both for compensatory and preview displays. The motion effect exists for both displays, even though it is smaller in percentage for the preview
display. This can clearly be seen in Table 5-1, and is also seen in the statistical results as a significant interaction of motion and display for target, disturbance and remnant frequencies tracking performance. This suggests human controllers indeed use motion feedback in preview tracking.

Regarding control activity, the statistical analysis indicates that only the display has a significant effect on the target frequencies. Because human controllers can distinguish between the target and disturbance signals on the preview display (and not on the compensatory display), they respond more linearly (less remnant) and they choose to respond less aggressively to the target signal. Figure 5-1. When preview is provided, without motion, there is a 58% decrease in the control activity, and a 33% increase in the disturbance control activity, which is not significant.

Motion feedback does not have a significant effect on the control activity. This can also be clearly seen in Figure 5-1 and Table 5-2, in which the change in control activity variance between the motion and no motion condition are very small.

## 5-2 Coherence

The average coherence for each condition is shown in Figure 5-2 for the target frequencies and in Figure 5-3 for the disturbance frequencies.

It is clear that all results are very close to 1, which validates the use of a quasi-linear model for the human. These results are 10 to 20% higher, depending on the frequency, than what was found in previous preview tracking experiments [16], [18], which can be explained by the amplitude filter used in this experiment. The use of an amplitude filter reduces the power of the high frequencies of the signal, which makes the task easier for the human controller. It should also be noted that the disturbance coherence at the higher frequencies is smaller than the target coherence.
Figure 5-2: Coherence between the target and control output signals, for the compensatory (a) and preview (b) tasks.

Figure 5-3: Coherence between the disturbance and control output signals, for the compensatory (a) and preview (b) tasks.
5-3 Crossover Frequency and Phase Margin

The crossover frequencies and phase margins are shown in Figures 5-4 and 5-5. In each figure, the results for each subject are presented, along with the mean of all subjects and the 95% confidence intervals of the means.

![Figure 5-4: Target (a) and disturbance (b) crossover frequency](image1)

![Figure 5-5: Target (a) and disturbance (b) phase margin](image2)

Figure 5-4 and 5-5 shows clear effect of both preview and motion feedback. On the one hand, preview significantly increases the target crossover frequency and phase margin. For target-tracking, preview allows the human to become more stable (increased phase margin),
Table 5-4: Crossover frequency and phase margin ANOVA results

<table>
<thead>
<tr>
<th></th>
<th>target</th>
<th>df</th>
<th>F</th>
<th>sig.</th>
<th>disturbance</th>
<th>df</th>
<th>F</th>
<th>sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>motion</td>
<td>(1,7)</td>
<td>1.487</td>
<td>-</td>
<td></td>
<td>(1,7)</td>
<td>12.126</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>$\omega_c$</td>
<td>display</td>
<td>(1,7)</td>
<td>39.044</td>
<td>**</td>
<td>(1,7)</td>
<td>2.401</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>mot. * disp.</td>
<td>(1,7)</td>
<td>3.195</td>
<td>-</td>
<td></td>
<td>(1,7)</td>
<td>1.902</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>motion</td>
<td>display</td>
<td>(1,7)</td>
<td>0.031</td>
<td>-</td>
<td>(1,7)</td>
<td>0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\phi_m$</td>
<td>display</td>
<td>(1,7)</td>
<td>82.872</td>
<td>**</td>
<td>(1,7)</td>
<td>1.079</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>mot. * disp.</td>
<td>(1,7)</td>
<td>1.320</td>
<td>-</td>
<td></td>
<td>(1,7)</td>
<td>1.217</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

1 The symbol - stands for not significant result ($p < 0.05$), * for significant result ($p < 0.05$) and ** for highly significant result ($p < 0.01$).

due to the ability to see the future target. The negative time delay present in the preview task provide phase lead to the human controller, which makes the system more stable. On the other hand, motion significantly increases the disturbance crossover frequency, as the disturbance task is easier for the human controller when using motion feedback. It should also be noted that there is an increase in the target crossover frequency when motion is added for the preview task, which is an indicator that motion feedback makes the task easier for the human controller. Neither motion feedback nor preview have a clear contribution to the disturbance phase margin, as can be seen in Figure 5-5(b), and indeed both effects are not significant, as seen in Table 5-4.

5-4 Human Controller Describing Functions

Using the Black-Box identification method described in Section 4-8, the human controller describing functions can be identified. The resulting Bode plots are shown in the following figures for each of the experimental subjects.
Obtained Results

Figure 5-6: Human Controller Describing Functions for Subject 1. Results for the compensatory condition without motion feedback (a), (d) and with motion feedback (b), (c), (e), (f) on top and preview without motion feedback (g), (h), (k), (l) and with motion feedback (i), (j), (m), (n)
Figure 5-7: Human Controller Describing Functions for Subject 2. Results for the compensatory condition without motion feedback (a), (d) and with motion feedback (b), (c), (e), (f) on top and preview without motion feedback (g), (h), (k), (l) and with motion feedback (i), (j), (m), (n).
Figure 5-8: Human Controller Describing Functions for Subject 3. Results for the compensatory condition without motion feedback (a), (d) and with motion feedback (b), (c), (e), (f) on top and preview without motion feedback (g), (h), (k), (l) and with motion feedback (i), (j), (m), (n).
Figure 5-9: Human Controller Describing Functions for Subject 4. Results for the compensatory condition without motion feedback (a), (d) and with motion feedback (b), (c), (e), (f) on top and preview without motion feedback (g), (h), (k), (l) and with motion feedback (i), (j), (m), (n)
Obtained Results

Figure 5-10: Human Controller Describing Functions for Subject 5. Results for the compensatory condition without motion feedback (a), (d) and with motion feedback (b), (c), (e), (f) on top and preview without motion feedback (g), (h), (k), (l) and with motion feedback (i), (j), (m), (n).
Figure 5-11: Human Controller Describing Functions for Subject 6. Results for the compensatory condition without motion feedback (a), (d) and with motion feedback (b), (c), (e), (f) on top and preview without motion feedback (g), (h), (k), (l) and with motion feedback (i), (j), (m), (n)
Figure 5-12: Human Controller Describing Functions for Subject 7. Results for the compensatory condition without motion feedback (a), (d) and with motion feedback (b), (c), (e), (f) on top and preview without motion feedback (g), (h), (k), (l) and with motion feedback (i), (j), (m), (n).
Figure 5-13: Human Controller Describing Functions for Subject 8. Results for the compensatory condition without motion feedback (a), (d) and with motion feedback (b), (c), (e), (f) on top and preview without motion feedback (g), (h), (k), (l) and with motion feedback (i), (j), (m), (n).
5-5 Model comparison

Given the similarity between the models, it was decided to test both the original preview model proposed by van der El et. al [16] and the proposed model for the preview with motion feedback condition. Both models were fitted to the results of the preview with motion feedback condition (PM), in order to understand if the addition of the motion channel causes a significant difference in the Variance Accounted For, the frequency response function, or the parameters of the model. The obtained frequency response functions for both models are presented in Figure 5-14.

![Figure 5-14](image)

**Figure 5-14:** Frequency response functions for Subject 8, fitted for the van der El model (VAF=92.38%) and the proposed model including motion feedback (VAF=92.79%).

It can be seen in Figure 5-14 that there is not a significant difference between the two models. The visual channel of the van der El [16] model is able to successfully model the entire response, with only a small change in the Variance Accounted For. The average model parameters are displayed in Table 5-5, along with the P results for reference.

For the visual time delay $\tau_v$ and the lead time constant $T_{l,e}$, the notably lower values in the proposed model are caused by the interaction with the motion feedback path, as described in Section 2-5. The far-viewpoint time constant $T_{l,f}$ seems to be the most affected by the
change in these parameters.

The visual channel is then able to fully model the response, which is due to the similar function performed by the visual and motion channels in the proposed model. This fact reveals some ambiguity in the proposed model: even though it can fit the human response, it is an overdetermined model. The results for tracking performance and crossover frequency show that indeed there is a change in the human controller, but the proposed model does not correctly fit to the data using the identification techniques presented in this project. We recommend further research on the separation of the motion and visual channels of the human controller, so that they can be uniquely identified and modeled. Considering these facts, the parameter estimation results obtained from the van der El *et al* model [16], without the motion feedback channel will be used for the PM condition.

### 5-6 Human Controller Model Parameters

The model parameters, for the different conditions, can be seen in Figures 5-15-5-20. For each condition, the parameters are shown for each subject using gray bars, along with the mean of all subjects and the 95% confidence interval of the mean.
5-6-1 Error feedback response parameters

For both the error response gain $K_{e\star}$ and lead time constant $T_{L,e\star}$, the effect of motion feedback is similar for compensatory and preview displays. $K_{e\star}$ increases when motion feedback is added, as the human responds more aggressively to the error. $T_{L,e\star}$, on the other hand, shows a significant decrease, as the human controller is required to generate less lead in his visual response. These results are consistent with previous work on compensatory tasks [5, 8].

![Figure 5-15: Error response gain (a) and lead time constant (b)](image)

5-6-2 Neuromuscular system parameters

Regarding the neuromuscular system parameters, motion feedback also has an important effect. There is an increase in the neuromuscular frequency $\omega_{nms}$ for both displays (see Figure 5-16(a)), with a 14% increase in the compensatory case and a 4% increase in the preview case. The increase for the compensatory task is according to what is commonly found in literature, [7, 8]. The neuromuscular damping $\zeta_{nms}$ registers a 21% increase for the compensatory case and a 25% increase for the preview case when motion is added.

5-6-3 Visual time delay

The visual time delay shows different effects for the compensatory and preview conditions. Using the compensatory display, when motion is added there is a 12% increase in the visual
time delay, in line with what was reported in [8]. For the preview conditions, however, when motion is added there is a 24% decrease in the visual time delay.

![Figure 5-16: Neuromuscular system parameters: natural frequency (a) and damping ratio (b)](image)

Figure 5-17: Visual time delay

5-6-4 Far-viewpoint response parameters

The effect of motion feedback on the far-viewpoint gain $K_f$ is small (see Figure 5-18(a)). It should also be noted that the parameter is extremely consistent across subjects and essentially a unit gain. The change in the far-viewpoint time-constant $T_{i,f}$ and position $\tau_f$ are also
small, which suggest that motion feedback doesn’t have a substantial effect in the way human controllers use preview.

**Figure 5-18:** Far-viewpoint gain (a) and lead time constant (b)

**Figure 5-19:** Far-viewpoint position

### 5-6-5 Motion feedback parameters

For the compensatory tracking task, both the motion gain $K_m$ and the motion time delay $\tau_m$ are consistent with literature results [8].
The obtained Variance Accounted For, shown in Figure 5-21 is well above 70% for all subjects in all conditions, which suggests the models used are an adequate representation of the human behavior. The proposed model for preview with motion feedback registers the lowest VAF found out of all model fits, with 75%, which is still a high value for this measure. In general, the model fits the experimental data well. The high values for VAFs across conditions are also justified by the fact that the data was averaged in the frequency domain, as in [17].
In this research, a human-in-the-loop tracking experiment was performed to study the role of motion feedback in preview tracking tasks in comparison with compensatory tracking.

Motion feedback allows humans to improve their performance in compensatory tracking tasks, which is consistent with many earlier investigations ([2], [3], [4], [5], [6], [7], [8], [9]), and was also predicted by the offline model simulations. Using motion feedback, humans are able to adapt their behavior, by controlling the system with an higher gain and being required to generate less lead. This result is thus highly consistent with compensatory literature, and confirms Hypothesis I.

When no motion feedback is present, preview allows humans to improve their performance significantly, as predicted by the offline model simulations. The ability to see the future target allows humans to improve tracking performance, which confirms Hypothesis II. Human controllers respond to an internal error, filtered by the far-viewpoint response dynamics, as was found in the work of van der El et. al [16].

For preview tracking, the effect of motion is seemingly similar as in compensatory tracking. Motion still allows a significant improvement in performance, and the human adaptation is shown by an increase of the error response gain $K_e$, and a decrease of the lead time constant $T_{L,e}$. The results are the opposite as predicted by offline model simulations, in which motion
feedback caused a performance degradation for preview tasks. It can be seen, however, that
the reduction in error at the disturbance frequencies is found in the experiment results, par-
tially confirming Hypothesis III. However, we were not able to prove the use of the additional
motion channel $H_{om}$, due to the ambiguity of the proposed model. The predicted increase
in error for the target frequencies was not found, a difference that may well be explained by
human adaptation, which was not taken into account in the offline model simulations. Mo-
tion does not cause a change in the way human controllers use preview parameters, with the
far-viewpoint parameters registering only small changes. Control activity is not significantly
affected by the availability of motion feedback, as found for the compensatory case.

The offline model simulations which were performed for the prediction of the experimental
results were not accurate. The adaptation of the human controller, not taken into account for
the model simulations, was likely an important factor, and the variation of only one parameter
did not yield accurate predictions.

Regarding the parameter estimation results, even though the proposed model is able to fit
the data correctly, it is ambiguous regarding the parameters on the motion feedback loop.
Based on this fact, we recommend further research that is able to clearly separate the visual
and motion channels.

This research successfully showed for the first time the role of motion feedback on preview
tracking tasks: when preview information is available, human controllers are still able to
adapt their control behavior and improve tracking performance, without a substantial change
in control activity.
This project studied the effect of yaw motion feedback on human control behavior in preview tracking tasks. We proposed a new quasi-linear human controller model for visual and preview tracking tasks with an additional motion feedback channel. First, the model was tested in an offline model simulation to predict the effects of motion feedback in compensatory and preview tracking tasks. Second, a human-in-the-loop tracking experiment was performed in the SIMONA Research Simulator at TU Delft to validate the offline predictions. Results show that motion feedback helps to improve performance similarly in preview tasks, as it does in compensatory tasks, with an increase in the error response gain and a reduction in the lead time constant. The target crossover frequency and phase margin are mostly influenced by preview, while the disturbance crossover frequency is mostly influenced by the motion feedback. With this research, the effects of motion feedback in preview were studied for the first time, effectively allowing to bridge the knowledge gap between compensatory tasks with motion and preview tasks, by showing that human controllers use motion feedback in preview tracking to adapt their control behavior.


7-1 Future Work

On the topic of preview with motion feedback, two main future research paths remain to be followed: further analysis of motion feedback and more realistic tracking tasks. On the one hand, the problem of separating the motion from the visual response still remains. In this sense, it would be important to develop a type of task or experiment which can truly separate the two channels. On the other hand, preview tasks can become more realistic, in an effort to bring preview research closer to driving simulation. One possible step would be to add vertical and horizontal perspective to the preview line in order to understand how the human response can be modeled in such a situation.


[7] Daan M. Pool, Herman J. Damveld, Marinus M. van Paassen, and Max Mulder. Tuning Models of Pilot Tracking Behavior for a Specific Simulator Motion Cueing Setting. In


The following pages contain the experiment briefing that was handed to the test subjects. This document contains all the information the subjects were required to know prior to starting the experiment. The briefing starts with a small description of the experiment and its objectives. Then it explains the control task to be performed and the experimental apparatus and procedure. The briefing is concluded by the description of the rights of the participant.
Role of Motion Feedback on Preview Tracking Tasks

In this experiment, we aim at finding what is the effect of motion feedback in a preview tracking task. The effects of motion in compensatory tasks were studied in the past, and we intend to extend that knowledge to preview tasks. For the experiment, a preview display inside the SIMONA Research Simulation Cockpit will be used, presenting both compensatory and preview displays, with and without motion feedback.

A-1 Objectives

The goal of this experiment is to understand how humans use motion feedback for a preview tracking task. On the one hand, effect of motion feedback in compensatory tasks is widely known and studied. On the other hand, previous research at the Faculty of Aerospace Engineering was able to obtain a model for preview tracking tasks. The current experiment aims to connect these two pieces of knowledge, by understanding how motion influences the preview task.

A-2 Control task

The control task in this experiment is a combined disturbance-rejection and target-following task, as can be seen in Figure A-1. Depending on the condition, the task will be performed with compensatory or preview displays, see Figure 2-1. The compensatory display (Fig. 2 (a)) presents a cross with the current tracking error, and a fixed circle in the center, representing the "crosshair". Your objective is to reduce the error, by placing the circle over the cross as accurately as possible. The preview display (Fig 2 (b)) shows a moving circle which represents the controlled element output. Two seconds of preview will be shown, displaying how the target will move for that period of time, represented by a curved line. The current target
position is the bottom of the preview line. The error can be deduced by the difference between \( x \) and \( f_t \). Both displays have an inside-out representation.

Your objective is to track the target, following the visual \( f_t \) signal. The output \( x \) is, for the motion case, the yaw rotation of the simulator. This output will be perturbed by the disturbance signal \( f_d \).

![Block diagram of the combined target-tracking and disturbance rejection task](image)

**Figure A-1:** Block diagram of the combined target-tracking and disturbance rejection task

![Compensatory (a) and preview display (b)](image)

**Figure A-2:** The compensatory (a) and preview display (b)

### A-3 Experimental apparatus

In this experiment, the SIMONA Research Simulator will be used. You will be seated on the right seat of the simulator cockpit, and use a side-stick to your right to provide the control input, by moving the stick to the left and right. The task will be presented on the primary flight display, in black background with green lines. For the motion case, the motion cue will be the yaw rotation of the simulator. All other motion cues are inactive.
A-4 Experimental conditions

The conditions will include two different displays and two different motion conditions. The displays will compensatory and preview, as described before. Regarding the motion feedback, there will be conditions without motion feedback, and conditions with yaw rotation of the simulator cockpit. This yields a total of four experimental conditions: compensatory without motion, compensatory with motion, preview without motion and preview with motion.

A-5 Experimental procedure

The experiment will consist of two main phases: a familiarization and a measurement phase. During the familiarization phase, you will have the time to get used to the displays, control task and motion feedback by performing a limited number of runs of each condition. During the training/measurement phase, the experimenter will track your performance, and after it is sufficiently stable, the actual measurement will start. In total, 8-10 runs are expected for each condition.

The experimenter will report your performance after each run, using the root mean square of the error between the target and your position. A lower value indicates a better performance.

The four experimental conditions will be tested in a random order. Each run will last for two minutes, and each condition is expected to take around 30 minutes. There will be breaks between conditions in order to avoid fatigue. The total experiment time is expected to be around 3 hours.

A-6 Your rights

Your participation in this experiment is voluntary, and you can terminate it at any time,
before or during the experiment.

The data collected in this experiment is anonymous and confidential. The treatment and presentation of the data will be done in a way so that only the experimenter can link the results to the participants, and all participants will remain anonymous. Your participation means that you allow the data to be published.

In order to confirm that you agree and understand all of the above, you will be asked to sign an informed consent form before you start the experiment.
The experiment performed in this report was a human-in-the-loop experiment on the SIMONA Research Simulator. In such an experiment, human factors play a large role in the results, thanks to the effects of fatigue, motivation, training, and others. In order to avoid confounds in the results, a balanced Latin-square design is used, so that the effect of these factors is minimized in the results.

Table B-1: Balanced Latin-Square Design

<table>
<thead>
<tr>
<th>Subject</th>
<th>Experimental order</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P  PM  C  CM</td>
</tr>
<tr>
<td>2</td>
<td>CM C PM P</td>
</tr>
<tr>
<td>3</td>
<td>PM CM P C</td>
</tr>
<tr>
<td>4</td>
<td>C  P  CM PM</td>
</tr>
<tr>
<td>5</td>
<td>P  PM C CM</td>
</tr>
<tr>
<td>6</td>
<td>CM C PM P</td>
</tr>
<tr>
<td>7</td>
<td>PM CM P C</td>
</tr>
<tr>
<td>8</td>
<td>C  P  CM PM</td>
</tr>
</tbody>
</table>
Appendix C

Choice of Control Variables

In this chapter, the process of choice of the different control variables in the experiment is outlined. The first section details the choice of the forcing function, while the second explains the choice of the display. The motion and controlled element choices are also explained in the following sections. In all of these elements, there was a compromise between similarity with previous literature on visual preview tracking experiments and previous compensatory tracking experiments with motion feedback.

C-1 Forcing Functions

Designing a forcing function for a simulator experiment requires finding a target and disturbance signal that include a number of characteristics. The signals need to be realistic and challenging but not too difficult to follow, as this tires the experiment subjects. Using motion feedback, they also need to be designed in such a way they are comfortable inside the simulator and do not pose a large risk of motion sickness on subjects.

The forcing functions used in previous preview experiments have an amplitude distribution as represented in Figure C-1. This forcing function, used by [16, 18] uses double-bands of input frequencies, and an amplitude step of -10dB at the higher frequencies.
When these forcing functions were tested with motion feedback, test subjects weren’t able to complete the experiment. The amplitude of the disturbance signal was too high for the task to be comfortable for the subjects using motion feedback. It was also noted that the forcing function included too many high frequencies for it to be realistic. In an effort to mitigate the first problem, it was decided to use a larger amplitude step. Tests were done using a -20db and a -26dB step, but none of these forcing functions were able to be both challenging and comfortable for the subjects.

In previous motion feedback experiments, single-band forcing functions were used. Regarding the amplitudes, instead of using an amplitude step, an amplitude filter is used. A common amplitude filter, found in literature regarding motion feedback, is shown in Equation (C-1).

\[ H_A(j\omega) = \frac{(1 + 0.1j\omega)^2}{(1 + 0.8j\omega)^2} \]  

(C-1)

This filter yields forcing functions with a power spectra such as can be seen in Figure C-2 [6]. Combining these two types of forcing functions, a new forcing function was designed for the present experiment. This forcing function includes the double-bands at the same frequencies as in [16] and the amplitude filter used in [6]. The final forcing function power spectra can be seen in Figure C-3. When this forcing function was tested in the simulator, test subjects were able to perform the task, using a comfortable yet challenging forcing function. It should be noted that, since the disturbance signal is inserted before the controlled element, it was
filtered with the inverse controlled element dynamics.

C-2 Display

The preview display used in previous preview tracking experiments is shown in Figure C-4 [16, 18]. Since the compensatory display only shows the error, it uses a fixed reference for the controlled element output. With this in mind, it was decided to use an inside-out preview display, with a fixed controlled element output and a moving preview line. The final displays used in the experiment are shown in Figure 2-1.
C-3 Motion Feedback

Three different types of motion feedback were initially considered for the experiment: lateral position, yaw and roll. These three types were chosen as they have a direct and easy to understand translation to preview control. Pitch was excluded, since the use of preview for pitch would require a different display from previous experiments, and the adaptation to such a display is not as straightforward as the other motion cues.

The mental image most commonly associated with preview is that of flying over a road or a river, using a birds-eye view. With this in mind, it was decided to test the control of the lateral position, which is the most straightforward approach to preview with motion feedback. The test runs conducted with this motion cue did not yield good results, as the motion cue was unpleasant to the test subjects. Test subjects felt the disturbance very strongly, and were not able to feel the movement following the target signal.
It was decided to test yaw as a second option for the motion cue. For this type of motion feedback, subjects no longer reported the previous issues, and it was defined the experiment would use yaw as the motion cue.

C-4 Controlled Element

In experiments using motion feedback, two classes of models have been used: models that approximate aircraft dynamics[6, 9] and simplified systems that approximate realistic dynamics in a certain frequency region, like gain, integrator or double integrator dynamics [8, 16].

Considering that previous preview experiments used integrators [16, 18], it was decided to use a controlled element of that type in the experiment, in order to reduce the number of different control variables from the present experiment to this literature.

It was also decided to test only the double integrator condition, disregarding gain and single integrator dynamics. In studies such as [8], it is found that the motion channel is clearly active for these dynamics, and humans indeed adapt their behavior to the motion feedback. This condition was also studied in preview experiments. It is therefore a controlled element which allows to connect previous studies, and testing only one dynamic also allows to reduce the number of experimental conditions and the experiment time demanded to the subjects.
Appendix  D

Variance Results

The variances of the error and control activity were obtained using the integration of the power spectral density. This method allows to separate the contribution of the target, disturbance and remnant frequencies. In the following figures, the contributions of each of these frequencies are shown for each of the eight test subjects are shown as gray bars. The average and 95% confidence interval are shown in black. The total variance split in the different contributions is also shown per subject.
Figure D-1: Variance of the tracking error (a) and control activity (b) for all subjects, split into target, disturbance and remnant frequencies

Figure D-2: Variance of the tracking error (a) and control activity (b) for target frequencies

Figure D-3: Variance of the tracking error (a) and control activity (b) for disturbance frequencies
Figure D-4: Variance of the tracking error (a) and control activity (b) for remnant frequencies
Appendix E

Estimated Model Parameters

The model parameters were estimated for each subject, for the average in the frequency domain of five measurement runs. 100 optimization runs, each starting with a different parameter set, were conducted. In the following tables, the full results for the parameter estimation are presented, for each of the four experimental conditions and for the eight test subjects.

Table E-1: Parameters for the compensatory task

<table>
<thead>
<tr>
<th>Subject</th>
<th>$K_e$</th>
<th>$T_{e,L}$</th>
<th>$\omega_{nm,s}$</th>
<th>$\zeta_{nm,s}$</th>
<th>$\tau_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0.972</td>
<td>8.937</td>
<td>0.208</td>
<td>0.201</td>
</tr>
<tr>
<td>2</td>
<td>0.422</td>
<td>0.942</td>
<td>8.400</td>
<td>0.285</td>
<td>0.277</td>
</tr>
<tr>
<td>3</td>
<td>0.444</td>
<td>1.057</td>
<td>12.487</td>
<td>0.167</td>
<td>0.235</td>
</tr>
<tr>
<td>4</td>
<td>0.368</td>
<td>1.040</td>
<td>10.782</td>
<td>0.184</td>
<td>0.248</td>
</tr>
<tr>
<td>5</td>
<td>0.198</td>
<td>2.105</td>
<td>9.804</td>
<td>0.250</td>
<td>0.257</td>
</tr>
<tr>
<td>6</td>
<td>0.346</td>
<td>1.397</td>
<td>11.101</td>
<td>0.223</td>
<td>0.263</td>
</tr>
<tr>
<td>7</td>
<td>0.433</td>
<td>0.891</td>
<td>9.195</td>
<td>0.169</td>
<td>0.254</td>
</tr>
<tr>
<td>8</td>
<td>0.442</td>
<td>1.119</td>
<td>11.934</td>
<td>0.290</td>
<td>0.262</td>
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</table>
Table E-2: Parameters for the compensatory task with motion feedback

<table>
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<th>Subject</th>
<th>$K_e$</th>
<th>$T_{L,e}$</th>
<th>$\omega_{nms}$</th>
<th>$\zeta_{nms}$</th>
<th>$\tau_v$</th>
<th>$K_m$</th>
<th>$\tau_m$</th>
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</thead>
<tbody>
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<td>0.276</td>
<td>0.260</td>
<td>0.438</td>
<td>0.118</td>
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<tr>
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<td>0.751</td>
<td>9.192</td>
<td>0.410</td>
<td>0.288</td>
<td>0.149</td>
<td>0.176</td>
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<tr>
<td>3</td>
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<td>0.368</td>
<td>14.429</td>
<td>0.086</td>
<td>0.277</td>
<td>0.350</td>
<td>0.210</td>
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<tr>
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<td>0.483</td>
<td>11.327</td>
<td>0.206</td>
<td>0.267</td>
<td>0.225</td>
<td>0.152</td>
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<tr>
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<td>0.452</td>
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<td>0.295</td>
<td>0.306</td>
<td>0.264</td>
<td>0.213</td>
</tr>
<tr>
<td>6</td>
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<td>0.660</td>
<td>13.221</td>
<td>0.333</td>
<td>0.283</td>
<td>0.188</td>
<td>0.261</td>
</tr>
<tr>
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<td>0.466</td>
<td>10.997</td>
<td>0.259</td>
<td>0.284</td>
<td>0.331</td>
<td>0.130</td>
</tr>
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<td>0.252</td>
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Table E-3: Parameters for the preview task

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<th>Subject</th>
<th>$K_e$</th>
<th>$T_{L,e}$</th>
<th>$\omega_{nms}$</th>
<th>$\zeta_{nms}$</th>
<th>$\tau_v$</th>
<th>$K_f$</th>
<th>$T_{L,f}$</th>
<th>$\tau_f$</th>
</tr>
</thead>
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<td>13.872</td>
<td>0.389</td>
<td>0.275</td>
<td>0.763</td>
<td>0.433</td>
<td>0.805</td>
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<td>0.276</td>
<td>0.946</td>
<td>0.969</td>
<td>1.250</td>
</tr>
<tr>
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<td>0.770</td>
<td>14.082</td>
<td>0.105</td>
<td>0.221</td>
<td>0.994</td>
<td>0.682</td>
<td>0.742</td>
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<tr>
<td>4</td>
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<td>0.731</td>
<td>11.966</td>
<td>0.076</td>
<td>0.208</td>
<td>0.963</td>
<td>0.525</td>
<td>0.581</td>
</tr>
<tr>
<td>5</td>
<td>0.306</td>
<td>1.769</td>
<td>10.915</td>
<td>0.087</td>
<td>0.239</td>
<td>0.866</td>
<td>0.385</td>
<td>0.643</td>
</tr>
<tr>
<td>6</td>
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<td>0.938</td>
<td>10.791</td>
<td>0.143</td>
<td>0.245</td>
<td>0.942</td>
<td>0.684</td>
<td>0.758</td>
</tr>
<tr>
<td>7</td>
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<td>10.295</td>
<td>0.127</td>
<td>0.229</td>
<td>0.876</td>
<td>0.249</td>
<td>0.711</td>
</tr>
<tr>
<td>8</td>
<td>0.827</td>
<td>0.680</td>
<td>11.172</td>
<td>0.163</td>
<td>0.205</td>
<td>0.977</td>
<td>0.656</td>
<td>0.650</td>
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</table>

Table E-4: Parameters for the preview task with motion feedback

<table>
<thead>
<tr>
<th>Subject</th>
<th>$K_e$</th>
<th>$T_{L,e}$</th>
<th>$\omega_{nms}$</th>
<th>$\zeta_{nms}$</th>
<th>$\tau_v$</th>
<th>$K_f$</th>
<th>$T_{L,f}$</th>
<th>$\tau_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.823</td>
<td>0.614</td>
<td>10.397</td>
<td>0.293</td>
<td>0.172</td>
<td>0.971</td>
<td>0.780</td>
<td>0.749</td>
</tr>
<tr>
<td>2</td>
<td>0.411</td>
<td>1.060</td>
<td>11.410</td>
<td>0.452</td>
<td>0.228</td>
<td>0.962</td>
<td>0.754</td>
<td>0.863</td>
</tr>
<tr>
<td>3</td>
<td>0.961</td>
<td>0.626</td>
<td>14.394</td>
<td>0.092</td>
<td>0.191</td>
<td>1.026</td>
<td>0.705</td>
<td>0.682</td>
</tr>
<tr>
<td>4</td>
<td>1.067</td>
<td>0.574</td>
<td>11.841</td>
<td>0.157</td>
<td>0.158</td>
<td>1.006</td>
<td>0.551</td>
<td>0.549</td>
</tr>
<tr>
<td>5</td>
<td>1.135</td>
<td>0.553</td>
<td>13.363</td>
<td>0.132</td>
<td>0.162</td>
<td>0.997</td>
<td>0.658</td>
<td>0.614</td>
</tr>
<tr>
<td>6</td>
<td>0.612</td>
<td>0.802</td>
<td>11.652</td>
<td>0.245</td>
<td>0.194</td>
<td>0.999</td>
<td>0.754</td>
<td>0.706</td>
</tr>
<tr>
<td>7</td>
<td>1.097</td>
<td>0.552</td>
<td>11.340</td>
<td>0.223</td>
<td>0.141</td>
<td>1.021</td>
<td>0.668</td>
<td>0.657</td>
</tr>
<tr>
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<td>0.688</td>
<td>11.208</td>
<td>0.122</td>
<td>0.196</td>
<td>1.020</td>
<td>0.719</td>
<td>0.654</td>
</tr>
</tbody>
</table>
In this section, the effects of the near-viewpoint response for the preview conditions will be analyzed. This section includes the comparison of the frequency response function, parameter estimation results and Variance Accounted For, for the preview conditions with and without motion feedback.

**F-1 Proposed Model with Near-Viewpoint Response**

The preview model for motion, including the near-viewpoint, is presented in Figure F-1.

![Diagram of proposed model](image)

**Figure F-1**: Proposed model included near-viewpoint response as in Van der El *et al.*

The near-viewpoint response is modeled as a pure differentiator, as proposed in [17]:

\[
\frac{df_t(t)}{dt} = f(t + \tau_n) - f(t)
\]
$$H_{on} = K_n j\omega$$  \hspace{1cm} (F-1)

in which $K_n$ stands for the near-viewpoint gain. The use of this model includes two extra parameters to estimate: the near-viewpoint gain $K_n$ and the near-viewpoint position $\tau_n$.

**F-2 Frequency Response Functions**

In the Figures 10-2 to 10-9, the frequency response functions of the model with and without near-viewpoint response are presented for all the experiment subjects.
Figure F-2: Frequency response functions for Subject 1, for the preview condition without motion feedback (a) and with motion feedback (b), with and without the near-viewpoint response.
Figure F-3: Frequency response functions for Subject 2, for the preview condition without motion feedback (a) and with motion feedback (b), with and without the near-viewpoint response.
Figure F-4: Frequency response functions for Subject 3, for the preview condition without motion feedback (a) and with motion feedback (b), with and without the near-viewpoint response.
Figure F-5: Frequency response functions for Subject 4, for the preview condition without motion feedback (a) and with motion feedback (b), with and without the near-viewpoint response.
Figure F-6: Frequency response functions for Subject 5, for the preview condition without motion feedback (a) and with motion feedback (b), with and without the near-viewpoint response.
Figure F-7: Frequency response functions for Subject 6, for the preview condition without motion feedback (a) and with motion feedback (b), with and without the near-viewpoint response.
Figure F-8: Frequency response functions for Subject 7, for the preview condition without motion feedback (a) and with motion feedback (b), with and without the near-viewpoint response.
Figure F-9: Frequency response functions for Subject 8, for the preview condition without motion feedback (a) and with motion feedback (b), with and without the near-viewpoint response
F-3 Parameter Estimation Results

The parameter estimate results including the near-viewpoint response are presented in the following tables.

**Table F-1:** Parameters for the preview task

<table>
<thead>
<tr>
<th>Subject</th>
<th>$K_e, s$</th>
<th>$T_{L,e}, s$</th>
<th>$\omega_{nms}, rad/s$</th>
<th>$\zeta_{nms}, -$</th>
<th>$\tau_v, s$</th>
<th>$\tau_n, s$</th>
<th>$K_f,-$</th>
<th>$T_{L,f}, s$</th>
<th>$\tau_f, s$</th>
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</thead>
<tbody>
<tr>
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<td>0.000</td>
<td>0.896</td>
<td>0.894</td>
<td>0.696</td>
</tr>
<tr>
<td>2</td>
<td>0.276</td>
<td>1.365</td>
<td>7.997</td>
<td>0.270</td>
<td>0.278</td>
<td>0.065</td>
<td>0.522</td>
<td>0.935</td>
<td>1.234</td>
</tr>
<tr>
<td>3</td>
<td>0.769</td>
<td>0.764</td>
<td>14.077</td>
<td>0.100</td>
<td>0.221</td>
<td>0.031</td>
<td>0.314</td>
<td>1.000</td>
<td>0.737</td>
</tr>
<tr>
<td>4</td>
<td>0.106</td>
<td>5.787</td>
<td>12.349</td>
<td>0.093</td>
<td>0.235</td>
<td>0.000</td>
<td>0.508</td>
<td>0.914</td>
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</tr>
<tr>
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<td>0.621</td>
<td>0.751</td>
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<tr>
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<td>0.951</td>
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<td>0.137</td>
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<td>0.022</td>
<td>0.332</td>
<td>0.945</td>
<td>0.740</td>
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<tr>
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<td>6.986</td>
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<td>0.172</td>
<td>0.483</td>
<td>0.567</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>0.734</td>
<td>0.780</td>
<td>11.569</td>
<td>0.144</td>
<td>0.217</td>
<td>0.066</td>
<td>0.270</td>
<td>0.987</td>
<td>0.791</td>
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</table>

**Table F-2:** Parameters for the preview task with motion feedback

<table>
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<th>Subject</th>
<th>$K_e, s$</th>
<th>$T_{L,e}, s$</th>
<th>$\omega_{nms}, rad/s$</th>
<th>$\zeta_{nms}, -$</th>
<th>$\tau_v, s$</th>
<th>$\tau_n, s$</th>
<th>$K_f,-$</th>
<th>$T_{L,f}, s$</th>
<th>$\tau_f, s$</th>
<th>$K_m,-$</th>
<th>$\tau_m, s$</th>
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<tbody>
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<td>0.836</td>
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<td>0.883</td>
<td>0.000</td>
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<td>0.185</td>
<td>0.130</td>
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<td>0.603</td>
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<tr>
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<td>1.470</td>
<td>12.132</td>
<td>0.270</td>
<td>0.136</td>
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<td>0.335</td>
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<td>0.000</td>
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<td>0.334</td>
<td>0.670</td>
<td>0.921</td>
<td>0.404</td>
<td>1.272</td>
<td>0.818</td>
</tr>
<tr>
<td>8</td>
<td>1.308</td>
<td>0.130</td>
<td>12.151</td>
<td>0.204</td>
<td>0.051</td>
<td>0.000</td>
<td>0.249</td>
<td>0.959</td>
<td>0.193</td>
<td>0.429</td>
<td>0.324</td>
</tr>
</tbody>
</table>
F-4 Variance Accounted For

The Variance Accounted For is a measure of the quality of the model fit. If including the near-viewpoint response lead to a substantial increase in the VAF of the model, there would be a reason to include it in the final model. The results of the VAF per subject are presented in Figure F-10.

![Figure F-10: Variance Accounted For with (grey) and without (black) near-viewpoint](image)

F-5 Model Comparison

For most subjects, there are no substantial changes in the describing function using the near-viewpoint response. The model without near-viewpoint is able to successfully model the response. It should be noted that the obtained parameters are different from the parameter estimates without using a near-viewpoint. The introduction of two extra parameters to estimate leads to a larger estimation uncertainty in the remaining parameters. It is also clear that the near-viewpoint gain $K_n$, for most subjects, has a small value. Regarding the Variance Accounted For, no significant difference is found using the near-viewpoint response.

Considering these facts, it was decided not to include the near-viewpoint response in the proposed model, to be presented in the results.
In this section, the results for the preview task with motion feedback are presented, using both the proposed model for preview with motion feedback and the van der El et al model, without the motion feedback channel. The frequency response functions, parameter estimates and Variance Accounted For are presented for the eight experiment subjects, for both models.

G-1 Frequency Response Functions

The frequency response functions for the eight experiment subjects are presented in the following figures. In each image, the two Bode diagrams of the describing functions $H_o$ and $H_{ox}$ are presented. The grey lines present the proposed model fit, the black lines the van der El et al model fit, and the black dots the Fourier coefficients.
Figure G-1: Frequency response functions for Subject 1, for the van der El model and the proposed model including motion feedback

Figure G-2: Frequency response functions for Subject 2, for the van der El model and the proposed model including motion feedback
Figure G-3: Frequency response functions for Subject 3, for the van der El model and the proposed model including motion feedback

Figure G-4: Frequency response functions for Subject 4, for the van der El model and the proposed model including motion feedback
Figure G-5: Frequency response functions for Subject 5, for the van der El model and the proposed model including motion feedback.

Figure G-6: Frequency response functions for Subject 6, for the van der El model and the proposed model including motion feedback.
Figure G-7: Frequency response functions for Subject 7, for the van der El model and the proposed model including motion feedback

Figure G-8: Frequency response functions for Subject 8, for the van der El model and the proposed model including motion feedback
G-2 Model Parameters

The model parameters are presented in the following tables, for the van der El et. al model and the proposed model.

Table G-1: Parameters for the preview task with motion feedback using the proposed model

<table>
<thead>
<tr>
<th>Subject</th>
<th>$K_e$, $-T_{L,e}, s$</th>
<th>$\omega_{nms}, rad/s$</th>
<th>$\zeta_{nms}, -$</th>
<th>$\tau_e, s$</th>
<th>$K_f$, $-T_{L,f}, s$</th>
<th>$\tau_f, s$</th>
<th>$K_m$, $\tau_m, s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.574 0.547</td>
<td>11.857</td>
<td>0.442</td>
<td>0.158</td>
<td>0.899 0.196</td>
<td>0.622</td>
<td>0.220 0.319</td>
</tr>
<tr>
<td>2</td>
<td>0.522 0.071</td>
<td>10.032</td>
<td>0.593</td>
<td>0.173</td>
<td>0.892 0.001</td>
<td>0.829</td>
<td>0.373 0.283</td>
</tr>
<tr>
<td>3</td>
<td>1.110 0.017</td>
<td>14.251</td>
<td>0.122</td>
<td>0.009</td>
<td>0.940 0.000</td>
<td>0.377</td>
<td>0.364 0.299</td>
</tr>
<tr>
<td>4</td>
<td>0.420 1.285</td>
<td>11.965</td>
<td>0.125</td>
<td>0.232</td>
<td>0.977 0.263</td>
<td>0.573</td>
<td>0.133 0.137</td>
</tr>
<tr>
<td>5</td>
<td>0.971 0.323</td>
<td>14.621</td>
<td>0.104</td>
<td>0.102</td>
<td>0.934 0.177</td>
<td>0.500</td>
<td>0.284 0.326</td>
</tr>
<tr>
<td>6</td>
<td>0.591 0.331</td>
<td>12.614</td>
<td>0.399</td>
<td>0.137</td>
<td>0.945 0.162</td>
<td>0.602</td>
<td>0.275 0.303</td>
</tr>
<tr>
<td>7</td>
<td>0.719 0.589</td>
<td>15.164</td>
<td>0.119</td>
<td>0.144</td>
<td>0.968 0.166</td>
<td>0.535</td>
<td>0.230 0.383</td>
</tr>
<tr>
<td>8</td>
<td>0.973 0.013</td>
<td>11.679</td>
<td>0.136</td>
<td>0.000</td>
<td>0.956 0.151</td>
<td>0.547</td>
<td>0.380 0.315</td>
</tr>
</tbody>
</table>

Table G-2: Parameters for the preview task with motion feedback using the van der El model

<table>
<thead>
<tr>
<th>Subject</th>
<th>$K_e$, $-T_{L,e}, s$</th>
<th>$\omega_{nms}, rad/s$</th>
<th>$\zeta_{nms}, -$</th>
<th>$\tau_e, s$</th>
<th>$K_f$, $-T_{L,f}, s$</th>
<th>$\tau_f, s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.823 0.614</td>
<td>10.397</td>
<td>0.293</td>
<td>0.172</td>
<td>0.971 0.780</td>
<td>0.749</td>
</tr>
<tr>
<td>2</td>
<td>0.411 1.060</td>
<td>11.410</td>
<td>0.452</td>
<td>0.228</td>
<td>0.962 0.754</td>
<td>0.863</td>
</tr>
<tr>
<td>3</td>
<td>0.961 0.626</td>
<td>14.394</td>
<td>0.092</td>
<td>0.191</td>
<td>1.026 0.705</td>
<td>0.682</td>
</tr>
<tr>
<td>4</td>
<td>1.067 0.574</td>
<td>11.841</td>
<td>0.157</td>
<td>0.158</td>
<td>1.006 0.551</td>
<td>0.549</td>
</tr>
<tr>
<td>5</td>
<td>1.135 0.553</td>
<td>13.363</td>
<td>0.132</td>
<td>0.162</td>
<td>0.997 0.658</td>
<td>0.614</td>
</tr>
<tr>
<td>6</td>
<td>0.612 0.802</td>
<td>11.652</td>
<td>0.245</td>
<td>0.194</td>
<td>0.999 0.754</td>
<td>0.706</td>
</tr>
<tr>
<td>7</td>
<td>1.097 0.552</td>
<td>11.340</td>
<td>0.223</td>
<td>0.141</td>
<td>1.021 0.668</td>
<td>0.657</td>
</tr>
<tr>
<td>8</td>
<td>0.820 0.688</td>
<td>11.208</td>
<td>0.122</td>
<td>0.196</td>
<td>1.020 0.719</td>
<td>0.654</td>
</tr>
</tbody>
</table>

G-3 Variance Accounted For

The Variance Accounted For is presented in Figure G-9 for both models.
G-4 Model Comparison

When analyzing the describing functions, it is clear that the visual channel from the van der El et al model is able to model the response. The additional motion feedback channel in the proposed model doesn’t make a substantial difference in the resulting describing function. There is a change in some of the parameters when using the van der El et al model, most notably the lead-time constant $T_{L,e}$, the time delay $\tau_v$ and the far-viewpoint time constant $T_{l,f}$. No substantial difference is found in the Variance Accounted For of the models.