QUASI-TRANSFER OF HELICOPTER TRAINING FROM FIXED- TO MOTION-BASE SIMULATOR

Davide Fabbroni [1], Stefano Geluardi [1], Carlo A. Gerboni [1], Mario Olivari [1], Lorenzo Pollini [2] and Heinrich H. Bülthoff [1]

[1] *Max Planck Institute for Biological Cybernetics, Tübingen, Germany*
[2] *University of Pisa, Pisa, Italy*

Abstract

This paper presents the experimental evaluation of a previously developed hover training program, designed for fixed-base helicopter simulators. In particular, it is investigated whether the skills developed on the fixed-base simulator are transferred to a highly realistic simulator (quasi-Transfer-of-Training experiment). The higher realism was achieved by using the motion-base MPI CyberMotion Simulator. Student pilots participants were asked to perform the hover maneuver controlling an identified model of a Robinson R44 civil light helicopter. Results showed that the skills acquired during fixed-base training were successfully transferred to the highly-realistic condition. The additional motion feedback helped participants achieve better levels of performance.

1. INTRODUCTION

The benefits of using flight simulators during initial helicopter pilot training are known and well documented [1, 2]. Since the first studies on helicopter training [3], simulators were considered effective in reducing pilots' training costs and duration. For this reason, simulators were increasingly used to reduce costs and risks of flight training by providing a cheap-to-use and safe environment.

The main factor that has driven so far the use of simulators has been the trade-off between cost and training efficiency. The training efficiency is usually associated with the ToT that simulators produce. By definition, ToT occurs if the skills developed in a prior learning phase influence the performance of a following activity. The transfer is considered positive when the developed skills allow the trainee to achieve better levels of performance in a following activity than a trainee that did not participate in the prior learning phase [4].

In general, high simulators fidelity has a positive influence on the ToT. In particular, realistic controls, visual [5] and motion [6] cues play an important role. However, the actual need for motion-base simulators for training purposes is still debated. In [2] it was shown that the simulator motion can provide a slight positive effect on ToT. However, the introduction of realistic motion cues represents a considerable additional cost. Moreover, in [7–10] it was pointed out that the effectiveness of a flight training depends more on the training program than on the fidelity provided by the simulator.

In a previous work, a novel training program was designed to teach the hover maneuver to inexperienced helicopter pilots in a fixed-base simulator [11]. The proposed training program was meant as a reliable, safe and cheap tool capable of improving initial pilot training in helicopter flight schools.

The goal of this paper is to evaluate the ToT that the fixed-base training program developed in [11] could produce in a real case scenario. In this way, the effectiveness of the training program is assessed. Thanks to the high level of realism achievable with the Max Planck Institute (MPI) CyberMotion Simulator (CMS) in Fig. 1, a quasi-Transfer-of-Training (qToT) [12] experiment was considered here as preliminary step before testing the ToT in the actual helicopter. In fact, the CMS allows for highly realistic flight scenarios to be reproduced as a result of its high agility and the large motion envelope. Therefore, it is a valid test bench for achieving the goal of the paper.

The paper is structured as follows: Section 2 presents an overview on the Training experiment performed in the fixed-base simulator. Section 3 includes the design of the quasi-Transfer-of-Training experiment. In Section 4 the results of the experiment are presented. Conclusions are drawn in Section 5.

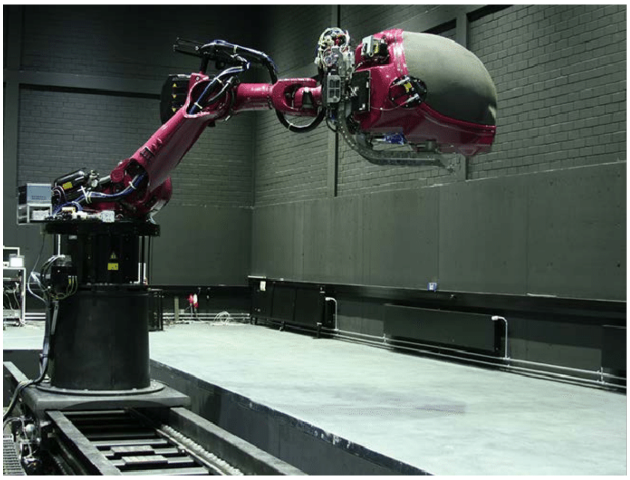

Figure 1: The MPI CyberMotion Simulator.
www.cyberneum.de/facilities-research/cmslab.html

2. TRAINING OVERVIEW

In [11], three software trainers were compared in terms of their effectiveness in training student pilots performing the hover maneuver. The paper presented a novel software trainer called Haptic Helicopter Trainer (HHT). The HHT was designed to imitate the action of an instructor pilot on dual controls by using a haptic force-feedback. The HHT was also adaptive that is, the amount of haptic feedback was gradually reduced as the students' performances improved. The second software trainer provided an adaptive augmentation system and was based on the Automated Helicopter Hover Trainer (AHT) proposed in [13]. The third trainer was used for the control group (CTR) and did not provide any augmentation or help to the students. In total, three groups of participants were selected as listed in Table 1.

Table 1: Experimental groups.

Group	Method of Training
gHHT	Adaptive haptic feedback
gAHT	Adaptive stability augmentation
gCTR	No help or augmentation

The three software training programs were tested in a fixed-base simulator, the MPI PanoLab Simulator described in [11], see Fig. 2. In total, 27 participants were trained in performing the hover maneuver. The training was divided in four phases, as outlined in Table 2. The first three phases focused on the use of a subset of control devices: pedals and collective only in the first phase, cyclic in the second and all the controls in the third. During these phases, the groups gHHT and gAHT were helped by the corresponding adaptive software trainer (HHT and AHT respectively). The evaluation was conducted in a Final Test in which, the student pilots had to control all the helicopter controls without any help from the software trainers.

Table 2: Training phases.

Phase	Focus	Duration
# 0	Familiarization	5 min
# 1	Pedals, Collective	20 min
# 2	Cyclic	20 min
# 3	All controls	30 min
Final Test	All controls	5 min

In the Final Test, participants had at their disposal 5 minutes in the simulator. To complete a trial, participants had to stabilize the helicopter for 60 seconds, minimizing the distance from the hover target position and the average linear velocity of the helicopter.

The results of the experiment showed that 75% of the participants were able to stabilize the helicopter by the end of the Training. The performances of participants in the Final Test of the Training are presented as box-whiskers plots in Fig. 3. In this figure, the scores were calculated as maximum errors from the target position and heading. The average linear velocity registered in a trial gives an indication of the helicopter stability.

Benefits of using the HHT during the Training were found, as explained in [11]. However, no statistical difference in final measures of performances of participants emerged. Moreover, it was concluded that the structure of the Training in Table 2 played a major role, since also the control group achieved acceptable levels of performance.

For this reason, the evaluation of the Transfer-of-Training presented in this paper was performed without distinguishing between the different experimental groups considered in [11].

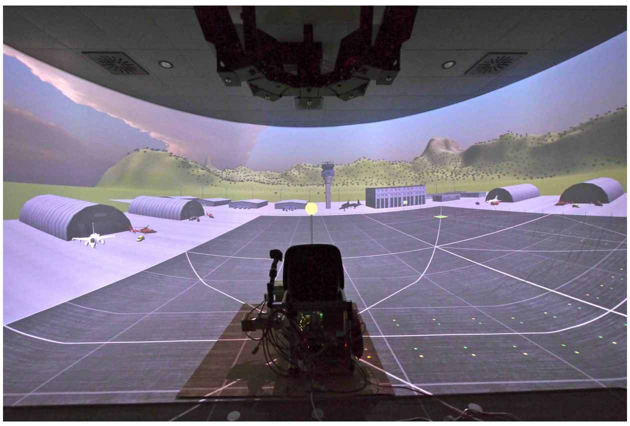

Figure 2: The MPI PanoLab Simulator.
www.cyberneum.de/research-facilities/panolab.html

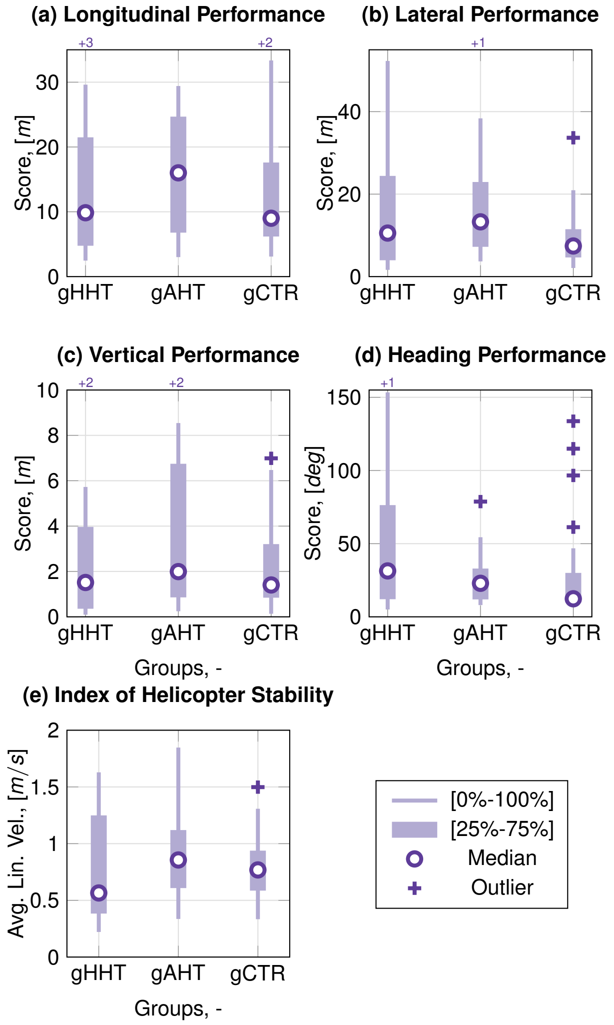

Figure 3: Performance measures in completed trials of the Final Test of the Training experiment.

Table 3: Experiment phases.

Task	Duration	Motion Enabled
Familiarization 1	5 trials	No
Familiarization 2	5 trials	Yes
Hover	20 trials	Yes

3. EXPERIMENTAL SETUP

A pilot-in-the-loop experiment was designed to test whether the skills acquired by participants trained in a fixed-base simulator could be transferred to an highly-realistic helicopter simulator, the MPI CyberMotion Simulator (CMS), see Fig. 1. In particular, 12 participants took part in this experiment, with an equal number of participants selected from each training group defined in [11] (see Table 1).

The quasi-Transfer-of-Training (qToT) experiment was organized as outlined in Table 3: after the first 10 trials of familiarization, participants performed the hover maneuver for 20 trials. As in the Training experiment in [11], each trial lasted 60 seconds. Only these last 20 trials were used for the analysis of the final results. In case of helicopter instability, a trial was interrupted and considered failed.

3.1. Apparatus

The CMS is a robotic arm (KUKA Roboter GmbH) mounted on a linear rail that possesses 8 degrees-of-freedom. The end-effector is a custom-built helicopter cockpit with a 140*deg* horizontal for 70*deg* vertical field-of-view that allows for virtual environments to be projected. The cockpit is equipped with a pilot seat, a conventional center-stick cyclic, collective lever and rudder pedals (Wittenstein GmbH), as shown in Fig. 5.

The motion of the CMS was generated by means of a motion cueing algorithm based on second-order high-pass washout filters [14]. Their gains were manually tuned based on the evaluations of an expert helicopter pilot until a good matching between visual and motion cues was achieved.

The visual scenery projected inside the cockpit was developed in Unity [15] and was the same used during the training in [11]: a heliport in which the helicopter could move without encountering any obstacle, see Fig. 4. Markers, such as lines and dots, were drawn on the heliport ground to help the student pilots understand the position of the helicopter in space. In the scene, an hover board was placed 45.7*m* (140*ft*) in front of the starting position, and a red sphere was placed half way. To perform an acceptable hover the red sphere had to be kept inside the green square on the hover board. As an additional reference, a green square was drawn on the heliport floor, identifying the hover target position with an accuracy of $\pm 3.0m$ (10*ft*). An outer yellow border was used to identify the target position with an accuracy of $\pm 4.5m$ (15*ft*). An artificial horizon was added to help the pilot estimate the attitude of the simulated helicopter.

The helicopter model to be controlled was an identified model of a Robinson R44 civil light helicopter, in hover condition [16].

3.2. Measures

Performances were evaluated as in [11] to allow for a direct comparison with the results obtained from the Training experiment. In particular, the following measures were calculated:

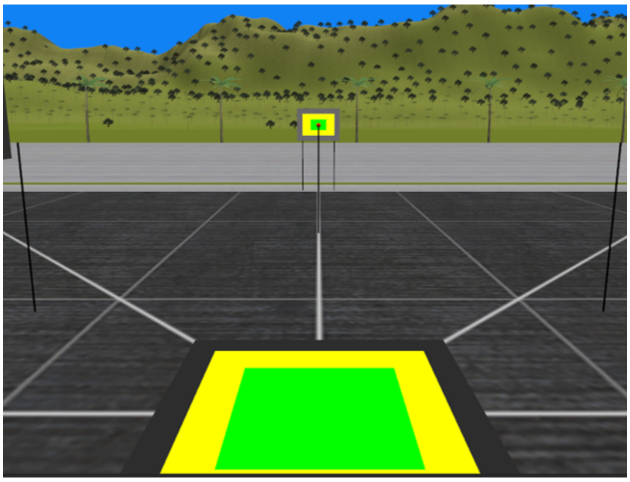

Figure 4: Detail of the projected scene seen by participants.

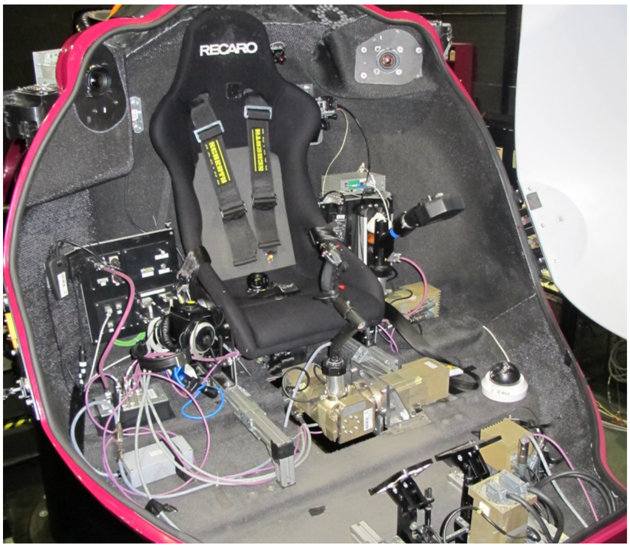

Figure 5: The MPI CyberMotion Simulator cockpit, equipped with helicopter controls and pilot seat.

- Number of completed trials.
- Index of helicopter stability.
- Index of performance (score).
- Index of control activity.

The completed trials are trials in which participants were able to maintain the control of the helicopter model for 60 seconds.

The index of helicopter stability was computed as the average linear velocity of the helicopter in each trial:

$$\overline{v}_{avg} = \frac{\sum_{k=1}^{N} \sqrt{|u_k|^2 + |v_k|^2 + |w_k|^2}}{N} \quad (1)$$

where u_k, v_k and w_k are longitudinal, lateral and vertical velocities of the helicopter at the time instant k, respectively. N is the number of collected data samples for each trials.

The index of performance was composed by four scores, calculated at the end of each trial as:

$$Score = \begin{bmatrix} \max_k(|e_x(k)|) \\ \max_k(|e_y(k)|) \\ \max_k(|e_z(k)|) \\ \max_k(|e_\psi(k)|) \end{bmatrix} \quad (2)$$

where $e_x(k)$, $e_y(k)$, $e_z(k)$, $e_\psi(k)$ are the longitudinal, lateral, vertical and heading errors at the time instant k.

The index of control activity of a participant during a trial was evaluated in term of control actions per second [17]. For each control device, the control action is defined as the number discrete movements per second. A discrete movement is the movement of a control between two positions with zero velocity. A threshold of 0.5 of the maximum control deflection was chosen here to filter the noise on the control deflection. This index gives an indication of how responsive were the participants to the helicopter dynamics during the hover control task.

4. RESULTS

The indexes of performance and helicopter stability (average linear velocity) are presented as box-whiskers plots. In Figs. 7-9, on each box, the circle represents the median over different data points. The box includes data points between the 25th and the 75th percentile. The two edges of the whiskers indicate the lowest and the highest data point within 1.5 of the interquartile range. All the data points not included in the whiskers are considered as outliers and they are represented by cross markers. The numbers on top of the figures accounts for outliers that are not shown being larger than the axes upper limits.

Table 4 shows the number of completed trials for each participant in the quasi-Transfer-of-Training (qToT) experiment. The shown results are divided into sections with 5 trials each to highlight possible learning curves. Moreover, the table lists the number of completed trials in the Final Test of the Training.

In the Final Test of the Training, participants achieved diverse levels of performance. Some participants were able to consistently stabilize the helicopter, completing 5 trials (the maximum possible). Some others were able to complete only few or no trials. Nevertheless, all participants completed at least 60% of the available trials in the CMS, with 90.4% completed trials overall.

Table 4: Number of completed trials for each participants in the Final Test of the Training and in each section of the quasi-Transfer-of-Training experiment.

PanoLab Sim.	**CyberMotion Sim.**				
Final Test	Trial 1:5	6:10	11:15	16:20	**Tot**
5	5	5	5	5	20
5	5	5	5	5	20
5	5	5	5	5	20
5	5	5	5	5	20
5	4	5	5	5	19
5	5	5	5	5	20
4	5	4	4	5	18
2	3	3	3	4	13
2	4	4	5	4	17
1	5	5	5	5	20
0	2	3	4	3	12
0	5	5	4	4	18

Caution must be paid when interpreting the fact that all participants were able to improve their ability in stabilizing the helicopter in the CMS. Indeed, the additional motion feedback helped participants stabilize the helicopter. However, a previous experiment showed that only one participants out of seven could stabilize the helicopter in the CMS without prior training [14]. Therefore, the experience gained during the Training experiment played a major role.

Fig. 7 shows the evolution of scores and average linear velocity achieved by participants through the sections of the qToT experiment, compared to those achieved in the Final Test of the Training experiment.

As can be noticed in Figs. 7(a)-7(b), participants achieved better longitudinal and lateral scores after the transfer. In fact, both median and variability of these measures were significantly reduced since the first section of the experiment. In particular, the medians improved by 47.7% and 30.1%, respectively. No further learning was registered on the control of longitudinal and lateral position. In fact, the associated scores did not improve throughout the sections.

Regarding the vertical performance score shown in Fig. 7(c), the overall performance worsened after the transfer. Nevertheless, a significant reduction in the variability was registered. Moreover, a learning curve can be observed on this variable. The median scores were reduced by 32% from section 1 to 4, though never reaching the same levels of the Final Test of the Training. This was due to a loss of calibration that caused an offset displacement on the collective lever. Participants were not trained to compensate the resulting downward drift since it was absent in the Training experiment in the fixed-base simulator. Fig. 6 shows the offset disturbance on the collective lever in trials from sections 1 and 4. Please note that this should not be mistaken for negative Transfer-of-Training, since every participant was able to learn how to detect and partially compensate the offset.

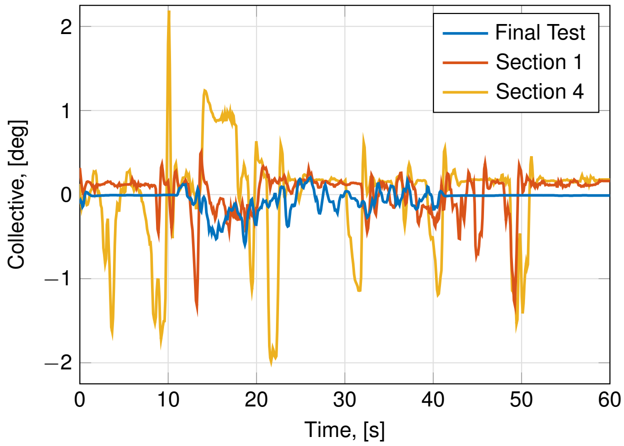

Figure 6: Collective displacement measurements of three explicative trials from a sample participant.

The heading score presented a negligible difference between performances of participants in the Final Test of the Training and in the first section of the qToT experiment, see Fig. 7(d). This was due to the fact that the configuration of the CMS used in this experiment only allowed small rotations of the cabin around the vertical axis. As a result, participants benefited less from the motion feedback on the yaw axis than on the other axes.

In terms of index of helicopter stability, participants achieved similar levels of performances as in the Final Test of the Training. In Fig. 7(e), both median and variability of registered average linear velocities did not improve in section 1. From section 2 performances slightly improved and remained steady until the end of the experiment.

in Fig. 8 the evolution of the index of control activity is shown for the Final Test of the Training and the four sections of the qToT experiment. The analysis of this index confirms the previous findings. In fact, the step change improvement in longitudinal and lateral score after the transfer is associated with an increased control activity on the cyclic stick since the first trial.

This was attributed to the additional motion feedback available, which improved participants' responsiveness to the helicopter dynamics. Similarly, the measured control activity on the collective lever, increased with respect to that registered in the Final Test of the Training.

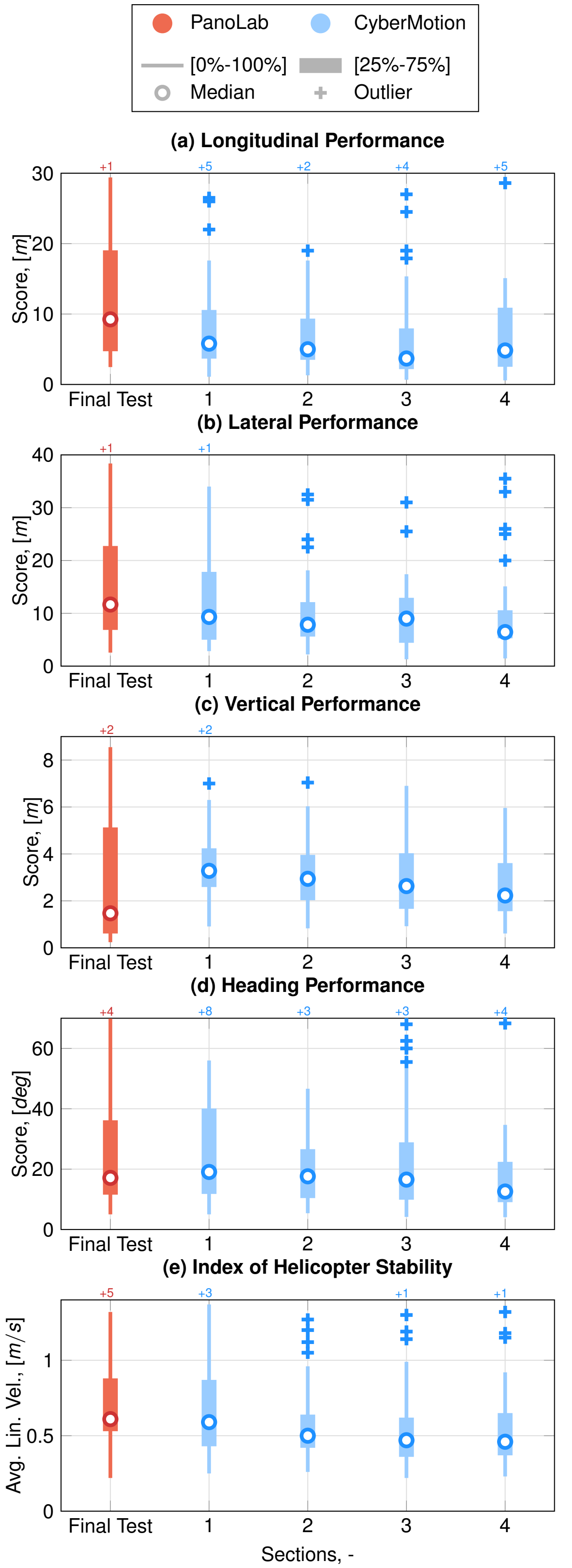

Figure 7: Evolution of scores and index of helicopter stability from the Final Test of the Training to the sections of the quasi-Transfer-of-Training experiment.

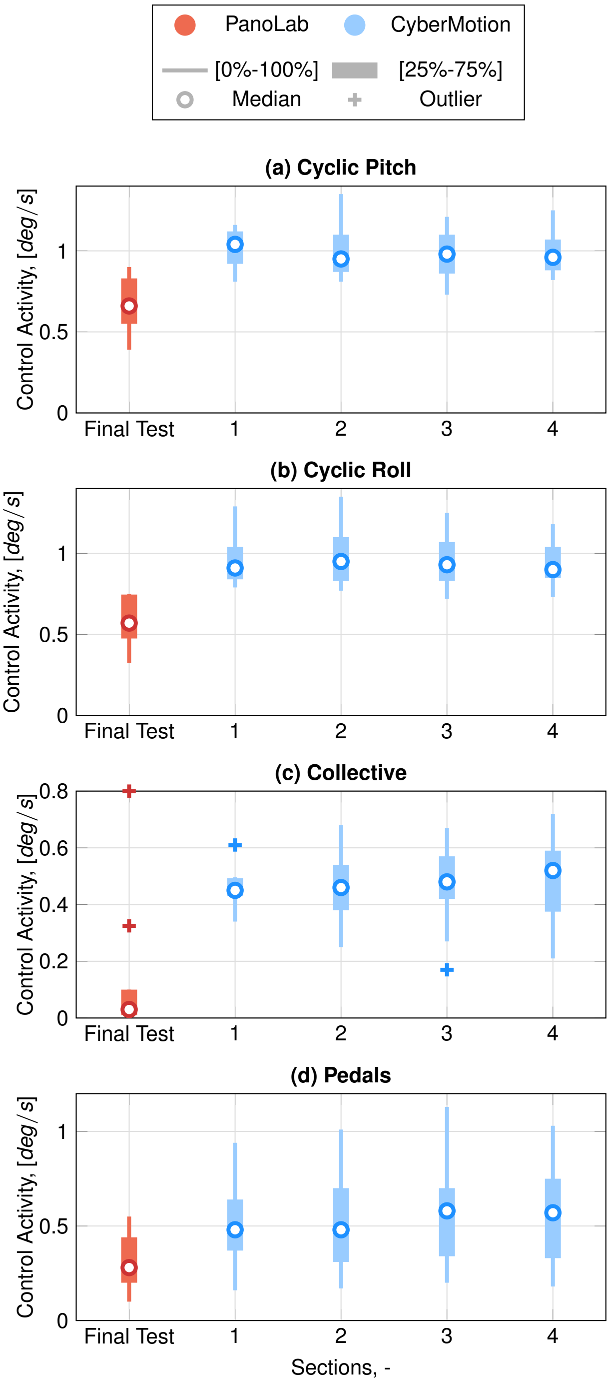

Figure 8: Evolution of the index of control activity from the Final Test of the Training to the sections of the quasi-Transfer-of-Training experiment.

Fig. 9 shows the comparison of the overall measures over all participants. Participants improved their performance (but the vertical score) thanks to the additional information provided by the motion feedback. This demonstrates that ToT happened. In fact, all participants trained in the fixed-base simulator achieved acceptable levels of performances, whereas in a previous experiment only one participant out of seven could stabilize the helicopter without prior training [14]. This result shows that the novel training program proposed in [11] is effective. Furthermore, the result encourages for a final ToT experiment on an actual helicopter that would represent a further assessment of the effectiveness and reliability of the proposed training.

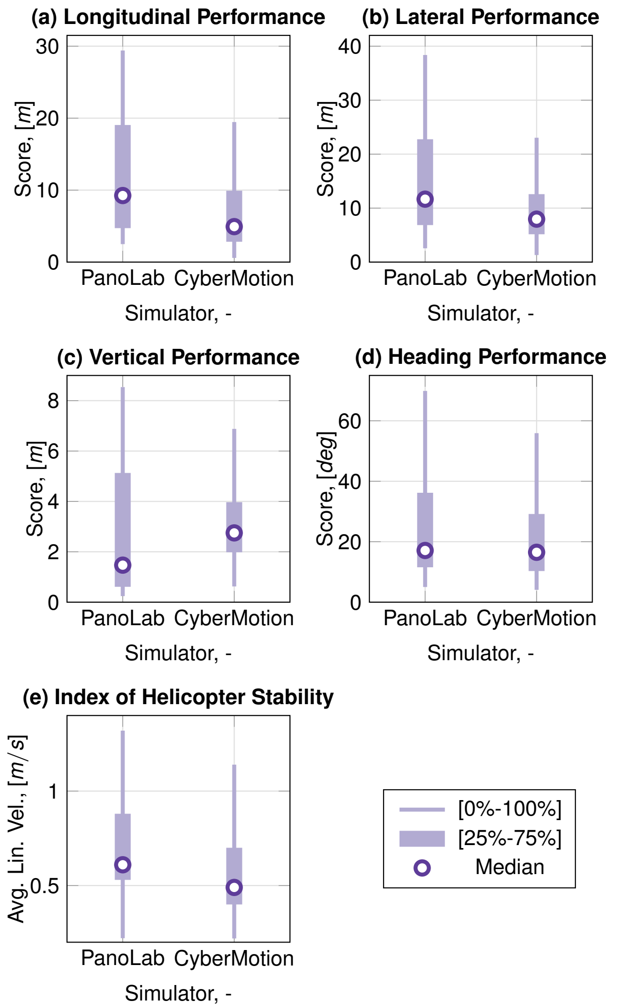

Figure 9: Comparison of performance measures in the Final Test of the Training and in the quasi-Transfer-of-Training experiment.

5. CONCLUSIONS

This paper presented the experimental validation of a training program developed in [11] for a fixed-base simulator, the MPI PanoLab Simulator. A quasi-Transfer-of-Training experiment was designed to test whether the student pilots could transfer the skills acquired in the prior learning phase to a highly-realistic motion-base helicopter simulator, the MPI CyberMotion Simulator.

Results showed that participants with prior training in the fixed-base simulator could consistently stabilize the helicopter in the motion-base simulator. In total, 90.4% of the trials were completed. Moreover, participants could improve their performance scores with respect to an evaluation phase performed at the end of the training, thanks to the additional motion feedback. These results demonstrated that Transfer-of-Training happened. In fact, in a previous experiment performed in the MPI CyberMotion Simulator, only one participant out of seven was able to stabilize the helicopter without prior training [14]. To conclude, the presented results showed that the skills acquired during fixed-base training were successfully transferred to the highly-realistic condition. Therefore, this study represents an important preliminary step for the evaluation of the potential Transfer-of-Training from fixed-base simulator to the actual helicopter.

Author contact

Davide Fabbroni:
davide.fabbroni@tuebingen.mpg.de

REFERENCES

[1] Valverde, H. H., "A Review of Flight Simulator Transfer of Training Studies," *Human Factors*, Vol. 15, No. 6, 1973, pp. 510–523.

[2] Vaden, E. A., *The Effect of Simulator Platform Motion on Pilot Training Transfer: A Meta-Analysis*, Thesis, Embry-Riddle Areonautical University, Daytona Beach, 2002, Paper 203.

[3] Caro, P. W. and Isley, R. N., "Helicopter Trainee Performance Following Synthetic Flight Training," *Journal of the American Helicopter Society*, Vol. 11, No. 3, 1966, pp. 38–44.

[4] Vincenzi, D. A., Wise, J. A., Mouloua, M., and Hancock, P. A., *Human Factors in Simulation and Training*, CRC Press, 2008.

[5] Stewart, J. E., Dohme, J. A., and Nullmeyer, R. T., "U.S. Army Initial Entry Rotary-Wing Transfer of Training Research," *The International Jour-*

nal of Aviation Psychology, Vol. 12, No. 4, 2002, pp. 359–375.

[6] Szczepansky, C. and Leland, D., "Move or Not to Move? Continuous Question," *AIAA Modeling and Simulation Technologies Conference, Denver, CO*, 2000.

[7] McCauley, M. E., "Do Army Helicopter Training Simulators Need Motion Bases?" Tech. rep., United States Army Research Institute for the Behavioral and Social Sciences, Naval Postgraduate School, 2006.

[8] Caro, P. W., "The Relationship between Flight Simulator Motion and Training Requirements," *Human Factors*, Vol. 21, No. 4, 1979, pp. 493–501.

[9] Bürki-Cohen, J., Go, T. H., and Longridge, T., "Flight Simulator Fidelity Considerations for Total Air Line Pilot Training and Evaluation," *Proceeding of the AIAA Modeling and Simulation Technologies Conference, Montreal, Canada*, 2001.

[10] Hays, R. T., Jacobs, J. W., Prince, C., and Salas, E., "Flight Simulator Training Effectiveness: A Meta-Analysis," *Military Psychology*, Vol. 4, No. 2, 1992, pp. 63–74.

[11] Fabbroni, D., Geluardi, S., Gerboni, C. A., Olivari, M., D'Intino, G., Pollini, L., and Bülthoff, H. H., "Design of a Haptic Helicopter Trainer for Inexperienced Pilots," *American Helicopter Society International 73rd Annual Forum, Fort Worth, TX*, 2017.

[12] Taylor, H. L., Lintern, G., and Koonce, J. M., "Quasi-Transfer as a Predictor of Transfer From Simulator to Airplane," *The Journal of General Psychology*, Vol. 120, No. 3, 2004, pp. 257–276.

[13] Krishnakumar, K. S., Sawal, D., Bailey, J. E., and Dohme, J. A., "A Simulator-Based Automated Helicopter Hover Trainer-Synthesis and Verification," *IEEE Transactions on Systems, Man and Cybernetics*, Vol. 21, No. 5, 1991, pp. 961–970.

[14] Geluardi, S., Venrooij, J., Olivari, M., Bülthoff, H. H., and Pollini, L., "Transforming Civil Helicopters into Personal Aerial Vehicles: Modeling, Control, and Validation," *Journal of Guidance, Control, and Dynamics*, 2017, Epub Ahead.

[15] Unity Technologies, "Unity ®," https://www.unity3d.com/, 2005.

[16] Geluardi, S., Nieuwenhuizen, F. M., Pollini, L., and Bülthoff, H. H., "Frequency Domain System Identification of a Light Helicopter in Hover," *Proceedings of the 70th Annual Forum of the American Helicopter Society*, Vol. 3, 2014, pp. 1721–1731.

[17] Perfect, P., Jump, M., and White, "Towards Handling Qualities requirements for Future Personal Aerial Vehicles," *Proceedings of the 69th Annual Forum of the American Helicopter Society, Phoenix, AZ, USA*, 2013.

COPYRIGHT STATEMENT