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# Interactions of Outside Visual Cues and Motion Cueing Settings in Yaw Tracking

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Knowledge of how human operators' tracking behavior is affected by simulator motion cueing settings is of great value for flight simulator design and fidelity evaluations. Previous studies have revealed strong effects of degraded motion cueing quality on human operator control behavior in compensatory tracking, but the presented visual cues in such studies are often not consistent with what operators perceive in more realistic settings, as they typically do not include the visual cues provided by the out-of-the-window view from their vehicle. This paper aims to investigate the effects of the interaction of such outside visual cues and of motion cueing settings on human operator behavior. Thereto, an experiment in a flight simulator was conducted in which participants performed a yaw-axis target-following disturbance-rejection tracking task. The presence of an outside visual scene and simulator motion feedback quality were varied independently. In the experiment, motion cues were either absent or presented with varying attenuation induced by changing the break frequency of a first-order high-pass yaw motion filter. The results indicate a strong effect of outside visual cues on human operator control behavior in the absence of motion feedback, which is comparable to the measured effect of motion feedback. Overall, human operator control behavior was found to be less affected by varying motion cueing settings when the outside visual cues were available in parallel.

## I. Introduction

In real flight, the pilots perceive matching and redundant visual and physical motion cues as feedbacks on the motion of their vehicle, in addition to the information provided by the cockpit's instrumentation. To create a realistic sensation of flight in simulators, these cues must both be simulated in a virtual environment at a sufficient level of fidelity.<sup>1</sup> To do this adequately, it must be understood how a visualization of the view from the aircraft's cockpit – referred to as an outside visual – and the simulator's inertial motion cues individually influence the simulator realism and hence its fidelity, but also how they interact in doing so. Due to the physical limitations of the simulator's motion system, inertial motion cues must often be attenuated and filtered.<sup>2,3</sup> This is done by so called motion cueing algorithms (or motion filters), which induce inherent differences between the visual and physical motion stimuli provided in simulators. The mismatch is a direct result of the chosen motion filter parameters (gains and break frequencies) and affects the fidelity of the flight simulator.<sup>2,4–7</sup> Knowledge on how human tracking behavior is affected by choices in motion filter settings is of great value for flight simulator design.

One approach considered for evaluating simulator fidelity is based on objective measures of human tracking behavior obtained from a *cybernetic approach*.<sup>8–10</sup> By comparing such measures in compensatory tracking tasks with and without physical motion cues, previous studies have shown that motion feedback strongly influences human operators' behavior when lead equalization is required.<sup>11–14</sup> Furthermore, it was found that as the quality of motion feedback degrades, by changes in the motion filter settings, human operators' tracking behavior approaches behavior as measured without motion feedback.<sup>2,15–17</sup> The performance increase observed for the addition of motion feedback reduces, as the mismatch of the motion cues increases, which is attributed to a reduction in control gain and an increase in the amount of visual lead generated.

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Unfortunately, the effects of degraded motion feedback on human operator behavior have nearly exclusively been studied in tracking tasks with pure compensatory displays. For these experiments, participants were provided with no additional visual cues than the tracking error presented on a (head-down) display. In other studies it has been shown, however, that providing human operators with feedback as available from outside visual cues *does* affect human tracking behavior.<sup>12,18–21</sup> Some studies have suggested that operators use the velocity of their vehicle as perceived from outside visual cues equivalent to how they use motion feedback for generating lead, though not as effectively.<sup>12,18,21</sup> Some experiment data even suggests that the information provided by visual velocity cues becomes redundant.<sup>12,18</sup> How the findings concerning the effects of motion cueing settings on tracking behavior translate to tasks with additional visual cues is as of yet still unknown, as the combined effects of these cues and of varying motion cueing settings have not been explicitly investigated.

In this paper this problem is addressed through a human-in-the-loop experiment conducted in the SIMONA Research Simulator (SRS) at TU Delft. The goal of the current study is to perform an explicit side-by-side comparison of the effects of varying motion cueing settings on human tracking behavior with and without an outside visual present. This is realized by measuring tracking behavior in a similar target-following disturbance-rejection yaw-axis tracking task as considered in an earlier experiment by Beckers et al.,<sup>22</sup> but where the presence of an outside visual scene and variations in the provided motion feedback are independently varied. In the experiment, a compensatory display is presented to participants using a head-up-display (HUD), overlaid on either a homogeneous black background or a realistic outside visual scene. The controlled element dynamics are a low-order of AH-64 Apache yaw dynamics,<sup>3,14,22,23</sup> which are known to require significant human operator lead equalization. A no motion feedback condition was tested, in addition to three different break frequency settings for a unity-gain high-pass yaw motion filter (0, 0.58, and 1.73 rad/s), resulting in 0 deg, 30 deg, and 60 deg phase distortion at 1 rad/s. Using measured tracking performance, control activity, crossover frequencies and phase margins, and estimated parameters of a multi-modal human operator model, the interaction of the outside visual cues and the varying motion cueing quality is quantified explicitly.

Background information regarding the control task considered in this paper is treated first, in Section II, as well as some known effects of additional (outside) visual cues on tracking behavior. Second, the methods for the human-inthe-loop experiment are described in Section III. The results of this experiment are presented in Section IV. Thereafter, in Section V, these results are discussed. Finally the conclusions regarding this study are given in Section VI.

# **II.** Background

#### **II.A.** Control Task

To measure the effects of degrading quality of motion feedback on human operator tracking behavior with and without additional outside visual cues, the same yaw-axis tracking task as studied in Ref. 22 is considered. In this tracking task the human operator is presented with the tracking error e on a HUD shown in Figure 1, in which the lateral displacement of the green line with respect to the fixed crosshair indicates the tracking error. In the current study, the compensatory HUD was overlaid either on a homogeneous black background as shown in Figure 1(a), or on an outside visual scene of Schiphol Airport as shown in Figure 1(b). The tracking error e, which is to be minimized by the human operator, is the difference between the controlled element yaw attitude  $\psi$  and the target signal  $f_t$ . While tracking the target signal the controlled element is also perturbed by a disturbance signal  $f_d$ . This type of control task is known as a target-following disturbance-rejection task and allows for multi-modal human operator identification and modeling.<sup>24,25</sup>

In the considered tracking task participants were also presented with yaw motion feedback. In case the visual scene or yaw motion feedback are available, human operators have different sources of feedback information that may (or may not) be used for control. Human control behavior in tracking tasks is generally modeled as a set of linear responses to the perceived variables and a remnant signal *n* that accounts for noise and the nonlinear part of the operator's response.<sup>26,27</sup> A schematic representation of the control task and human operator control organization for our task is given in Figure 2, which is based on previous research by Hosman and Van der Vaart.<sup>12,28</sup> In this figure, the human operator's linear response to the tracking error is indicated by  $H_{p_e}(j\omega)$ , while his linear responses to the provided physical motion cues and the outside visual cues are indicated by  $H_{p_m}(j\omega)$  and  $H_{p_{ov}}(j\omega)$ , respectively. It can be observed in Figure 2 that the yaw acceleration  $\ddot{\psi}$  is passed through a motion filter  $H_{mf}(j\omega)$  before reaching the operator. The resulting operator's control input *u* is a summation of the linear responses and the remnant *n*. The stick gain is denoted by  $K_s$  and the corresponding control surface deflection is symbolized as  $\delta_r$ , which includes the disturbance  $f_d$ . The dynamics of the controlled element are indicated as  $H_c(j\omega)$ .

(a) Display with no outside visual



(b) Display with an outside visual of Schiphol Airport



Figure 1. The considered display configurations.



Figure 2. Block diagram of the target-following disturbance-rejection task considered in this study.

#### II.A.1. Controlled Element

The controlled element dynamics  $H_c(j\omega)$  in this study are a low-order linear approximation of the yaw dynamics of the AH-64 Apache, which are given by Eq. (1):<sup>3,22,23</sup>

$$H_c(j\omega) = \frac{K_c}{s^2 + \omega_b s} = \frac{5}{s^2 + 0.27s}$$
(1)

These dynamics approximate a single integrator (K/s) for frequencies below 0.27 rad/s, and a double integrator  $(K/s^2)$  for higher frequencies. Therefore, significant human operator lead equalization is required for adequate control of the dynamics given by Eq. (1).<sup>27</sup>

#### II.A.2. Motion Cueing

Motion feedback is provided to the operator through a physical yaw rotation of the simulator. The motion filter dynamics  $H_{mf}(j\omega)$ , see Figure 2, determine the attenuation – and hence quality – of these provided physical motion cues. In the current study, motion attenuation from a first-order high-pass filter, Eq. (2), is considered.

$$H_{mf}(j\omega) = K_{mf} \frac{j\omega}{j\omega + \omega_{mf}}$$
<sup>(2)</sup>

The filter gain  $K_{mf}$  controls the frequency-independent scaling of simulator motion cues and is kept constant at 1 in the current study (unity-gain filters). The break frequency  $\omega_{mf}$  defines the frequency below which presented

motion cues are attenuated by the high-pass filter. Note that if  $\omega_{mf}$  is equal to 0 rad/s, the controlled yaw motion is thus presented one-to-one (no filtering). With  $K_{mf} = 1$  and increasing  $\omega_{mf}$ , the presented motion cues are affected by  $H_{mf}(j\omega)$  up to an increasingly higher frequency and the quality of the motion feedback is degraded.

#### II.B. Human Operator Modeling

Tracking tasks in which human operators are (only) presented with the tracking error e are known as compensatory tracking tasks.<sup>27</sup> In the current study, when the outside visual scene is absent (see Figure 1(a)), the tracking task can thus be considered compensatory. The state-of-the-art in the modeling of compensatory human operator control, including the added roles and effects of motion and outside visual feedback, will be addressed in this section.

#### II.B.1. Compensatory Tracking

In compensatory tracking tasks the human operator's response to the displayed error  $H_{p_e}(j\omega)$  see Figure 2, is known to adapt according to the dynamics of the controlled element  $H_c(j\omega)$ .<sup>27</sup> The combined open-loop dynamics, in this case equal to  $H_{p_e}H_c(j\omega)$ , are known to approximate an integrator in a wide range around the crossover frequency.<sup>27</sup> As the dynamics of the controlled element studied in this paper approximate a  $K/s^2$  system over a broad frequency range around crossover, the human operator's error response  $H_{p_e}(j\omega)$  takes the form of Eq. (3).<sup>12,27</sup> In this equation,  $H_{nm}(j\omega)$  represents the dynamics of the neuromuscular system, which are typically modeled as a second-order massspring-damper system, as given in Eq. (4). The visual gain and lead time-constant are indicated by  $K_{p_e}$  and  $\tau_L$ , respectively, while the error response time delay is indicated by  $\tau_e$ .

$$H_{p_e}(j\omega) = K_{p_e} \left(1 + \tau_L j\omega\right) e^{-j\omega\tau_e} H_{nm}(j\omega)$$
(3)

$$H_{nm}(j\omega) = \frac{\omega_{nm}^2}{(j\omega)^2 + 2\,\omega_{nm}\,\zeta_{nm}\,j\omega + \omega_{nm}^2} \tag{4}$$

#### **II.B.2.** Compensatory Tracking with Motion Feedback

Providing motion feedback to human operators gives them the opportunity to perform feedback control on the perceived motion of the controlled element. For yaw and other rotational degrees-of-freedom, rotational accelerations are sensed with the semicircular canals of the vestibular system. The dynamics of the semicircular canals  $H_{SCC}(j\omega)$  are often modeled using Eq. (5),<sup>29</sup> which approximates an integrator over the frequency range of interest for manual control (0.1-10 rad/s). Based on previous work by Hosman and Van der Vaart,<sup>28,29</sup> operators' linear responses to inertial motion cues,  $H_{p_m}(j\omega)$  in Figure 2, are modeled as in Eq. (6).

$$H_{SCC}(j\omega) = \frac{0.1097j\omega + 1}{5.924j\omega + 1}$$
(5)

$$H_{p_m}(j\omega) = K_{p_m} H_{SCC}(j\omega) \ e^{-j\omega\tau_m} \ H_{nm}(j\omega) \tag{6}$$

For compensatory tracking tasks, motion feedback is known to improve performance in both target-following and disturbance-rejection.<sup>11,12,14,18</sup> It has been shown that due to the effective lead available from the added motion cues (Eq. (6)), human operators decrease their visual lead time-constant  $\tau_L$ , while increasing their  $K_{pe}$ , resulting in improved tracking performance.<sup>11,16,17,30</sup>

Numerous studies have reported that these beneficial effects of motion feedback are suppressed when motion feedback is attenuated by high-pass filters.<sup>3, 16, 17, 31</sup> In Ref. 17 an effort was made to quantify these effects, by deriving first-order prediction equations for the expected changes in human operator control parameters, as well as crossover frequencies and phase margins, from a database of a large number of previous studies. As the "predictor" variable the motion filter gain at 1 rad/s, symbolized as  $K_S$ , was used. Note that this same 1 rad/s motion filter gain  $K_S$  is also a key metric in well-known motion cueing criteria.<sup>3,31</sup> The prediction equations of Ref. 17, here included as Eq. (7) to (12), will be used for comparison with our collected experiment data.

$$K_{p_e}(K_S) = K_{p_e}(1) \left[ 0.19(K_S - 1) + 1 \right]$$
(7)

$$\tau_L(K_S) = \tau_L(1) \left[ -0.29(K_S - 1) + 1 \right] \tag{8}$$

$$\tau_e(K_S) = \tau_e(1) \left[ 0.069(K_S - 1) + 1 \right] \tag{9}$$

$$\omega_{nm}(K_S) = \omega_{nm}(1) \left[ 0.058(K_S - 1) + 1 \right]$$
(10)

$$\omega_{c_d}(K_S) = \omega_{c_d}(1)[0.23(K_S - 1) + 1]$$
(11)

$$\varphi_{m_d}(K_S) = \varphi_{m_d}(1)[-0.10(K_S - 1) + 1]$$
(12)

#### II.B.3. Tracking with Additional Visual Feedback

The presence of the outside visual scene as shown in Figure 1(b) is likely to affect human control behavior, as it provides human operators with additional feedback of  $\dot{\psi}$ , similar as the supplied motion feedback does (Eq. (6)). This has been confirmed in a number of experiments investigating the separate contributions of central and peripheral visual cues on human manual control behavior.<sup>12, 18, 28</sup> In these studies, displays that presented a vertically moving checkerboard pattern were placed in the peripheral visual field to provide a roll rate stimulus. The conclusion from a direct comparison to the effect of physical motion feedback was that human operators indeed use the additional visual velocity information to generate lead, though with a less strong effect on task performance than observed for motion feedback. Given these earlier observations, it is likely that human operators' responses to the outside visual cues provided by our display ( $H_{p_{ov}}(j\omega)$ , see Figure 2), is also an additional stabilizing rate response. Similar conclusions are drawn for human operator control in pursuit tracking tasks.<sup>20,21,32,33</sup> Note that the combi-

Similar conclusions are drawn for human operator control in pursuit tracking tasks.<sup>20,21,32,33</sup> Note that the combination of the outside visual scene and the superimposed compensatory HUD shown in Figure 1(b) essentially results in pursuit display configuration, in addition to providing visual flow (velocity) cues. For double integrator controlled elements, the extra information supplied by a pursuit display is known to result in improved task performance compared to compensatory tracking. Recent data collected by Vos et al.<sup>21</sup> also suggests that human operator dynamics in pursuit tracking tasks with double integrator dynamics are best modeled with an additional rate feedback response.

#### III. Methods

A human-in-the-loop experiment was conducted in the SIMONA Research Simulator (SRS) at TU Delft. In the experiment, data was collected from participants performing the yaw-axis tracking task introduced in Section II.A, while motion cueing settings, and the presence of the outside visual scene, were varied over different experiment conditions. This section first provides the details of the experimental setup, then explains the methods used to analyze the obtained data, and finally presents the hypotheses.

#### **III.A.** Forcing Functions

To excite and identify the participants' control behavior, two multisine forcing functions were applied in the yaw tracking task. The participants were to follow a target signal  $f_t$  while being perturbed by a disturbance signal  $f_d$ , as shown in Figure 2. Both signals were multisines, summations of 10 individual sinusoids with different amplitudes, frequencies and phases. Both signals were generated according to Eq. (13), in which  $A_{t,d}(k)$ ,  $\omega_{t,d}(k)$  and  $\phi_{t,d}(k)$  represent the k-th sine's amplitude, frequency and phase, respectively.

$$f_{t,d}(t) = \sum_{k=1}^{10} A_{t,d}[k] \sin\left(\omega_{t,d}[k]t + \phi_{t,d}[k]\right)$$
(13)

The experiment's measurement time  $T_m$  was 81.92 s. All sinusoid frequencies were defined to be integer multiples  $(n_{t,d})$  of the measurement time base frequency  $w_0 = \frac{2\pi}{T_m}$  to avoid spectral leakage. To yield forcing function signals with reduced power at higher frequencies, the amplitudes  $A_{t,d}(k)$  were defined using a low-pass filter as described in Ref. 34. The target and disturbance signals were designed such that they had a variance of 15 deg<sup>2</sup> and 3.75 deg<sup>2</sup>, respectively, on the yaw attitude  $\psi$ . This tracking task can therefore be considered a dominant target-following task. For the phases, five different phase-sets ( $\phi_{t,d}(k)$ ) were used in this experiment to create five different realizations of both forcing functions, to ensure that the forcing functions remained unpredictable for the participants, even after repeated tracking. The phase-sets were chosen such that the resulting forcing function signals had an average crest factor, using a method detailed in Ref. 35. All parameters of the considered forcing functions are listed in Table 1.

 $_{k}$ 5 7 9 10 1 2 3 4 6 8 target forcing function,  $f_t$  $n_t, -$ 6 13 27 41 53 73 103 139 194 229 0.303 0.109 4.283 9.472 1.352 0.728 0.489 0.192 0.140 0.010  $A_t(k), \deg$  $\omega_t(k), \operatorname{rad/s}$ 0.460 0.997 2.071 3.145 4.065 5.599 7.900 10.661 14.880 17.564  $\phi_{t,1}(k)$ , rad 1.939 1.366 4.044 0.063 2.965 2.625 1.156 3.354 4.646 2.022  $\phi_{t,2}(k)$ , rad 0.745 0.967 5.643 2.722 2.822 1.672 3.343 4.029 1.242 4.384  $\phi_{t,3}(k)$ , rad 0.672 0.811 4.353 0.316 3.583 1.985 3.215 0.436 1.236 6.012 0.306 0.782  $\phi_{t,4}(k)$ , rad 1.640 1.872 3.421 3.160 0.178 3.721 4.131 1.352  $\phi_{t,5}(k)$ , rad 1.953 0.623 0.671 2.190 4.143 2.369 3.271 3.013 3.029 4.203 disturbance forcing function,  $f_{a}$  $n_d, -$ 5 11 23 37 51 71 101 137 171 226  $A_d(k), deg$ 0.074 0.233 0.488 0.639 0.737 0.867 1.096 1.457 1.893 2.798  $\omega_d(k)$ , rad/s 0.384 0.844 2.838 3.912 1.764 5.446 7.747 10.508 13.116 17.334  $\phi_{d,1}(k)$ , rad 6.615 3.233 5.613 9.154 7.981 7.181 8.876 4.754 4.735 4.738 4.248  $\phi_{d,2}(k)$ , rad 4.360 3.284 9.070 4.718 4.235 8.285 3.925 5.383 7.987  $\phi_{d,3}(k)$ , rad 7.068 8.271 6.304 9.213 3.945 5.921 6.159 8.363 5.956 3.594  $\phi_{d,4}(k)$ , rad 7.067 7.711 6.711 3.291 4.891 6.474 8.938 7.155 9.138 3.165  $\phi_{d,5}(k)$ , rad 2.827 3.066 6.252 4.581 4.958 6.838 9.355 8.450 5.196 4.306

Table 1. Multisine target and disturbance forcing function properties.

#### **III.B.** Apparatus

The experiment was performed in the SRS at TU Delft, see Figure 3(a). The SRS is a six-degree-of-freedom flight simulator and has a hydraulic hexapod motion system that allows for a maximum displacement of  $\pm$  41.6 deg in yaw.<sup>36</sup> The motion system's latency is approximately 35 ms.<sup>36</sup> The outside visual system of the SRS used in this experiment consists of three projectors that generate a 180 × 40° collimated visual scene. The visual system's delay is in the order of 30 ms and was ran at a 60 Hz refresh rate.<sup>37</sup>



Figure 3. The SRS (a) and a participant performing the experiment in the SRS (b).

Participants were seated in the right pilot seat in the SRS cockpit during the experiment, as shown in Figure 3(b). To ensure pure yaw cueing, the simulator's yawing motion was performed around an axis aligned with the backrest of the right pilot seat. The participants gave control inputs u using the roll axis of an electrical side-stick. The active stick was set to have a linear force-deflection characteristic of 1.5 N/deg with no breakout-force. Deflections were limited to  $\pm$  15 deg. The stick gain  $K_s$  shown in Figure 2 was set to 1.5. This value was tuned so that the maximum deflection limits of the side-stick would not be reached, while the subjects could still give accurate control inputs.

To mask the acoustic noise from the simulator's motion system, participants wore a noise-canceling headset, visible in Figure 3(b). In addition, masking aircraft engine noise was played over the headphones throughout the experiment.

#### **III.C.** Independent Variables

For the experiment a full factorial variation in two independent variables was considered. First, the outside visual scene could be either off or present (see Figure 1). Second, four different motion cueing settings were tested, giving a total of eight experimental conditions. A no-motion (fixed-base) condition was included, as well yaw motion feedback settings obtained with the first-order high-pass motion filter given by Eq. (2) with  $K_{mf}$  fixed at 1 and with three different settings of  $\omega_{mf}$ . Break frequency settings resulting in a 60 deg (°), 30 deg or 0 deg filter-induced phase mismatch at 1 rad/s were evaluated, corresponding to  $\omega_{mf}$  values of 1.732 rad/s, 0.577 rad/s and 0 rad/s, respectively. These phase-mismatches were chosen based on the results of the experiments of Ref. 22, where clear differences in the perceived simulator motion fidelity over these settings were reported.

#### **III.D.** Participants and Procedures

Eight male subjects voluntarily participated in the experiment. The participants were 24 to 51 years old and all had previous tracking experience. The participants received a detailed briefing before the experiment. They were instructed to continuously minimize the error presented to them on the HUD, see Figure 1.

All subjects were first familiarized with the task and the experiment, by performing at least one run of every experimental condition. After this familiarization, the eight conditions were tested sequentially. The order of conditions for each participant was based on a Latin square design, to balance out the effects of fatigue and learning. Before collecting the measurements, the participants performed at least three training runs, more if needed, until their proficiency in performing the tracking task had stabilized. Then, five further repetitions of the same experimental condition were collected as measurement data, each performed with a different forcing function realization (see Table 1).

After each run, participants were informed of their performance, expressed through the root mean square (RMS) of the error signal e (lower error RMS, better performance). Breaks were taken regularly to avoid fatigue, typically after every 2-3 evaluated conditions (around 16-24 runs). Each run in the experiment lasted 110 s of which 81.92 s was used as the measurement, with a fade-in of 10 s and a fade-out of 8.08 s. The data were logged at 100 Hz.

#### **III.E.** Dependent Variables

To quantify and compare changes in human operator behavior and performance over the different experimental conditions, a number of dependent variables is presented in this paper:

- Task Performance and Control Effort. The variances of the error signal  $\sigma_e^2$  and of the control input  $\sigma_u^2$  were used as measures of task performance and control effort, respectively. Furthermore, these variances were decomposed into contributions attributable to the target, disturbance and remnant signals.<sup>30</sup>
- Crossover Frequencies and Phase Margins. As typically done for tracking tasks with two input signals,<sup>30,34</sup> the dynamics of the combined pilot-vehicle system were analyzed by comparing the target and disturbance open-loop crossover frequencies,  $\omega_{c_t}$  and  $\omega_{c_d}$ , and phase margins,  $\varphi_{m_t}$  and  $\varphi_{m_d}$ .
- Human Operator Modeling. To explicitly quantify human control dynamics a quasi-linear human operator model was fit to the data. The considered operator model is shown in Figure 4, in which the dynamics of the human operator responses  $H_{p_e}(j\omega)$  and  $H_{p_x}(j\omega)$  are modeled according to Eq. (3) and (14).

$$H_{p_x}(j\omega) = H_{p_{ov}}(j\omega) + (j\omega)^2 H_{mf}(j\omega) \\ H_{p_m}(j\omega) = K_{p_x} j\omega \ e^{-j\omega\tau_x} H_{nm}(j\omega)$$
(14)





This human operator model is equivalent to models used for successful quantification of human operator behavior in earlier studies, see references in Sections II.B.2 and II.B.3. The main assumption in our modeling approach for the current study is the combination of the responses to outside visual and motion feedback in the model for  $H_{p_x}(j\omega)$ , see Eq. (14), where  $H_{p_{ov}}(j\omega)$  and  $H_{p_m}(j\omega)$  are the operator's responses to the outside visual and inertial motion cues, respectively. If both the outside visual cues and inertial motion cues are present,  $H_{p_x}(j\omega)$  describes the human's combined response to these cues, i.e., the operator's total response to x.  $H_{p_x}(j\omega)$  is assumed to be absent in case both the outside visual and motion feedbacks are not available and models both individual responses in conditions where only one of the cues is present. This choice for  $H_{p_x}(j\omega)$  in the human operator model facilitates direct comparison of the model parameters over our different motion conditions. The model has seven free parameters, collected in a parameter vector  $\theta$ , to estimate:

$$\theta = \begin{bmatrix} K_{p_e} & \tau_L & \tau_e & \omega_{nm} & \zeta_{nm} & K_{p_x} & \tau_x \end{bmatrix}$$
(15)

All dependent variables are presented with calculated sample means and 95% confidence intervals over the eightparticipant dataset. Statistical analysis of the data was performed using two-way repeated measures ANalysis Of VAriance (ANOVA) tests, where the effects of outside visual cues and motion feedback were accounted for separately, with independent statistical factors "OV" and "MOT", respectively.

#### III.F. Human Operator Identification and Modeling

For the collected data, different human operator identification and modeling methods were applied for quantitative analysis of human control responses and dynamics. First, describing functions for the human operator error  $(H_{p_e}(j\omega))$  and controlled element output  $(H_{p_x}(j\omega))$  responses were calculated using two methods:

- *FCE*: The main method used for obtaining describing function estimates was the spectral method elaborated in Refs. 38–40. For tracking tasks with two independent multisine forcing functions, this method allows for accurate and reliable estimation of two human operator describing functions.<sup>25,39,40</sup> Here, these describing function estimates are referred to as the Fourier Coefficient Estimates (FCEs) of the human operator dynamics and were used as the basis for estimating our human operator models.
- ARX: Linear time-invariant AutoRegressive models with eXogeneous inputs (ARX)<sup>39</sup> were used to obtain a second independent estimate of the human operator frequency responses  $H_{p_e}(j\omega)$  and  $H_{p_x}(j\omega)$ . ARX models with different assumed orders (ranging from 3 to 5 for both the numerator and the denominator polynomials) were fit to the data, from which the lowest order model providing a good fit to the data was selected as the final ARX result. The ARX models were used for bilateral verification of the FCE describing functions.

For modeling the measured human operator behavior, the operator model described in Section III.E, was fit to the data. Also for this quantitative modeling, two different methods were applied in parallel:

• *FDE*: The main method applied for modeling human operator error and controlled element output responses  $(H_{p_e}(j\omega) \text{ and } H_{p_x}(j\omega))$  used the estimated frequency-domain FCE describing functions. This human operator model estimate is here referred to as the Frequency-Domain Estimate (FDE). The normalized quadratic frequency-domain (complex) cost function given by Eq. (16) was used to find the optimal set of model parameters  $\theta$  for the FDE:

$$J(\theta) = \left[\sum_{k=1}^{20} \frac{|\hat{H}_{p_e}^{FDE}(j\omega_{t,d}|\theta) - \hat{H}_{p_e}^{FCE}(j\omega_{t,d})|^2}{|\hat{H}_{p_e}^{FCE}(j\omega_{t,d})|^2} + \sum_{k=1}^{20} \frac{|\hat{H}_{p_x}^{FDE}(j\omega_{t,d}|\theta) - \hat{H}_{p_x}^{FCE}(j\omega_{t,d})|^2}{|\hat{H}_{p_x}^{FCE}(j\omega_{t,d})|^2}\right] W \quad (16)$$

In Eq. (16),  $\hat{H}_{p_e}^{FDE}(j\omega_{t,d}|\theta)$  and  $\hat{H}_{p_x}^{FDE}(j\omega_{t,d}|\theta)$  represent the modeled human operator frequency responses at the target and disturbance forcing functions frequencies.  $\hat{H}_{p_e}^{FCE}(j\omega_{t,d})$  and  $\hat{H}_{p_x}^{FCE}(j\omega_{t,d})$  indicate the estimated describing functions to which the models are fit. In this equation, W represents a vector of weights on the modeling errors at each  $\omega_{t,d}$ . Through this weight vector a zero weight was assigned to the highest and lowest frequency points in the FCEs, as well as a lower weight of 0.4 to the second and third lowest frequencies. This was done, as the FCE data at these frequencies has an inherent lower reliability.<sup>39,41</sup>

• *TDE*: For verification of the FDE, a second independent method – the time-domain identification method of Ref. 25 – was applied to obtain a second fit of the operator model to the measured data. As this method fits the human operator model to the time-domain data, the resulting fitted model is here referred to as the Time-Domain Estimate (TDE).

The quality of all fitted human operator models was verified using the Variance Accounted For (VAF), as given by Eq. (17). The VAF calculates the percentage of the measured human operator control input u that is explained by the modeled control input  $\hat{u}$ .

$$VAF = \left(1 - \frac{\sum_{k=1}^{N} (u[k] - \hat{u}[k])^2}{\sum_{k=1}^{N} u^2[k]}\right) \times 100\%$$
(17)

#### **III.G.** Hypotheses

Based on earlier findings and a literature search, the following hypotheses were formulated for the current experiment:

- **H1:** Outside visual cues result in improved tracking performance through human operators' use of a controlled element output response. Previous experiments have shown that for tasks requiring human operator lead equalization, the presence of outside visual results in improved task performance.<sup>12,14,18</sup> Some evidence exists that human operators' use of outside visual cues is equivalent to how they utilize physical motion feedback,<sup>12,18</sup> i.e., as an alternative source of lead. For this reason, it is expected that the model for  $H_{p_x}(j\omega)$  defined in Section III.E, which essentially is a response proportional to the controlled element output rate, will be able to accurately describe the measured  $H_{p_x}(j\omega)$  describing functions for conditions with outside visual cues.
- **H2:** The positive effects of outside visual feedback on human operator behavior and performance are less pronounced than those of motion feedback. This hypothesis is based on a number of previous studies that have reported a distinctly reduced performance benefit of outside visual cues compared to physical motion feedback.<sup>12, 14, 18, 33</sup>
- H3: Increased motion filter break frequency will result in reduced use of motion feedback and attenuated performance benefits. Consistent with earlier findings (see Section II.B.2, e.g., Ref. 17) increased motion phasemismatch is expected to result in worse task performance, decreased disturbance crossover frequency  $\omega_{c,d}$ , a reduction in the human operator error response gain  $K_{p_e}$ , and increased visual lead equalization (higher  $\tau_L$ ).
- **H4:** Outside visual cues do not change the effects of increased motion filter break frequency on human operator behavior. With the hypothesized dominance of motion feedback (H2), any changes in crossover frequencies, phase margins, and human operator model parameters with varying motion filter break frequency (H3) are expected to be unaffected by the presence of outside visual cues. The motion feedback contribution to human operators'  $H_{p_x}(j\omega)$  (see Eq. (14)) will thus dominate the outside visual component, even with degraded motion feedback quality.

# **IV.** Results

In this section the results of the experiment are presented. In all figures, the different motion settings (MOT) are indicated as NM ("No Motion"),  $60^{\circ}$ ,  $30^{\circ}$ , and  $0^{\circ}$ , the numbers referring to the motion filter-induced phase-mismatch at 1 rad/s (see Section III.C). Data for conditions with and without the outside visual cues are labeled as "with OV" or "no OV", respectively. For each dependent variable, the individual effects of outside visual cues ("OV") and motion feedback quality ("MOT") are discussed, as well as their interaction ("OV × MOT"). Noted effects are further substantiated with the results of two-way repeated measures ANOVAs, presented in tables with each data figure.

#### IV.A. Task Performance and Control Effort

Figure 5(a) shows the variance of the error signal  $\sigma_e^2$ , decomposed in the contributions of the target  $(f_t)$ , disturbance  $(f_d)$  and remnant (n) signals. Lower  $\sigma_e^2$  indicates better tracking performance. Note in Figure 5(a) that the target signal contribution to the tracking error variance has the largest magnitude, as is expected for a predominantly target-following task (see Section III.A). For the NM conditions, participants performed markedly better when the outside

visual cues were available, as the total error variance is 50% lower for "with OV" than for "no OV". All three contributions to  $\sigma_e^2$  (i.e., target, disturbance and remnant) show this prominent decrease. Compared to the pure compensatory condition (no OV, NM), the performance benefit of outside visual cues (OV, NM) seems comparable to the effect of adding 1-to-1 motion feedback (no OV, 0°), as the total  $\sigma_e^2$  for these conditions is nearly identical. Also for all other motion settings, performance was generally better with OV, a significant effect, see Table 2 ("OV").



Figure 5. Tracking performance ( $\sigma_e^2$ ) and control effort ( $\sigma_u^2$ ), decomposed in the target, disturbance and remnant signal contributions.

Table 2. Results of repeated measures ANOVA for tracking performance and control effort data, where \*\* is highly significant (p < 0.01), \* is significant (p < 0.05), and – is not significant ( $p \ge 0.05$ ).

Independent variable	Dependent variable											
		$\sigma_e^2$	$\sigma_u^2$									
Factor	df	F	sig.	df	F	sig.						
OV	1.000	18.686	**	1	0.209	_						
MOT	1.086 <sup>gg</sup>	15.232	**	3	3.570	*						
$OV \times MOT$	1.105 <sup>gg</sup>	11.513	**	3	3.692	*						

<sup>gg</sup> = Greenhouse-Geisser sphericity (homogeneity of variance) correction applied

Figure 5(a) shows that improving quality motion feedback (from NM to  $0^{\circ}$ ) resulted in reducing tracking error variances and thus improved performance, a significant effect, see Table 2 ("MOT"). With much improved performance for the conditions with OV, the further improvement due to motion feedback is more modest than observed for the corresponding "no OV" conditions. The presence of outside visual cues thus influences the effect of motion filter settings on tracking performance, which is confirmed by the significant interaction effect (OV × MOT) listed in Table 2. The main explanation for this interaction seems to be that the target-tracking error (black bars) is no longer affected by the presence and phase-mismatch of the motion feedback when outside visual cues are available.

The variance of the control input signal  $\sigma_u^2$  is shown in Figure 5(b), again decomposed in the components of  $f_t$ ,  $f_d$ , and n. Except for the NM conditions, where an increase in  $\sigma_u^2$  is observed that is consistent with the reduction in  $\sigma_e^2$ , control effort is not found to be affected by the availability of outside visual cues (see also Table 2). Except for the clearly lower control effort for (no OV, NM), to which the significant effects of motion (MOT) and the interaction effect (OV × MOT) in Table 2 are attributable,  $\sigma_u^2$  shows no further consistent variation over the different experimental conditions.

#### **IV.B.** Crossover Frequencies and Phase Margins

Figure 6 shows the target and disturbance crossover frequencies and phase margins measured for all experiment conditions. Data for conditions without ("no OV") and with outside visual cues ("with OV") are indicated with black and red markers. Variance bars indicate 95% confidence intervals. For reference, Figures 6(b) and (d) also present the evaluated prediction equations from Ref. 17 for  $\omega_{c_d}$  and  $\varphi_{m_d}$ , Eq. (11) and (12), respectively.

Figure 6 and Table 3 show that the target and disturbance crossover characteristics are affected by the presence of outside visual cues. For the NM conditions,  $\omega_{c_d}$  and  $\varphi_{m_t}$  are seen to be markedly higher with OV, which is expected, as these parameters are strongly correlated with disturbance-rejection and target-following performance improvements, respectively.<sup>18</sup> Also, an average increase in  $\omega_{c_t}$  of around 0.5 rad/s is noted for NM. For the motion conditions,



Figure 6. Measured target and disturbance crossover frequencies and phase margins.

Table 3. Results of repeated measures ANOVA for crossover frequencies and phase margins, where \*\* is highly significant (p<0.01), \* is significant (p<0.05), and – is not significant ( $p \ge 0.05$ ).

Independent variable	Dependent variable													
		$\omega_{c_t}$		$\omega_{c_d}$				$\varphi_{m_t}$		$\varphi_{m_d}$				
Factor	df F sig.		df	F	sig.	df F		sig.	df	F	sig.			
OV	1	4.781	_	1	2.917	2.917 –		95.871	**	1	0.320	_		
MOT	3	0.935	_	3	40.283	**	3	35.119	**	3	0.939	_		
$\text{OV} \times \text{MOT}$	3	5.772	**	1.262 <sup>gg</sup>	21.780	**	3	3.317	*	3	0.743	-		

<sup>gg</sup> = Greenhouse-Geisser sphericity (homogeneity of variance) correction applied

the differences between the "no OV" and "with OV" data seem to become smaller with improving motion feedback quality. Only for  $\varphi_{m_t}$  a consistent increase of around 10 deg is found for all experiment conditions, a significant effect as can be judged from Table 3, and in line with the results reported in Refs. 12 and 18. Overall, these results suggest that human operators adapted their control behavior to the presence of outside visual cues.

For the effect of motion feedback, increased  $\omega_{c_d}$  and  $\varphi_{m_t}$  are known to be responsible for performance improvements in disturbance rejection and target following, respectively.<sup>12, 18</sup> Hence, for a combined target-following and disturbance-rejection task as considered in this paper, both parameters are expected to increase with improving motion feedback quality. Figure 6(b) and (c) indeed show these expected changes, which are also both statistically significant effects (see Table 3). Between the NM to 0° conditions,  $\omega_{c_d}$  is seen to increase by 0.5-1 rad/s, which matches well with the prediction obtained from Eq. (11), while  $\varphi_{m_t}$  increases by around 10 deg. For  $\omega_{c_t}$  and  $\varphi_{m_d}$  much less variation over the different tested motion settings – and no significant effects, see Table 3, "MOT" – are observed in Figure 6(a) and (d), respectively. Despite seeming to follow the slight trend predicted by Eq. (12), the disturbance phase margin is seen to remain approximately constant at 30-35 deg for all experimental conditions.

As can be noted from Figure 6 and Table 3,  $\omega_{c_t}$ ,  $\omega_{c_d}$ , and  $\varphi_{m_t}$  also show statistically significant interactions between the effects of motion feedback quality and the presence of outside visual cues. Compared to the  $\omega_{c_t}$  values around 2.5 rad/s found for the 30° and 0° motion settings, Figure 6(a) shows slightly lower values for 60° and NM without OV, while with OV slightly increased  $\omega_{c_t}$  are seen. With already increased  $\omega_{c_d}$  and  $\varphi_{m_t}$  values for the NM conditions with outside visual cues, the further increases in both parameters due to added motion feedback are both smaller in magnitude than those observed for "no OV". Matching the observations made from the  $\sigma_e^2$  data in Figure 5(a), this indicates that outside visual cues change the effect of varying motion filter-induced phase mismatch on human operator behavior.

#### **IV.C.** Human Operator Modeling Results

#### IV.C.1. Human Operator Modeling Validity

In Section III.E the two-channel human operator model that was used to model measured human operator dynamics from the experiment was introduced. This study is, to our knowledge, the first to attempt to identify a human operator output feedback response  $(H_{p_x}(j\omega))$  for tasks with added outside visual cues, as well as outside visual cues and motion feedback presented in parallel. For this reason, before presenting the obtained final estimates of the human operator model parameters, first the quality-of-fit of the model, and hence its validity, is discussed in some detail.

Figure 7 shows the example human operator identification results for subject 7 for the condition with no motion feedback, but with outside visual cues. The results of subject 7 are displayed because they are typical and representative for all subjects. The describing functions determined from Fourier Coefficient Estimates (FCEs) at the frequencies of  $f_t$  and  $f_d$  are presented with red and white-filled markers, respectively. The frequency response of the fitted ARX model (see Section III.F), here used as a second independent describing function estimate, is indicated with a dashed gray line. The two fits of the human operator model – the Time Domain Estimate (TDE) and the Frequency Domain Estimate (FDE) – are presented with solid gray and black lines, respectively.



Figure 7. Example Bode plots of estimated describing functions and human operator model fits for the  $H_{p_e}(j\omega)$  and  $H_{p_x}(j\omega)$  human operator responses, for subject 7 in the NM condition with OV.

Overall, Figure 7 shows that the chosen human operator model captures the estimated FCE describing function at high accuracy, especially for the FDE. As is clear from Figure 7, the error response  $H_{p_e}(j\omega)$  shows significant lead equalization, as expected for a tracking task with the dynamics of Eq. (1). Furthermore, the identified output response  $H_{p_x}(j\omega)$  shows approximate differentiator dynamics, consistent with the response proportional to controlled element velocity (lead) that the chosen model for  $H_{p_x}(j\omega)$  describes. All describing function estimates and fitted models are in clear agreement, except for the phase of the output response (Figure 7(d)). Where the FCE and the FDE fitted to this describing function data match well, the ARX and TDE results suggest lower phase lag at high frequencies for  $H_{p_x}(j\omega)$ .

To further analyze the nature and consequences of these observed differences between the FDE and TDE – and motivate our selection of the former to provide the final operator model estimates – Figure 8 shows a comparison of the measured operator control input u and the modeled control inputs  $\hat{u}$  for both models. The plotted time traces represent the same example dataset as Figure 7. Overall, it can be observed that the time responses of the FDE (72% VAF) and TDE (76% VAF) seem to describe the measured data with equivalent high accuracy.



Figure 8. Example time traces of the modeled control input  $\hat{u}$  obtained from the FDE and TDE – with VAFs of 72% and 76%, respectively – compared to the measured control input u, for subject 7 in the NM condition with OV.



Figure 9. Variance Accounted For (VAF) values for the FDE and TDE model fits.

The results shown in Figure 8 are in general representative for the human operator model fits obtained for all experimental conditions and subjects. Figure 9 shows a side-by-side comparison of the FDE and TDE model VAFs, averaged over all subjects, which shows on average slightly higher VAFs for the TDE. Such slightly higher VAFs are expected, as the TDE optimization actively strives for highest possible VAF.<sup>25</sup> Consistent with Figure 8, Figure 9 shows that the VAF improvement for the TDE is on average marginal, up to 3%, and that the FDE model fits thus have a high quality-of-fit in the time domain as well. In addition, the FDE models show, in general, better correspondence with the obtained FCE describing functions for  $H_{p_x}(j\omega)$  (e.g., see Figure 7). Based on this analysis of the human operator model identification results, the FDE is selected for providing the final estimated human operator model parameters that are analyzed in the next subsection.

#### IV.C.2. Human Operator Model Parameters

The average human operator model parameters determined from the frequency-domain human operator model fits are shown in Figure 10. Again, the variance bars indicate 95% confidence intervals and the results for the conditions without and with outside visual cues are presented using black and red markers, respectively. Furthermore, for  $K_{p_e}$ ,  $\tau_L$ ,  $\tau_e$ , and  $\omega_{nm}$  (Figures 10(a) to (d)) also show the corresponding Ref. 17 prediction equation results, obtained using Eq. (7) to (10), respectively. Finally, Table 4 presents the ANOVA results for the operator model parameters. Note that the ANOVAs for  $K_{p_x}$  and  $\tau_x$  were performed only on the data from the conditions with motion feedback, as for the NM setting no data are available without OV.

Figure 10 and Table 4 show a number of different direct effects of outside visual cues on human operators' control behavior. When considering the measurements for the NM conditions, first the clearly nonzero values found for  $K_{px}$  (see Figure 10(f)) suggest that human operators indeed utilize an active  $H_{px}(j\omega)$  response also when only outside visual cues are available. Interestingly, Figure 10(g) shows that the corresponding values for  $\tau_x$  (around 0.4 s on average) are markedly higher than the  $\tau_x$  found for motion conditions (around 0.15 s), but also than the error response delay  $\tau_e$  (around 0.23 s). While this result is in clear agreement with the phase of the measured FCE describing functions, shown in Figures 7(c) and (d), this suggests, however, that human operators' responses to the outside visual cues were in fact significantly slower than the pure perceptual delays of around 0.2 s expected for outside visual



Figure 10. Average human operator model parameter estimates as obtained from the FDE.

Table 4. Results of repeated measures ANOVA for the human operator model parameters obtained from the FDE, where \*\* is highly significant (p<0.01), \* is significant (p<0.05), and – is not significant ( $p \ge 0.05$ ).

Independent variable	Dependent variables																				
	$K_{pe}$			$ au_L$			$ au_e$			$\omega_{nm}$			$\zeta_{nm}$			$K_{px}$			$\tau_x$		
Factor	df	F	sig.	df	F	sig.	df	F	sig.	df	F	sig.	df	F	sig.	df	F	sig.	df	F	sig.
OV	1	12.588	**	1	4.155	_	1	0.232	-	1	3.059	-	1	1.648	_	1	0.030	-	1	1.056	-
MOT	3	13.613	**	3	14.781	**	3	1.382	-	3	18.075	**	1.445 <sup>gg</sup>	1.907	-	2	9.903	**	2	3.663	-
$\text{OV} \times \text{MOT}$	3	1.436	-	3	0.547	-	3	2.288	-	3	0.640	-	3	3.046	-	2	0.101	-	2	1.679	-

<sup>gg</sup> = Greenhouse-Geisser sphericity (homogeneity of variance) correction applied

cues.<sup>28,42</sup> In addition to the use of the  $H_{p_x}(j\omega)$  feedback path, the NM condition data also seems to show slightly decreased values of  $\tau_e$ , a slight increase in  $K_{p_e}$ , and and small changes in the neuromuscular system parameters. Finally, when considering all experimental conditions, Figure 10(a) and (b) show a consistent drop in  $K_{p_e}$  and a consistent increase in  $\tau_L$  when outside visual cues are available. The former effect is statistically significant, see Table 4, "OV".

As indicated with the solid gray lines in Figure 10, a reduction  $K_{p_e}$ , an increase in  $\tau_L$ , a slight decrease of  $\tau_e$ , and a drop in  $\omega_{nm}$  are expected when comparing the reduced quality motion conditions to the 1-to-1 motion setting (0°). The estimated error response gains, lead time-constants, and neuromuscular frequencies indeed confirm these expectations and even show larger magnitude variations over all conditions than predicted. Between the NM and 0° motion settings,  $K_{p_e}$  approximately doubles,  $\tau_L$  is reduced by around 50%, and  $\omega_{nm}$  increases by over 2 rad/s. All three effects are statistically significant, as can be verified from Table 4. For the error response delay  $\tau_e$ , the neuromuscular damping ratio  $\zeta_{nm}$ , and the output response delay  $\tau_x$  no consistent variation with the applied motion setting is observed. Finally, the human operator output response gain  $K_{p_x}$  shows a strongly increasing trend with improving quality of motion feedback, seemingly independent of the presence of the outside visual cues. This increasing  $K_{p_x}$ , a significant effect as can be seen from Table 4, indicates that human operators put more emphasis on their  $H_{p_x}(j\omega)$  response with lower motion phase mismatches.

Any differences in the changes of human operator model parameters over the different motion settings between the conditions with and without OV are especially relevant to this study, as these would reveal true interactions of both cues on human operator behavior. As opposed to the measured crossover frequencies and phase margins (Table 3), for the estimated human operator parameters no statistically significant OV × MOT interactions were found, as is shown in Table 4. This seems to be due to the larger spread in the parameter estimates, as especially the means of the  $K_{pe}$ and  $\tau_L$  data – Figures 10(a) and (b), respectively – seem to show lower magnitude variations over the motion settings with outside visual cues. While these interactions would be consistent with those found for the crossover frequency and phase margin data, based on the current human operator parameters it cannot be concluded that the presence of outside visual cues affects the variation in human operator parameters over the varying motion filter settings.

# V. Discussion

The goal of this paper was to measure and quantify the individual and interaction effects of varying motion cueing settings and outside visual cues on human tracking behavior. This was achieved by measuring tracking behavior in a yaw tracking task with a controlled element requiring significant human operator lead (simplified Apache yaw dynamics model) in an eight-subject human-in-the-loop experiment performed in the SIMONA Research Simulator at TU Delft. Four yaw motion cueing settings – a no-motion condition and three (increasing) break frequency settings of a first-order high-pass filter – were tested both with and without outside visual cues present. Measured tracking performance, control effort, crossover frequencies, phase margins and human operator modeling results were used to compare measured human operator behavior and performance.

The addition of outside visual cues in a compensatory tracking task without motion feedback was found to have a strong effect on human control behavior. Significant task performance improvement – for both target-following and in disturbance-rejection – was observed, in addition to considerable increases in control activity, target phase margin  $\varphi_{m_t}$ , and in the disturbance crossover frequency  $\omega_{c_d}$ . These effects were expected (Hypothesis H1) and highly congruent with earlier findings.<sup>12,18</sup> The obtained human operator modeling results confirmed our hypothesis that this performance improvement results from human operators' use of an added controlled element output response  $(H_{p_x}(j\omega))$  enabled by the available outside visual cues. In addition to the added feedback response, a slight but consistent increase in the visual error response gain  $K_{p_e}$  was observed from the obtained human operator model parameter estimates, suggesting that operators also adapt and optimize their  $H_{p_e}(j\omega)$  response dynamics when outside visual cues are available.

Based on results from earlier studies investigating the effects of additional visual velocity cues on human operator behavior, <sup>12, 18, 33</sup> the impact of outside visual cues was expected to be markedly less strong than the effect of motion feedback (Hypothesis H2). Interestingly, when comparing the measures of task performance, control effort, crossover frequencies, and phase margins, the individual added effects of outside visual cues and 1-to-1 (0°) motion feedback seem very much comparable and of similar magnitude. While both cues allow human operators to attain an identical level of task performance, human operator modeling results show distinct differences in how this performance is attained in both cases. Most notably, operators' visual error gains  $K_{p_e}$  and the output gains  $K_{p_x}$  are both found to be significantly higher with motion feedback than with outside visual cues, thereby still partially confirming Hypothesis H2. A key difference between the current study and the referenced previous investigations<sup>12, 18, 33</sup> lies in the nature of the presented outside visual stimulus. It is possible that the realistic outside visual scene considered in this paper provides a stronger visual flow stimulus than the visuals available in these previous studies, producing a matching stronger effect on especially the target-following capabilities of human operators. However, more research is required to confirm this.

For the conditions without outside visual cues, the expected worsening of tracking performance, reduced human operator control gains, and increased visual lead time-constants with increasing motion filter-induced phase distortion were all observed from the data, thereby confirming Hypothesis H3. When outside visual cues were also available, tracking performance was found to be consistently better on average, but also much less affected by the applied variation in motion cueing. In line with earlier findings,<sup>12, 18</sup> it seems that outside visual cues in the *absence* of motion enhance both target following and disturbance rejection, while when motion feedback is also present only targetfollowing performance is (further) improved. Key performance-related human operator model parameters – e.g.,  $K_{p_e}$ ,  $\tau_L$ , and  $K_{p_r}$  – were also found to show highly similar trends over the different motion feedback settings, both with and without the outside visual cues. Especially human operators' output feedback gains  $K_{p_x}$  were found to show identically strongly increasing values with decreasing high-pass filter break frequency in both cases. However,  $K_{D_{e}}$ and  $\tau_L$  are found to be consistently lower and higher, respectively, for all conditions with outside visual cues and motion feedback. This optimization of  $H_{p_e}(j\omega)$  response parameters, indicating a stronger reliance on lead generated from the compensatory display, explains the attenuated effect of variations in motion cueing on tracking performance. Thus, despite largely similar observed variations in human operator parameters, the presence of outside visual cues does seem to partially mitigate the effects of degraded simulator motion feedback quality on human operator behavior, in contrast to our Hypothesis H4.

In this paper, human operators' controlled element output feedback responses  $(H_{p_x}(j\omega))$  for conditions with only outside visual cues, only motion cues, or both were all quantified with the same structurally identical model, describing a response proportional to controlled element velocity.<sup>12, 16, 18, 24, 30</sup> While this model was found to accurately capture measured human operator behavior for all different experiment conditions, it is unfortunate that the hypothesized individual responses to the outside visual cues  $(H_{p_{ov}}(j\omega))$  and motion cues  $(H_{p_m}(j\omega))$  cannot be separated, as this would provide more explicit insight in the relative contribution of both responses. Furthermore, this would facilitate direct identification of human operators' true responses to filtered simulator motion feedback, where now the motion filter

dynamics  $H_{mf}(j\omega)$  were lumped into the modeled  $H_{p_x}(j\omega)$ . Development of human operator modeling techniques and experimental paradigms that enable the separation of such parallel human operator feedback paths is therefore strongly desired.

A somewhat surprising observation from the human operator modeling results is that the controlled element output response time delay  $\tau_x$  was found to be significantly higher (around 0.4 s) when only outside visual cues are available, compared to the values for all motion conditions (around 0.15 s). This difference could explain why motion feedback still affects human operator behavior when outside visual cues are present. The estimates of  $\tau_x$  in conditions with motion feedback are highly consistent with previous experiment data,<sup>12,19,43</sup> while the  $\tau_x$  values found for pure outside visual feedback seem very high compared to previously reported visual velocity perception delays.<sup>28,42</sup> This difference could be explained by the fact that the modeled  $\tau_x$  represents the time delay in humans' control responses, not their perception delay. More research, however, is required to further investigate and verify the estimated time delay values for operators' responses to outside visual cues.

In the current study, human operators were found to utilize outside visual cues to support a human feedback control organization similar to that observed in tasks with physical motion feedback, i.e., a visual error response supplemented with an additional feedback response proportional to the controlled element velocity (lead). This similarity in human control dynamics might suggest that initial simulator-based training for control tasks with motion feedback may be effectively performed in a simulator *without* motion feedback, but with (strong) outside visual cues. To verify the extent to which the controlled element output response learned with outside visual cues actually transfers to a motion setting, it would be of great interest to perform a dedicated transfer-of-training study and use human operator modeling techniques to explicitly quantify skill development and transfer.<sup>44,45</sup>

## VI. Conclusions

This paper described the results of a human-in-the-loop experiment conducted to investigate the individual and interaction effects of outside visual cues and varying motion cueing settings on human operator tracking behavior in a flight simulator. Eight participants performed a compensatory yaw-axis target-following and disturbance-rejection task where the motion cueing (break frequency of a first-order high-pass motion filter) and the presence of outside visual cues were varied independently over eight experimental conditions. Measured tracking performance, control activity, crossover frequencies, phase margins, and human operator modeling results show that outside visual cues have a strong influence on human operators' tracking behavior. In absence of motion feedback, outside visual cues enable human operators to achieve better tracking performance with an additional lead generating controlled element output feedback response, resulting in control dynamics similar to those observed in the presence of motion feedback. Furthermore, when outside visual cues are available in parallel with physical motion feedback, human operators show consistently more visual lead equalization and lower visual error response gains; a control strategy that seems less affected by variations in the motion cueing settings compared to when outside visual cues are absent. While key human operator parameters as the visual error gain and lead time-constant still showed clear variations with increasing motion filter break frequency settings when an outside visual scene was present, the degrading quality of motion feedback was found to have less impact on task performance, operators' control effort, and measured human operator model parameters.

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