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A Cybernetic Approach to Assess the Training of Manual Control Skills

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Abstract: This paper presents a cybernetic approach to assess the training of manual control skills in simulators. The approach uses multi-channel pilot models that separate pilots' responses to visual and motion stimuli. This allows for a quantitative analysis of pilots' use of visual and motion cues for manual aircraft control, as well as the evolution of these control skills during training and after transfer. The cybernetic approach was applied to data from a quasi-transfer-of-training experiment performed in the SIMONA Research Simulator at Delft University of Technology. In this experiment, fully task-naive participants were trained to perform an aircraft pitch attitude tracking task in a fixed-base simulator environment. After training, participants were transferred to a motion-base simulator environment. Results indicate that the cybernetic approach is successful in revealing progressive changes in participants' utilization of visual and motion cues – i.e., their equalization dynamics – during training and after transfer. Furthermore, the results show that convergence to a final skill-based manual control strategy requires significant training.

Keywords: manual control, flight simulators, pilot training, pilot modeling, training effectiveness

1. INTRODUCTION

The increase of long-haul flights and cockpit automation over the last decades has significantly reduced manual flying time and consequently, manual flying proficiency among pilots. This reduction in manual flying proficiency is thought to have increased the likelihood of pilot error in unexpected aircraft upset events or sudden transitions to manual flying. Today, there is a growing concern that pilots are not provided adequate training to regain and maintain adequate levels of manual flying proficiency (Anonymous, 2016). Novel approaches are needed to improve the training of manual flying skills within current training programs.

Most pilot training is performed in motion-base flight simulators with limited motion capabilities. Previous studies show that this limited motion significantly affects pilot manual control behavior and performance (Zaal et al., 2009b; Pool et al., 2010b). However, the impacts on the initial and recurrent training of manual flying skills, and the transfer of training, are less well understood. More knowledge is required to be able to develop adequate simulator motion cueing strategies that improve the training of manual flying skills.

The transfer-of-training paradigm is considered the most valid means of investigating training effectiveness of motion in the acquisition of manual control skills (de Winter

et al., 2012). Most previous transfer-of-training studies use task performance measures to analyze training effectiveness (Levison et al., 1979; Martin, 2008). However, these measures tend to be less sensitive to differences in motion fidelity and provide no insight into pilots' use of motion cues in developing manual control skills. The modeling of skill-based manual control behavior, often called a cybernetic approach, can give this insight and has been used in many experiments investigating the effects of motion on manual control, but not in the context of training (Zaal and Sweet, 2014; van Paassen and Mulder, 1998; Pool et al., 2010a).

This paper presents a cybernetic approach to assess the acquisition of skill-based manual control skills in motion-base simulators. The approach utilizes a multi-channel pilot model, allowing for an analysis of how pilots' skill in the utilization of visual and motion cues changes during training and after transfer. The novel approach is applied to data from a recent quasi-transfer-of-training experiment performed in the SIMONA Research Simulator at Delft University of Technology (Pool et al., 2016).

The paper is structured as follows. First, Sections 2 and 3 describe the cybernetic approach and the details of a recent transfer-of-training experiment, respectively. Section 4 describes the experiment results obtained using the cybernetic approach. The paper ends with our main conclusions.

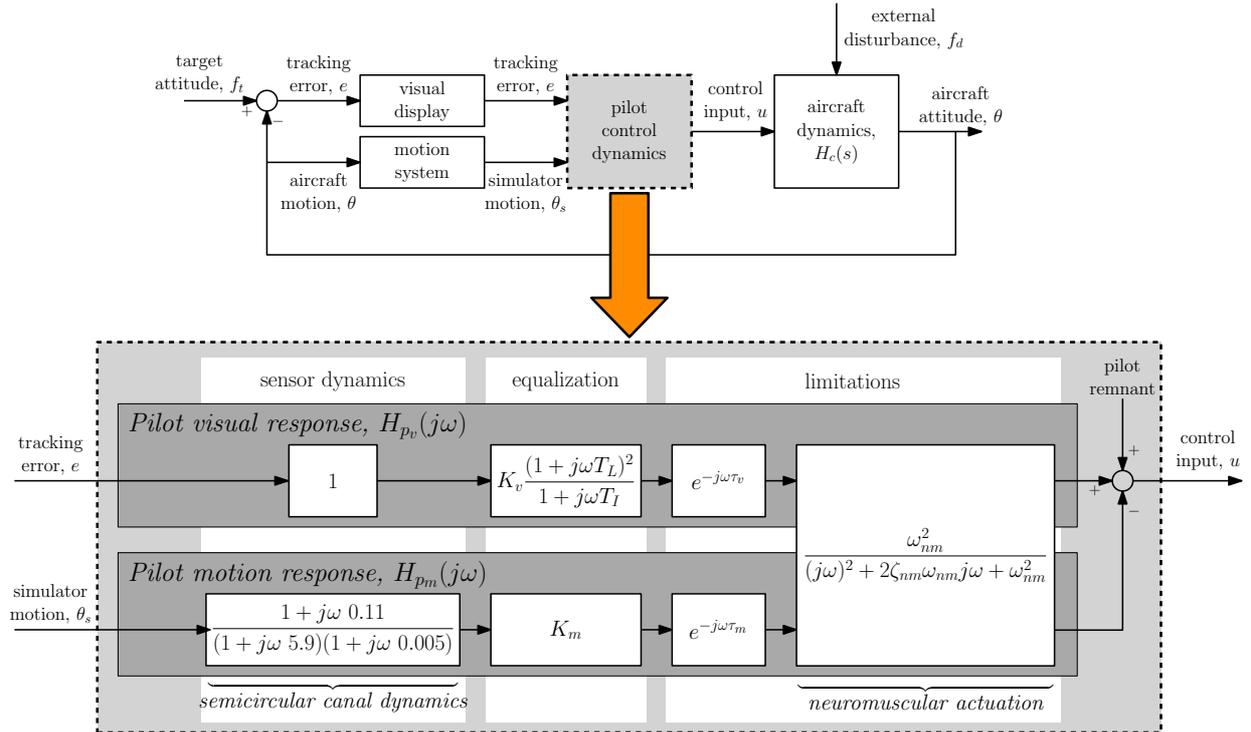


Fig. 1. Schematic representation of the cybernetic approach: assessing simulator quality from objective measurements of human control dynamics.

2. THE CYBERNETIC APPROACH

Obtaining meaningful quantitative measurements of pilots' manual control skills for evaluating simulator-based training effectiveness is by no means straightforward. Even though skill-based control behavior is inherently nonlinear and varies over time, in controlled and somewhat simplified control tasks it can be modeled by linear transfer functions and a remnant signal that accounts for nonlinearities and noise (McRuer and Jex, 1967). The inputs of the linear describing functions are the stimuli perceived by the pilot, while the sum of the outputs is the pilot's control action. Many control tasks are inherently multi-loop with feedback from visual, somatosensory, and vestibular cues. By using multi-channel models, with different transfer functions for each perceived stimulus, insight can be gained into pilots' use of different perceptual modalities, such as visual and vestibular, to make a control action. This approach to analyzing manual control behavior has often been referred to as a *cybernetic approach* (Wiener, 1961), and has been used in many applications (Pool et al., 2010a; Mulder et al., 2013).

The top part of Fig. 1 depicts a block diagram of a control task typically used for the analysis of manual control behavior. In this closed-loop compensatory tracking task, a human pilot uses a control effector to give control inputs (u) to the controlled aircraft dynamics, H_c . The aircraft attitude θ , and changes in the attitude, can be perceived using visual and motion (i.e., multimodal) feedbacks. In a flight simulator, these visual and motion stimuli are generated by visual displays and a motion system, respectively. In order to effectively quantify pilots' responses to visual and motion cues *separately* using system identification techniques, these cues need to be sufficiently different. This

is typically accomplished by performing tracking tasks with two sum-of-sine forcing function signals. The first signal is added as an external disturbance (f_d) on the aircraft dynamics, see Fig. 1. This signal directly drives both the visual and motion feedbacks available to the pilot. The second signal is a reference target attitude f_t that drives the visual display only. For a compensatory task, the visual stimulus available to the pilot is the tracking error e between the current aircraft attitude and the target attitude.

A pilot model capable of modeling pilots' multi-channel control organization in the control task of Fig. 1 is depicted in the lower part of the figure. The pilot model contains a visual (H_{pv}) and motion (H_{pm}) response function. Each response function consists of sensor, equalization, and human limitation dynamics. The visual sensor dynamics are typically modeled by a unity gain. The control task in Fig. 1 considers rotational motion only, and hence semicircular canal dynamics are the sensor dynamics in the motion response channel (Hosman, 1996). The equalization dynamics represent the pilot's control strategy, i.e., the use and weighting of the different available information. These dynamics are dependent on the controlled aircraft dynamics and other task variables. The equalization dynamics in Fig. 1 are normally found for the control of aircraft pitch attitude (Zaal et al., 2009b; Pool et al., 2010b, 2016). The pilot's control output is limited by separate time delays in the visual and motion response paths and neuromuscular actuation dynamics.

The cybernetic approach is centered on the use of control-theoretic models as shown in Fig. 1 for quantifying human manual control behavior. This is achieved by fitting these models to measured human pilot data. For the model of

Fig. 1, the free model parameters that characterize pilots' control behavior are the equalization parameters – i.e., the visual and motion gains K_v and K_m , as well as the visual lead and lag time constants T_L and T_I – and human limitation parameters – i.e., the visual and motion delays τ_v and τ_m , as well as the neuromuscular system frequency ω_{nm} and damping ratio ζ_{nm} . Different techniques exist to estimate such pilot model parameters from measurements of visual and motion stimuli and the pilot control input (van Paassen and Mulder, 1998; Zaal et al., 2009b). Applying this approach to *individual tracking run data* recorded at different instances during training and after transfer, allows us to explicitly quantify how pilots utilize visual and motion cues in the training and transfer of manual control skills. Thereby, the cybernetic approach enables structured and quantitative comparison of different training scenarios, e.g., different pilot groups trained with different simulator motion cueing optimizations (Zaal et al., 2015).

3. SIMULATOR EXPERIMENT

3.1 Control Task

Participants were trained to perform a skill-based compensatory pitch tracking task, for which the basic control diagram is shown in Fig. 1. Participants' task was to minimize the tracking error e , shown on a compensatory display. The error is the difference between the reference signal, f_t , and the controlled pitch attitude, θ . The compensatory display used in this experiment is depicted in Fig. 2. The display presents the pitch error as a vertical offset of a horizontal line from a stationary aircraft symbol. The simulator's motion system generated pitch motion stimuli in the experiment trials with motion feedback. The aircraft dynamics which participants controlled were the linearized elevator-to-pitch dynamics of a small jet aircraft (Zaal et al., 2009b):

$$H_c(s) = 10.62 \frac{s + 0.99}{s(s^2 + 2.58s + 7.61)} \quad (1)$$

To facilitate multi-channel pilot identification (van Paassen and Mulder, 1998; Zaal et al., 2009a), two sum-of-sine forcing function signals were used in the tracking task: f_t and f_d , see Fig. 1. The experiment focused primarily on the disturbance-rejection task, with the target signal scaled to 25% of the power of the disturbance signal.

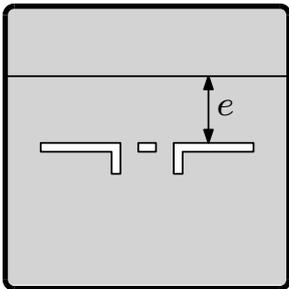


Fig. 2. Compensatory visual display.



Fig. 3. The SIMONA Research Simulator.

3.2 Apparatus

The experiment was performed in the SIMONA Research Simulator at Delft University of Technology, see Fig. 3. Participants sat in the right pilot seat and used an electric sidestick on the right-hand side of the seat to give control inputs u to the controlled system. The stick's roll-axis was locked upright, to ensure pure pitch commands. The compensatory display of Fig. 2 was shown on the primary heads-down display in front of the participant. No other visual information, e.g. by the simulator's out-the-window visual system, was presented in the experiment. Simulator pitch motion matching the controlled pitch attitude was generated by the motion drive of the simulator in the motion-base tests.

3.3 Experiment Design and Procedures

To evaluate the effectiveness of initial fixed-base training of manual pitch control skills, a quasi-transfer-of-training experiment was performed. Such transfer-of-training experiments typically consist of two phases, here referred to as the *training* and *evaluation* phases, see Fig. 4. During the training phase, participants are trained for their task in the training condition, after which they are transferred to the evaluation condition. Signs of further skill development in the evaluation phase are indicative of sub-optimal transfer of the skills acquired during the training phase.



Fig. 4. Quasi-transfer-of-training experiment schedule.

As shown in Fig. 4, the experiment was divided in seven blocks of 25 runs, performed over seven subsequent work days (no sessions were planned during the weekend). Participants were trained the task in a fixed-base (FB) condition and subsequently transferred to the motion-base (MB) condition. Participants performed 100 and 75 tracking runs in total during the training and evaluation phases, respectively. Care was taken to balance out the number of morning and afternoon time slots, as well as the position of experiment-free weekends in the seven-day measurement periods, over the participants.

Participants for this experiment were fully task-naive students from Delft University of Technology without prior experience with skill-based manual control. While data from a much larger participant population was collected (Pool et al., 2016), this paper shows the data from three representative participants. This allows us to focus on individual trends.

3.4 Data Analysis

This paper presents example results from this experiment, in two categories. First, the variances of the tracking error (e) and control signal (u) time traces were calculated as measures of task proficiency and control activity, respectively. Such indirect output-based metrics are often used to track skill development during training, and evaluate

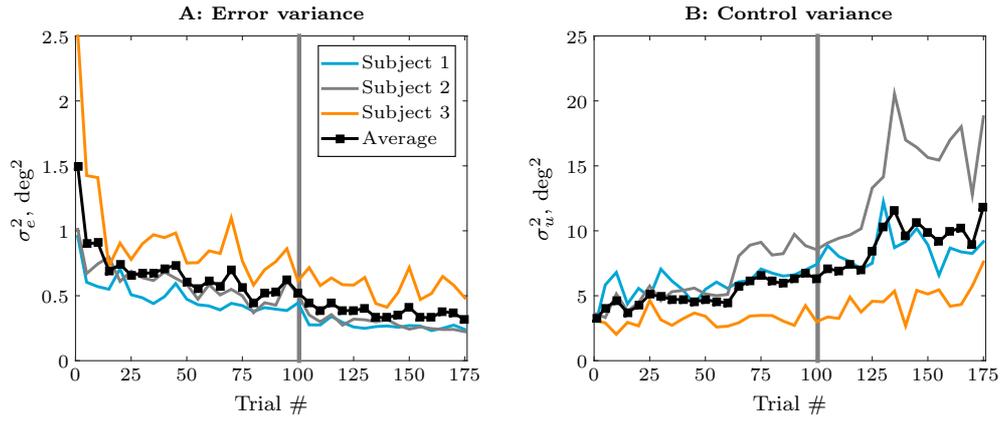


Fig. 5. Progression of tracking error and control variances over the course of the experiment for three participants.

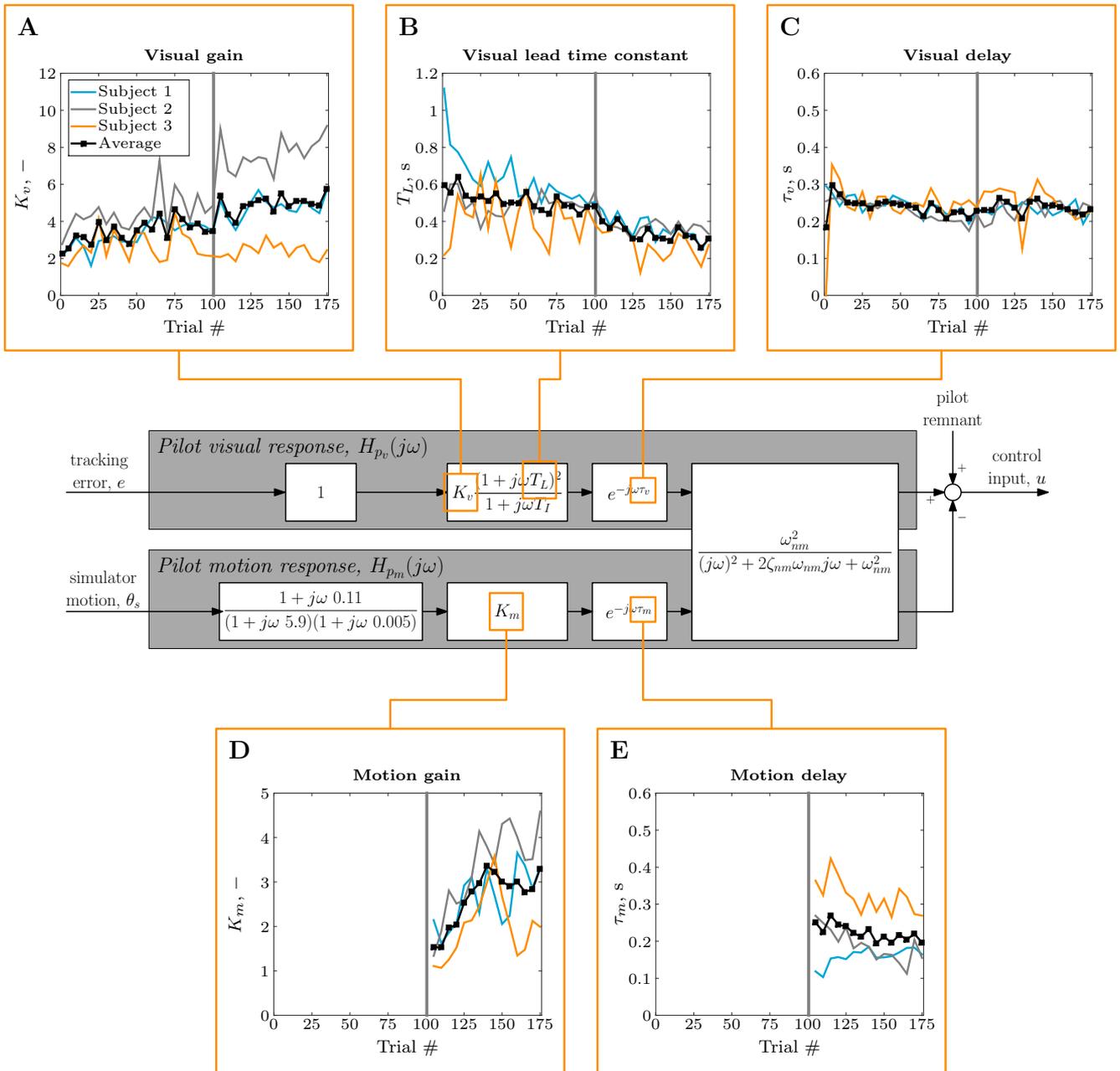


Fig. 6. Progression of pilot model parameters over the course of the experiment for three participants.

the transfer effectiveness of learned skills (Lintern et al., 1990; Go et al., 2003; Sparko et al., 2010; de Winter et al., 2012). In addition, a cybernetic approach was applied by estimating parameters of the multi-channel pilot model of Fig. 1, to enable direct and quantitative insight into the learned (multimodal) control strategy. These parameters were estimated using the time-domain identification approach of Zaal et al. (2009a). Note that for the fixed-base training phase, only the pilot visual response H_{p_v} was fitted to the data, while for the motion-base evaluation-phase data the full multi-channel model was used. Data from both sets of metrics were calculated for each of the tracking runs performed by each subject, to allow for determining the progression in these parameters over the course of the experiment.

4. EXAMPLE RESULTS

Fig. 5 shows the progression in the tracking error and control variances over the course of the transfer-of-training experiment for the three participants. Training-phase (trials 1-100) and evaluation-phase (trials 101-175) data are separated by a vertical gray line, indicating the moment of transfer. During initial fixed-base training, all participants are seen to steadily improve their task proficiency (decreasing σ_e^2), as well as increase their control activity. Both these trends are consistent with pilots' optimization of control behavior to the tracking task (McRuer and Jex, 1967). Notable is the slow optimization of skill-based behavior: all participants start to converge to a performance asymptote only after at least 50 tracking runs.

From experiments with skilled participants, it is known that motion-base task proficiency is typically considerably better than observed in a fixed-base setting (Zaal et al., 2009b; Pool et al., 2010b). Furthermore, for tasks that are predominantly disturbance-rejection tasks, control activity is also known to increase when motion feedback is available. Thus, a decreased σ_e^2 and increased σ_u^2 during the experiment's evaluation phase would signal effective use of the available motion feedback. As is clear from Fig. 5, participants in our experiment did not show these effects *directly after transfer*, with σ_e^2 and σ_u^2 remaining close to their end-of-training values during the first evaluation-phase runs. Furthermore, all participants show continued reduction of the error variance and increase of their control variance throughout the evaluation phase; indicative of further learning during the motion-base evaluation. Matching the results from earlier investigations (Levison et al., 1979; Martin, 2008), these observations suggest limited transfer of the skills acquired during fixed-base training to a motion-base setting.

Fig. 6 presents the estimated pilot model parameters for the three-participant data set. The top row of graphs (A-C) show the parameters of the pilot visual response, H_{p_v} , while the bottom two graphs (D and E) present the estimates of the two parameters of the motion response H_{p_m} . For the fixed-base training phase, Fig. 6A-C show that the enhanced task proficiency is achieved through an increased visual response gain K_v , decreased lead time-constant T_L and slightly decreased visual response delay τ_v . These pilot parameter changes are consistent with improved task performance and control activity (McRuer and

Jex, 1967). Matching the σ_e^2 and σ_u^2 results of Fig. 5, the adaptation of these pilot parameters over the 100 training trials is seen to be slow, with parameter adjustments only leveling off close to the end of the training phase.

Upon transfer to the motion-base setting, the pilot visual delay remains approximately constant at 0.25 s (Fig. 6C), but the visual gain K_v and lead time-constant T_L are seen to continue their increasing and decreasing trends, respectively. These effects are consistent with earlier findings for skilled pilots (Zaal et al., 2009b; Pool et al., 2010b), as increased visual response gains and reduced lead time-constants are typically found for tracking with motion feedback. The estimated parameters of the pilot motion response H_{p_m} (Fig. 6D and E) reveal a clear increase in the motion response gain K_m , with a learning trend consistent with those observed for K_v and T_L , while no consistent variation in τ_m is observed. Overall, the changes in K_v , T_L , and K_m are highly consistent with the development of a multimodal control strategy that makes effective use of the available motion feedback. Matching the performance data of Fig. 5, this adaptation to the motion-base setting is seen to be slow, requiring at least 50 trials before reaching asymptotic parameter values, as is especially clear for T_L (Fig. 6B) and K_m (Fig. 6D). Overall, the cybernetic approach thus revealed that the lacking transfer of skills learned in a fixed-base environment predominantly results from an untrained adaptation of the equalization dynamics to motion feedback; i.e., the pilot's weighting and integration of visual and motion information.

5. CONCLUSIONS AND FUTURE WORK

This paper introduces a cybernetic approach for quantifying the effectiveness of skill-based manual control behavior training based on multi-channel pilot modeling techniques. Applied to data from a recent transfer-of-training experiment, in which fully task-naive participants were trained for a pitch tracking task, this approach was found to provide unique insight into pilots' control skill development during training and after transfer. Even after extended training in a fixed-base setting, especially pilots' equalization parameters – i.e., the visual and motion response gains and the visual lead time constant – revealed pilots' notable and slow further optimization of their control strategy upon transfer to a motion-base setting. The results of this experiment therefore suggest that initial fixed-base training is hardly effective when aiming at the development of multimodal skill-based control behavior.

In future work, we will utilize our cybernetic approach to verify the effects of imperfect simulator motion feedback and additional outside visual cues, as often present in flight simulators used for pilot training, on initial manual control skill training. Furthermore, by explicitly considering the extent to which learned skills are retained over time, we plan to collect quantitative data to support the development of optimal recurrent training procedures for skill-based manual control.

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