# Deliverable D3.4

# Results from force/visual feedback experiments on realistic scenarios

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| PP | Restricted to other programme participants (including the Commission Services) | |
| RE | Restricted to a group specified by the consortium (including the Commission Services) | |
| CO | Confidential, only for members of the consortium (including the Commission Services) | |

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## Executive Summary

In this deliverable, the results of several experimental evaluations are presented. In the first study, a human-machine interface based on a combination of a haptic shared control framework and a highway-in-the-sky display is evaluated. These technologies could provide an easy-to-use control interface for non-expert pilots. In the study, various display and haptic approaches were evaluated in a flight control task with a personal aerial vehicle. It was shown that a tunnel or a wall representation of the flight trajectory lead to best performance and lowest control activity and effort. Similar results are obtained when haptic guidance cues were based on the error of a predicted position of the vehicle with respect to the flight trajectory. Such haptic cues are also subjectively preferred by the pilots. This study indicated that the combination of a haptic shared control framework and highway-in-the-sky display can provide non-expert pilots with an easy-to-use control interface for flying a PAV.

The second study explores how haptic and automated pilot support systems can affect pilot behaviour. External aids are required to increase safety and performance during the manual control of an aircraft. Automated systems allow surpassing the performance usually achieved by pilots. However, they suffer from several issues caused by pilot unawareness of the control command from the automation. Haptic aids can overcome these issues by showing their control command through forces on the control device. To investigate how the transparency of the haptic control action influences performance and pilot behaviour, a quantitative comparison between haptic aids and automation is needed. An experiment was conducted in which pilots performed a compensatory tracking task with haptic aids and with automation. The haptic aid and the automation were designed to be equivalent when the pilot was out-of-the-loop, i.e., to provide the same control command. Pilot performance and control effort were then evaluated with pilots in-the-loop and contrasted to a baseline condition without external aids. The haptic system allowed pilots to improve performance compared with the baseline condition. However, automation outperformed the other two conditions. Pilots control effort was reduced by the haptic aid and the automation in a similar way. In addition, the pilot open-loop response was estimated with a non-parametric estimation method. Changes in the pilot response were observed in terms of increased crossover frequency with automation, and decreased neuromuscular peak with haptics.

The third study is an extension of work reported in deliverable “D3.2: Experimental assessment of Human-Machine interfaces for PAVs”. In this work, a descriptive study is reported that addresses the relationship between flight control performance and instrument scanning behaviour. This work was performed in a fixed-based flight simulator. It targets the ability of untrained novices to pilot a lightweight rotorcraft in a flight scenario that consisted of fundamental mission task elements such as speed and altitude changes. The results indicate that better control performance occurs when gaze is more selective for and focused on key instruments. Ideal instrument scanning behaviour is proposed and its relevance for training instructions and visual instrument design is discussed. Although this work was performed

with an instrument panel with separate flight instruments, it can be generalised to modern Primary Flight Displays or perspective display to investigate scanning behaviour on integrated displays.

## Table of Contents

# 1. Haptic shared control and a highway-in-the-sky display for PAVs

This study was published and presented at the AIAA SciTech 2014 conference:

F.M. Nieuwenhuizen and H.H. Bülthoff, “Evaluation of Haptic Shared Control and a Highway-in-the-Sky Display for Personal Aerial Vehicles,” *Proceedings of the AIAA Modeling and Simulation Technologies Conference and Exhibit, National Harbor (MD),* AIAA-2014-0808, 13-17 Jan. 2014.

**Abstract**

Highway-in-the-sky displays and haptic shared control could provide an easy-to-use control interface for non-expert pilots. In this paper, various display and haptic approaches are evaluated in a flight control task with a personal aerial vehicle. It is shown that a tunnel or a wall representation of the flight trajectory lead to best performance and lowest control activity and effort. Similar results are obtained when haptic guidance cues are based on the error of a predicted position of the vehicle with respect to the flight trajectory. Such haptic cues are also subjectively preferred by the pilots. This study indicates that the combination of a haptic shared control framework and highway-in-the-sky display can provide non-expert pilots with an easy-to-use control interface for flying a personal aerial vehicle.

# Evaluation of Haptic Shared Control and a Highway-in-the-Sky Display for Personal Aerial Vehicles

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**Highway-in-the-sky displays and haptic shared control could provide an easy-to-use control interface for non-expert pilots. In this paper, various display and haptic approaches are evaluated in a flight control task with a personal aerial vehicle. It is shown that a tunnel or a wall representation of the flight trajectory lead to best performance and lowest control activity and effort. Similar results are obtained when haptic guidance cues are based on the error of a predicted position of the vehicle with respect to the flight trajectory. Such haptic cues are also subjectively preferred by the pilots. This study indicates that the combination of a haptic shared control framework and highway-in-the-sky display can provide non-expert pilots with an easy-to-use control interface for flying a personal aerial vehicle.**

## I. Introduction

Within the European Union, a Personal Aerial Transportation System (PATS) has been presented as a potential solution to problems associated with predicted volumes of traffic of the future.[1] The European project myCopter[a] investigates enabling technologies for such a transportation systems.[2] Apart from the socio-economic aspects of a PATS, autonomous flight capabilities of Personal Aerial Vehicles (PAV) (such as vision-based localization, swarming and collision avoidance), and handling qualities and training requirements for PAVs, the project also studies novel technologies for human-machine interfaces (HMI). In the context of a PATS, users should be able to control their PAV with a minimum amount of training, and the interface between the pilot and a highly augmented PAV should provide the pilot with continuous feedback while the pilot remains in control.

Control interfaces for vehicular control in aerospace systems are predominantly focused on two opposing approaches: manual control and automation. Automation can be used to overcome disadvantages of manual control, but can also have undesirable effects, especially during control of more safety-critical dynamic processes in unpredictable environments.[3] The use of automation can also lead to loss of skills, and it has been argued that human errors due to loss of skills or over-reliance on automation could lead to a vicious circle of increased regulations that take away more responsibilities of the human, which in turn leads to increased loss of skills.[4]

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[a]`http://www.mycopter.eu`

Therefore, it has been proposed to combine the advantages of manual control and automation in a system where the human and automation continuously share control through force interactions on a control interface: haptic shared control.[3] The human and automation both exert forces on the control inceptor, and its position provides input to the controlled system. Such a system would allow the human to interact with automation directly and overrule it if necessary. In this way, the human retains ultimate control authority. It has been shown that such systems can result in increased performance in vehicular control tasks.[5,6,7]

An alternative way for informing a pilot about his control task is to include additional information in the visual display. Current displays, such as the Primary Flight Display, combine information about the current aircraft state and the target that the pilot has to follow in single view. On the contrary, perspective cues on the future path, such as provided by a tunnel-in-the-sky or highway-in-the-sky (HITS) display, are not presented. Displays with perspective cues have only recently found their way into the cockpit of general aviation aircraft, and have been shown to enhance pilot performance in the task of flight guidance.[8,9,10]

The goal of this paper is to investigate whether the combination of a haptic shared control framework and a HITS display could result in an easy-to-use control interface and better performance for non-expert pilots. These novel control interfaces are integrated with a dynamic model for a PAV, which is developed within the myCopter project. Subsequently, this setup is evaluated experimentally to assess to which extent participants without formal flight training benefit from haptic cues and enhanced visual information.

# II. A control task for personal aerial vehicles

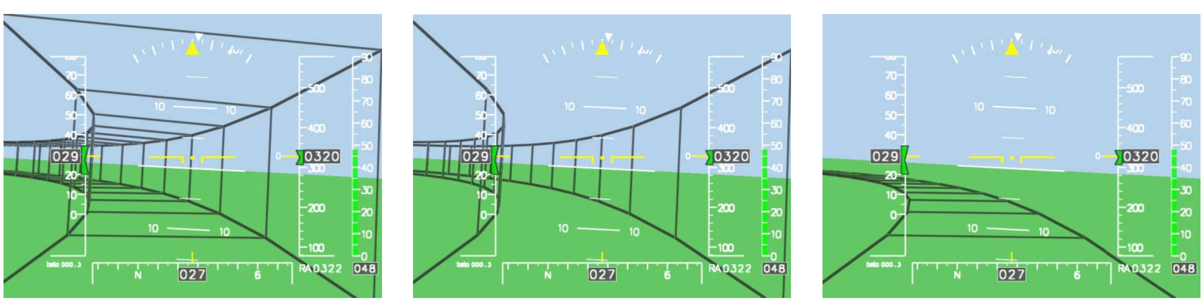
Within the context of the myCopter project, PAV pilots will have limited flight experience. A highway-in-the sky display and haptic shared control system need to be integrated into a control task that can be performed precisely and without much training. In this section, the flight control task is detailed. First, the PAV dynamic model is introduced. After that, the HITS display and haptic shared control architecture are described.

## II.A. Dynamic response of a personal aerial vehicle

One of the goals of the myCopter project is to develop handling qualities guidelines and criteria for PAVs. Conventional rotorcraft response types, such as rate-command attitude-hold, are unsuitable for prospective PAV-pilots with minimal flight training. Therefore, a generic PAV dynamics model has been implemented by the University of Liverpool such that response type requirements can be identified for varying levels of flying skills, in order to ensure safe and precise flight.[11,12]

In this paper, the generic PAV dynamics model is used in its so-called *hybrid* mode. In this mode, the dynamic response in forward flight corresponds to attitude-command attitude-hold (ACAH) in roll, acceleration-command speed-hold (ACSH) in pitch and rate-command attitude-hold (RCAH) in heave. Each of these degrees of freedom is independent from the others. This configuration results in Level 1 handling qualities, which makes it the most suitable for non-expert pilots controlling PAVs.[12]

For this research, the control task is limited to the roll degree of freedom. The longitudinal and vertical degrees of freedom of the PAV are controlled by an autopilot. The speed of the PAV was fixed at 50 knots.



(a) Tunnel representation (b) Wall representation (c) Highway representation

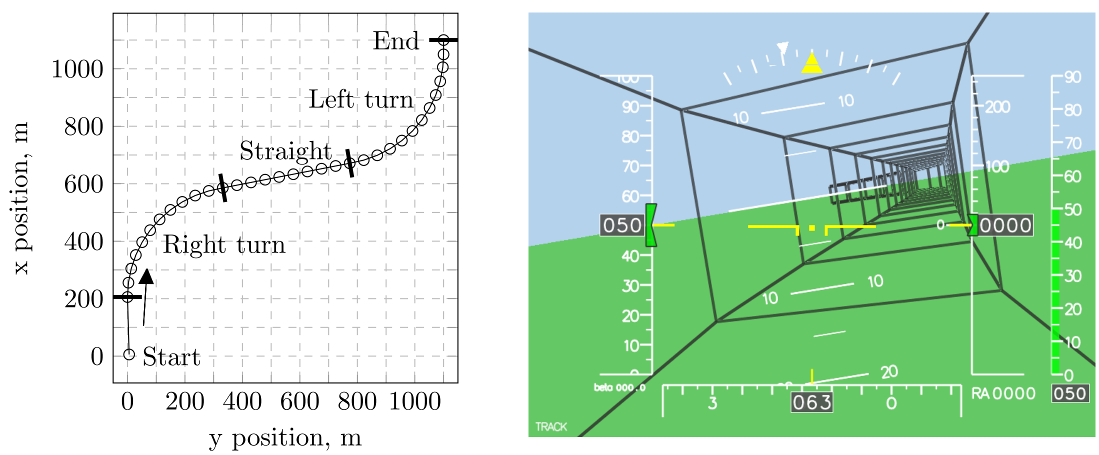
Figure 1: Various representations of a flight trajectory in a Highway-in-the-Sky display (developed by the German Aerospace Center DLR).

### II.B. Highway-in-the-sky display

Within the myCopter project, a highway-in-the-sky display (HITS) has been developed by the German Aerospace Center DLR that can display the perspective information of a flight trajectory. The myCopter HITS shows a three-dimensional tunnel trajectory on a modified Primary Flight Display (PFD), which can help the pilot in following a specific trajectory. Additionally, target indicators for parameters like altitude, airspeed and attitude can be displayed on the PFD. The tunnel trajectory can be represented in various ways, see Figure 1. The most common representation consists of an enclosed tunnel (Figure 1a). A configuration that only shows the walls of the tunnel is preferred by test pilots from DLR (Figure 1b). A novel way of representing the tunnel trajectory is equivalent to a highway, which would be the most common representation for pilots without formal flight training but with car driving experience (Figure 1c).

For the control task in this research, a flight trajectory is generated according to a circle-line-circle approach.[13] These trajectories connect a starting point with an end point through a turn with a predefined radius, a straight section, and another turn, respectively. The radius of the turn can be calculated according to the speed of the PAV and a maximum bank angle. Any changes in altitude between the start and end of the flight trajectory would be performed in the straight section, but in the current task the altitude is kept constant throughout the trajectory.

A schematic representation of the flight trajectory for the control task is shown in Figure 2a. The pilot controls the PAV with a constant speed from a start position through a right turn, a straight section and a left turn to the end of the trajectory. Given that the generic PAV dynamics model has a ACAH response in the roll axis, the pilot can perform the turns with a constant lateral input on the control inceptor. The pilot would perceive this flight trajectory as shown in the HITS display in Figure 2b. The tunnel dimensions are 40 m horizontally and 30 m vertically and the tunnel gates are placed at equal distances.




(a) The trajectory represented in the horizontal plane

(b) The trajectory in the HITS display at the end of the right turn

Figure 2: The flight trajectory for the control task.

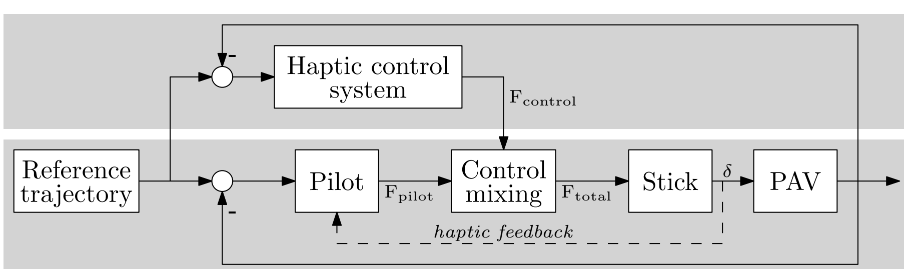



Figure 3: A haptic-shared control architecture.

### II.C. Haptic shared control

In haptic shared control, the human and an automatic control system continuously share control authority through force interactions on the control inceptor.[3] These forces can guide the user along a certain optimal trajectory. Additionally, the forces can indicate operational boundaries of the controlled system. The architecture of haptic shared control used in this paper is presented in Figure 3. In this architecture, a human pilot is tasked with following a reference trajectory while a haptic control system provides guidance forces on the control inceptor. The influence of the guidance forces from the haptic control system are limited in magnitude, such that it can be ensured that the human can always choose to overrule the haptic control system.

The haptic forces are calculated according to the geometrical relation between the predicted position of the PAV with respect to the flight trajectory. Prediction of the future position of the PAV is used to mimic look-ahead behavior of pilots. This relation is schematically shown in Figure 4.

The current position of the PAV is represented by $p$. The predicted position $p_{\text{pred}}$ is calculated as follows:

$$p_{\text{pred}} = p + V_{\text{PAV}} \cdot t_{\text{pred}} \ , \tag{1}$$

in which $V_{\text{PAV}}$ presents the current velocity vector of the PAV and $t_{\text{pred}}$ the prediction time.

The error of the predicted position with respect to the flight trajectory $e$ is calculated through geometrical relations between a point and a line in three dimensions, see Figure 4. The error $e$ is then projected onto the PAV body reference frame and decomposed into its horizontal and vertical components ($e_{\text{hor}}$ and $e_{\text{vert}}$, respectively). In this way, the error of the predicted position is related to the different independent degrees of freedom of the PAV.

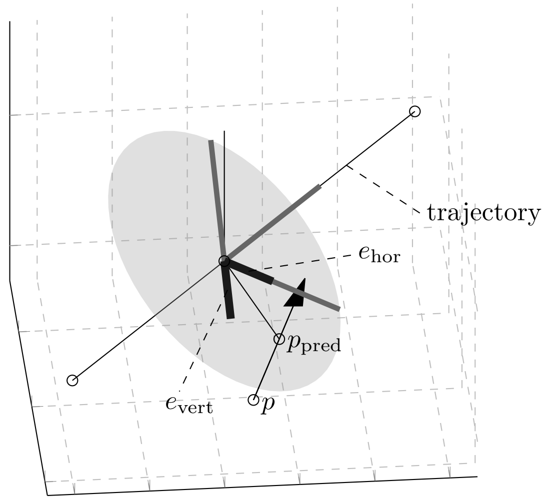



Figure 4: Determination of the horizontal and vertical error of a point with respect to a flight trajectory.

In this control task, pilots do not have to control their altitude and speed, and only have to use the roll axis of the control inceptor to follow the flight trajectory. The haptic forces are proportional to $e_{\text{hor}}$:

$$F_{\text{roll}} = \begin{cases} F_{\text{max}}/10 \cdot e_{\text{hor}} & \text{if } -10 \leq e_{\text{hor}} \leq 10 \\ F_{\text{max}} & \text{if } e_{\text{hor}} > 10 \\ -F_{\text{max}} & \text{if } e_{\text{hor}} < -10 \end{cases} \ , \tag{2}$$

in which $F_{\text{max}}$ represents the maximum force that can be generated by the haptic control system. This is set to 2.5 N to prevent the system from exerting forces that are too high for the pilot to counteract comfortably. At the same time this ensures that the pilot needs to be engaged during the entire control task, as the haptic control system can not follow the flight trajectory automatically.

# III. Experimental evaluation

The control task described in Section II was evaluated experimentally. The experimental design and results are presented in this section.

## III.A. Experiment design

### *III.A.1. Conditions*

The experiment was designed to evaluate whether the combination of a haptic shared control framework and a HITS display could result in an easy-to-use control interface and better performance for non-expert pilots. The three HITS display configurations as shown in Figure 1 were evaluated: a tunnel representation, a wall representation and a highway representation of the flight trajectory. Furthermore, a condition without haptic guidance was tested, as well as three values for the prediction time of the haptic cues $t_{\text{pred}} = 0, 1.5, 3$ s. The experiment had a full $3 \times 4$ factorial design, which resulted in 12 experimental conditions.

### *III.A.2. Apparatus*

The experiment was performed on a fixed-based simulator that consisted of a VIEWPixx display from VPixx Technologies Inc., USA, with a refresh rate of 120 Hz and a electrical control-loaded sidestick from Wittenstein Aerospace & Simulation GmbH, Germany. The HITS display, see Figure 2b, was shown on the display that was located 1 m in front of the participants. The sidestick had a maximum deflection of $\pm 14$ deg and did not have a breakout force. The pitch axis of the sidestick was kept a zero position. The stiffness in the roll axis was set to 1 N/deg.

### *III.A.3. Participants*

In total, ten participants performed the experiment, of which three were female. Their age ranged between 23 and 35. None of the participants had formal flight training, although some were familiar with manual control tasks in flight simulators. Before the experiment, participants were briefed about their task. They were informed that they would experience different haptic support cues, but were not told about the underlying algorithms. Participants were asked to follow the center of the tunnel trajectory in the HITS display as accurately as possible.

### *III.A.4. Procedure*

The experiment had a within-participant design in which all participants performed all twelve conditions. As the experimental control task was rather easy, participants only performed 1 or 2 training trials to familiarize themselves with the PAV dynamics and the HITS display. During the experiment, the order of the conditions was based on a Latin square design such that the conditions were presented quasi-randomly. Participants were not told which condition was presented and performed three experimental trials for each condition. Each trial lasted 70 seconds in which participants traversed the entire flight trajectory. Participants all completed the experiment within 75 minutes. Data were logged at 100 Hz.

## III.B. Results

Various dependent measures were recorded during the experiment. The root-mean-squared value of the horizontal error signal $e_{\text{hor}}$ is used as a measure for pilot performance. The variance of the lateral input signal $\delta_{\text{lat}}$ indicates the control activity of the pilots. Finally, the variance of the lateral input force $F_{\text{lat}}$ serves as a metric for pilot effort.

The measured data were averaged over all trials and all participants to reduced the variance of the dependent measures. The error bars in the results represent the interval where it is 95% confident that it contains the population mean. These error bars have been corrected for variability between participants by adjusting the participant means for between-participant effects. The measured data are presented separately for the different segments of the flight trajectory.

*III.B.1. Pilot performance*

The pilot performance for the flight trajectory is presented in Figure 5. It is clear that the highway representation of the flight trajectory leads to worse performance in following the flight trajectory compared to the wall or tunnel representation when pilots are not supported with haptic cues. When pilots have access to haptic guidance forces, performance is increased as they become better at minimizing the lateral error.

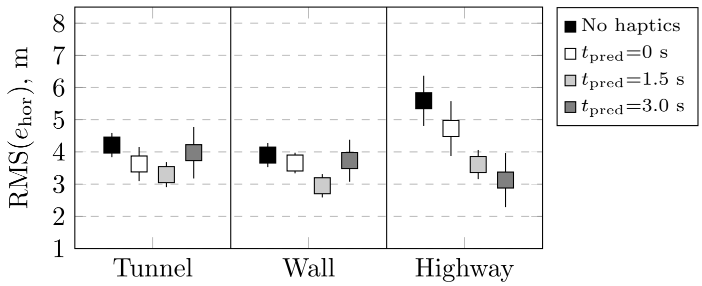
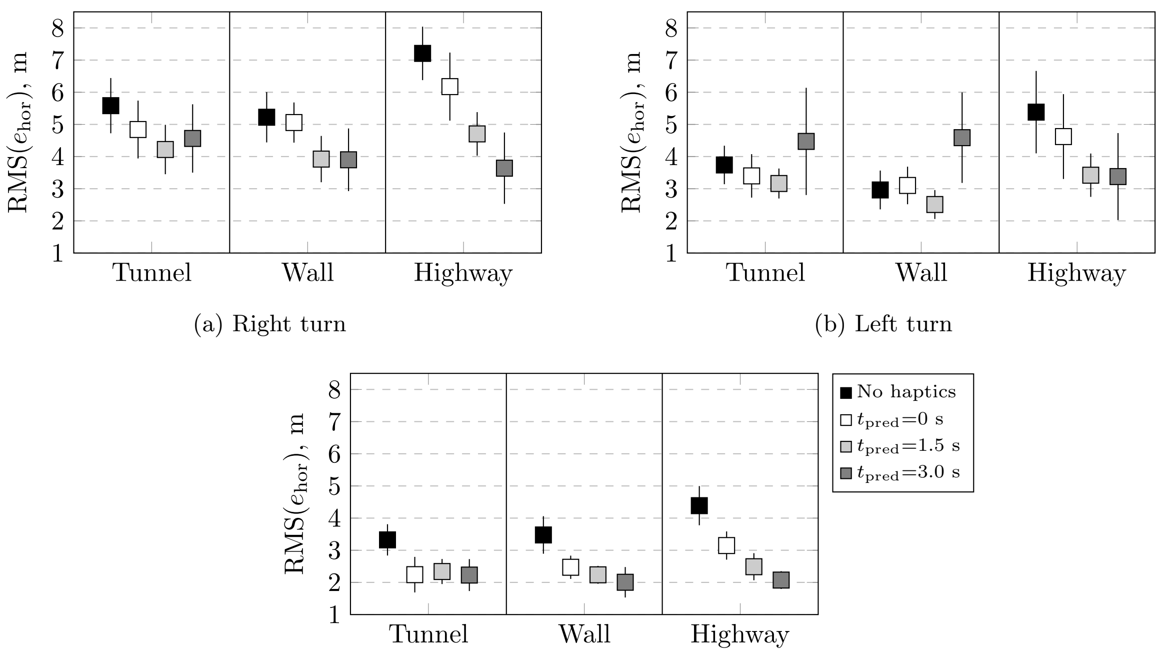



Figure 5: Pilot performance for the entire flight trajectory.

Pilot performance is shown separately for the different segments of the flight in Figure 6. In general, an increase in prediction time $t_{pred}$ leads to increasing performance. However, during the final flight segment (the left turn) pilot performance becomes more variable when $t_{pred} = 3.0$ s. During the right turn and the straight segment, the haptic cues based on the largest prediction time lead to the best pilot performance and allow pilots to perform the flight control task with a highway representation with similar performance to the tunnel and wall representations.




(a) Right turn

(b) Left turn

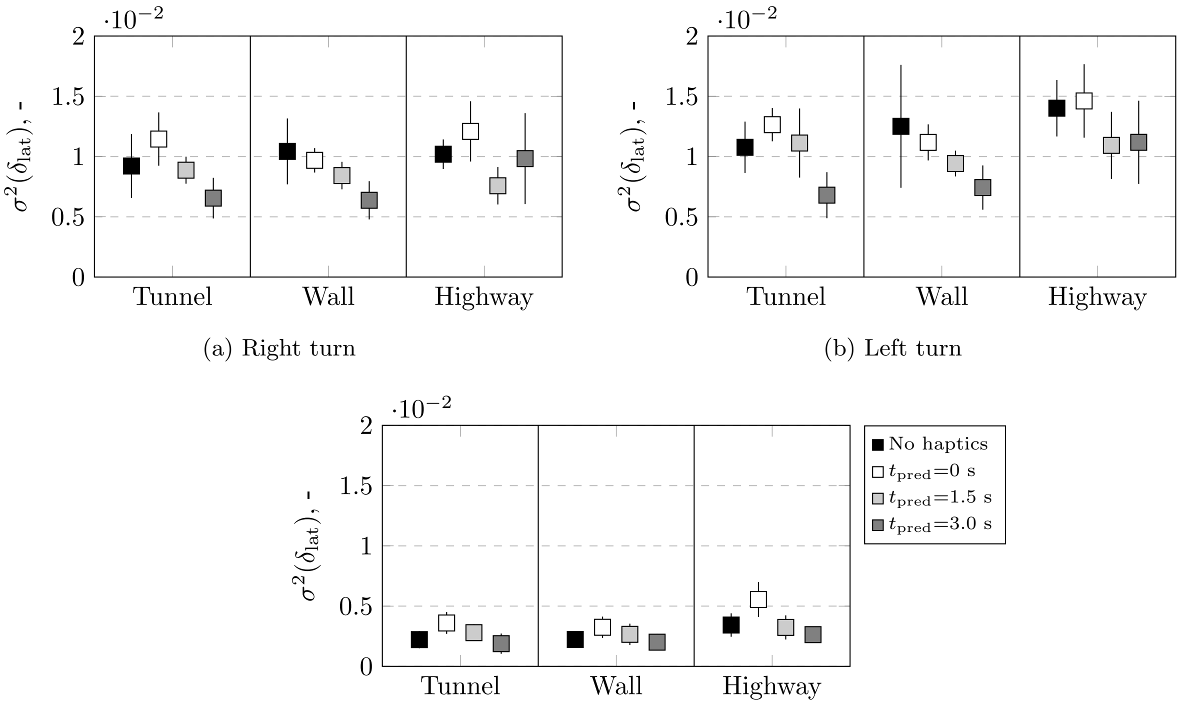
(c) Straight section

Figure 6: Pilot performance.

*III.B.2. Pilot control activity*

The variance of the lateral input signal $\delta_{lat}$ is regarded as a measure for pilot control activity. As shown in Figure 7, pilot control activity is very low for this control task, which can be explained by the dynamic response of the PAV. With an attitude-command attitude-hold response it is only necessary to give a constant lateral control input to perform a turn. During the straight segment, pilots need to keep the sidestick centered. Only small additional inputs are required during the control task to make corrections to the flight path.

Even though the pilot control activity is small for all flight segments, there is a clear influence of the experimental conditions. Control activity tends to be slightly larger for the highway representation. When $t_{\text{pred}} = 0.0$ s, pilot control activity is increased with respect to the other haptic conditions, which indicates that the haptic cues provided in this condition did not match the pilot's intentions. This is also in-line with pilot comments, which indicated that the haptic condition with a prediction time of 1.5 s and 3.0 s were preferred. In general, control activity attained the lowest values in conditions with $t_{\text{pred}} = 3.0$ s.




(a) Right turn

(b) Left turn

(c) Straight section

Figure 7: Pilot control activity.

*III.B.3. Pilot effort*

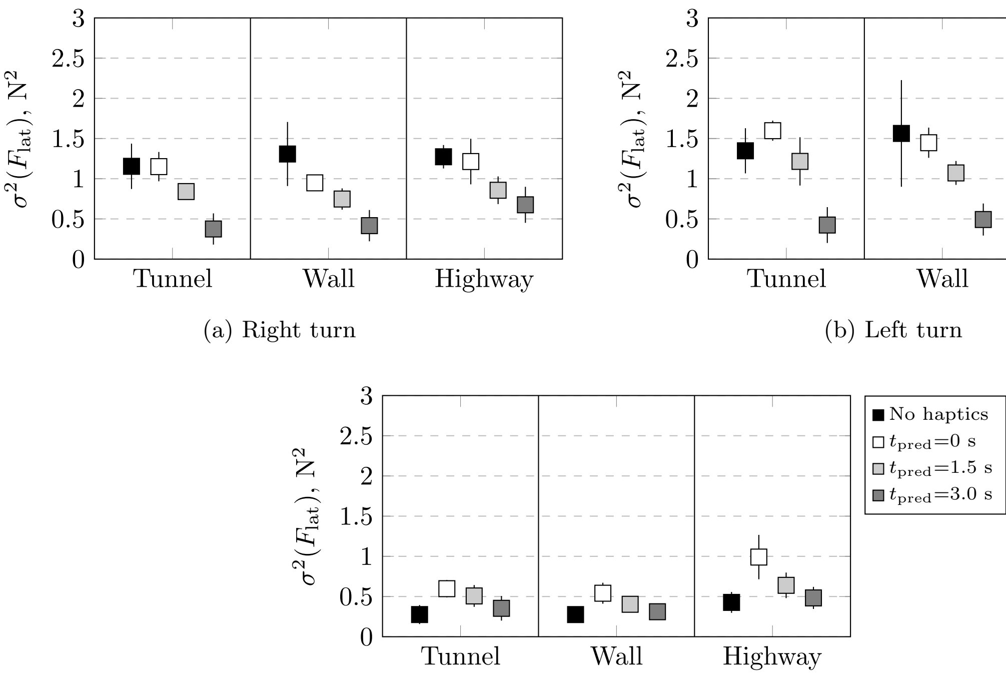
Pilot effort was measured through the variance of the pilot lateral input force $F_{\text{lat}}$ on the sidestick. It is clear from Figure 8 that pilot effort is slightly higher in the turns compared to the straight flight segment. This is consistent with the measure for pilot control activity.

During the turns, an increase in prediction time $t_{\text{pred}}$ resulted in lower effort with respect to the condition without haptic guidance. However, pilot effort was slightly increased when $t_{\text{pred}} = 0.0$ s, similar to the increase in pilot control activity found in this condition. This indicates that the haptic cues provided in this condition did not match the pilot's intentions.

In the straight flight segment, any haptic cues resulted in slightly increased pilot effort with respect to the condition without haptic guidance. However, this increase is very small and the resulting pilot effort is still low compared to the effort exerted during the turns.

## IV. Conclusion

An experiment was performed in which it was investigated whether the combination of a haptic shared control framework and a highway-in-the-sky display could result in better performance for non-expert pilots flying a personal aerial vehicle. Various representations of a flight trajectory in a highway-in-the-sky display were evaluated. It was found that a tunnel and a wall representation led to the best performance, whereas a highway representation resulted in worse performance and higher control activity and effort.




(a) Right turn

(b) Left turn

(c) Straight section

Figure 8: Pilot effort.

Haptic guidance cues on the sidestick allowed pilots to achieve better performance with lower control activity. However, pilots had to increase their control effort when the haptic guidance cues were not based on the error of the predicted position of the PAV with respect to the flight trajectory. Best performance, lowest control activity and effort were attained with the highest prediction time of 3.0 s, which was also subjectively the preferred condition of most pilots.

This study indicates that the combination of a haptic shared control framework and highway-in-the-sky display can provide non-expert pilots with an easy-to-use control interface for flying a PAV. Future work will focus on extending this approach to other degrees of freedom.

# V. Acknowledgments

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## 2. A comparison of haptic and automated pilot support systems

This study was published and presented at the AIAA SciTech 2014 conference:

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**Abstract**

External aids are required to increase safety and performance during the manual control of an aircraft. Automated systems allow surpassing the performance usually achieved by pilots. However, they suffer from several issues caused by pilot unawareness of the control command from the automation. Haptic aids can overcome these issues by showing their control command through forces on the control device. To investigate how the transparency of the haptic control action influences performance and pilot behaviour, a quantitative comparison between haptic aids and automation is needed. An experiment was conducted in which pilots performed a compensatory tracking task with haptic aids and with automation. The haptic aid and the automation were designed to be equivalent when the pilot was out-of-the-loop, i.e., to provide the same control command. Pilot performance and control effort were then evaluated with pilots in-the-loop and contrasted to a baseline condition without external aids. The haptic system allowed pilots to improve performance compared with the baseline condition. However, automation outperformed the other two conditions. Pilots control effort was reduced by the haptic aid and the automation in a similar way. In addition, the pilot open-loop response was estimated with a non-parametric estimation method. Changes in the pilot response were observed in terms of increased crossover frequency with automation, and decreased neuromuscular peak with haptics.

# An Experimental Comparison of Haptic and Automated Pilot Support Systems

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## I. Introduction

Manual control of an aircraft is a difficult task. Pilot's loss of control is the primary cause of fatal accidents for general aviation vehicles, and this happens primarily during phases that require the pilot to

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perform a large number of critical tasks (e.g, landing, maneuvering).[1,2] To improve the safety of flying, pilots need to be supported with external aids that can facilitate the control task.

Automation is defined as "devices or systems that accomplish (partially or fully) a function that was previously carried out (partially or fully) by a human operator".[3] By delegating complex tasks to automated systems, the control of an aircraft can be simplified. Furthermore, performance of automated systems generally surpass human pilots.[4] A common belief is that safety and performance would drastically increase with a fully automated aircraft, where the automation is able to perform all control tasks without human interaction.[5] However, this is far from being realized. Automation is inefficient when unpredicted changes happens on the external environment, or when a novel decision must be taken.[6] The human operator is needed to supervise the automated system and handle unexpected critical situations.

The presence of human operators gives rise to several issues related to human factors that could happen with an improper design of automated systems. Main issues are the degradation of pilot skills of manually controlling the aircraft, over-reliance on automation and vigilance decrement.[7–9] Furthermore, improper automation could lead to a loss of situational awareness. Situational awareness indicates "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future", or, shortly, "knowing what's going on".[10,11] With automation, letting pilots know "what's going on" is a key problem. The most common approach is to provide visual or auditory alerts about automation functionality and failures. However, this approach suffers from a number of pitfalls, like overloading of information and presence of false alarms.[12] Ignoring such issues could lead to severe problems. For example, pilots may require too much time to detect failures of the automation, and they may not be able to recover from these failures.[13] Therefore, an improper design of automation could expand problems instead of simplifying the manual control task.[7]

To overcome these issues, a main guideline has been put forward: pilots should always receive feedback from automation about its control strategy.[4,14] These feedback would allow the pilot to be always *in-the-loop*, detect possible errors of automation and respond to them. The feedback should be intuitive and not too invasive for pilots, in order to "keep people well informed, on the top of the issues, but not annoyed and irritated".[4]

Haptic aids have been proposed as a powerful solution to keep the pilot in-the-loop.[5,14–16] Haptic systems provide tactile feedback that aims to help pilots during the manual control task. In the most common approach, i.e. the Direct Haptic Aid (DHA), the haptic system calculates a control action that would allow the aircraft to perform a certain task, and continuously shows this control action to pilots by means of forces on the stick.[17–19] Pilots are always aware of the DHA control strategy, and can always decide either to be compliant or to override it if they disagree with the system.

Despite the growing interest on the theoretical advantages of haptic aids, there is still some question about their performance compared to automation. Most studies tend to compare haptics with baseline conditions without any external aids. In these cases, haptic aids lead to better performance and reduced control effort.[15,20,21] In a more recent work dealing with car driving, a haptic pedal was compared with full automated system during a curve negotiation task.[22] During the curve negotiation with the automation, the driver could not give input to the car. The haptic aid improved performance compared with the manual control (measured through the peak of lateral error), but it reached lower performance than automation (the peak was larger with haptic aid than with automation). To the best of our knowledge, in literature there are no analogous works regarding typical flight tasks.

The goal of the paper is to compare automation and haptic aids in a compensatory tracking task of an aircraft.[23] A DHA haptic system was designed to help pilots in performing the task. Furthermore, an automated system (AUT) was designed to be "equivalent" to the DHA system, in the sense that it gave the same performance *without pilot in-the-loop*. Since the performance is low, pilots still need to actively control the aircraft. The AUT and DHA systems were tested in an experimental setup *with pilot in-the-loop*. Performance and control activity were evaluated and compared with the manual control task without aids. Furthermore, the open-loop pilot response was estimated to obtain a better insight on the influence of haptics and automation in the pilot control behavior.

Section II presents the compensatory tracking task and a model that describes the overall pilot response in this task. Section III and IV present the design of the haptic aid and the automated system, respectively. In Section V the experiment design is described, and in Section VI results are presented. Finally, conclusions are drawn in Section VII.

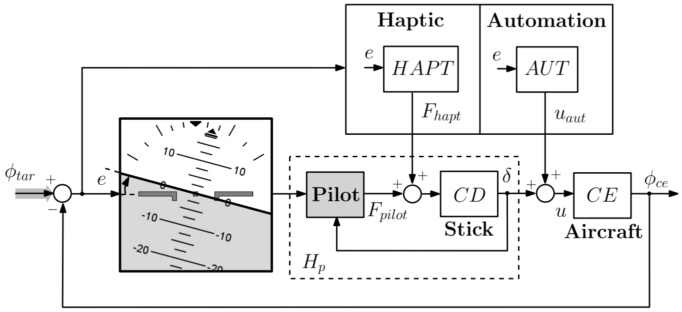



**Figure 1. Compensatory tracking task with haptic aid or automation.**

## II. Control Task and Identification of Pilot Behavior

This paper focuses on the design of aids for a compensatory tracking task in the roll axis, as depicted in Figure 1. The task consists of tracking a target roll trajectory $\phi_{tar}$ with the aircraft (i.e., the Controlled Element CE). Only the tracking error $e$ between the target trajectory and the actual roll angle $\phi_{ce}$ is shown to the pilot on the compensatory display. The pilot controls the roll dynamics of the aircraft by applying the force $F_{pilot}$ on the stick (i.e., the Control Device CD). This results in a change of the stick deflection $\delta$ and consequently in a command signal $u$ for the aircraft. The haptic aid HAPT or the automation AUT can be used to help pilots during the control task. The haptic aid generates forces $F_{hapt}$ on the stick, while the automation provides an additional command $u_{aut}$ directly into the aircraft. Note that, in this model, the pilot can feel the haptic forces through the variations that they cause on the stick deflection $\delta$.

The pilot behavior in a compensatory tracking task has been extensively investigated in literature. McRuer provided quantitative models that describe the pilot response to the tracking error for different controlled elements.[23–25] These models assess that pilots adapt their response such that the open-loop transfer function between the tracking error $e$ and the roll angle of the aircraft $\phi_{ce}$ resembles an integrator-like dynamics at frequencies around the crossover frequency $\omega_c$:[23,24]

$$H_p H_{ce} = \frac{\omega_c e^{-s\tau_s}}{s} \tag{1}$$

Here, $H_{ce}$ represents the transfer function of CE, while $H_p$ is the transfer function from the tracking error $e$ to the stick deflection $\delta$. Note that $H_p$ includes the dynamics of the pilot and the stick, see Figure 1. The parameters $\omega_c$ and $\tau_s$ represent the crossover frequency and the pilot visual delay, respectively. However, McRuer's theories did not consider haptic aids or automation in the control loop. The question arises as to whether McRuer's theories are still valid when haptic aids or automation are employed. To answer this question, it is necessary to estimate the open-loop transfer function in tracking tasks with haptic aids or automated systems.

Identification methods that operate in the frequency domain can be used for this purpose.[26,27] These methods require an external signal that excites the system in the frequency range of interest. For this reason, the target trajectory $\phi_{tar}$ was chosen as a multisine signal:[28]

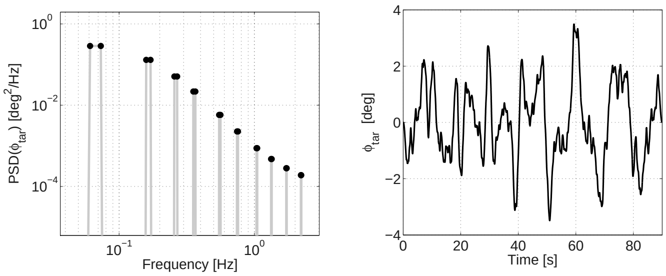
$$\phi_{tar}(t) = \sum_{j=1}^{N_t} T_j \sin(2\pi f_{T_j} t + \psi_{T_j}) \tag{2}$$

where $T_j$, $f_{T_j}$, and $\psi_{T_j}$ are the amplitude, the frequency and the phase of the $j^{th}$ sinusoidal component of the signal $x_{tar}$. Each frequency $f_{T_j}$ is obtained as an integer multiple of a base frequency $f_0$, i.e. $f_{T_j} = j \cdot f_0$.

Figure 2 shows the time realization and the Power Spectral Density of the target trajectory used in our paper. The PSD has power on a finite set of frequency points $\{f_t\}$ in the range $[0.05 - 3]$ Hz, which is sufficiently large to capture the dynamical properties of pilot response. Furthermore, the time realization of $\phi_{tar}$ is unpredictable for pilots. More details on $\phi_{tar}$ are given in Section V.

The estimation of the pilot open-loop transfer function is given by:[26]

$$\hat{H}_{ol}(f) = \frac{\hat{S}_{\phi_{tar}\phi_{ce}}(f)}{\hat{S}_{\phi_{tar}e}(f)}, \qquad f \in \{f_t\}. \tag{3}$$




(a) PSD. (b) Time realization.

**Figure 2. Target trajectory $\phi_{tar}$.**

Here, $\hat{S}_{vw}$ represents the estimate of the cross-spectra between the generic signals $v$ and $w$, obtained as:

$$\hat{S}_{vw}(f) = \hat{V}(f)W(f) \tag{4}$$

where $V$,$W$ are the Discrete Fourier Transform of $v$ and $w$, respectively, and $\hat{V}$ is the complex conjugate of $v$. The coherence functions $\Gamma^2(\cdot)$ can be used as a reliability indicator of the estimate:

$$\Gamma^2(f) = \frac{|\hat{S}_{\phi_{tar}e}(f)|^2}{\hat{S}_{\phi_{tar}\phi_{tar}}(f)\hat{S}_{ee}(f)}, \qquad f \in \{f_t\}. \tag{5}$$

The coherence can assume values between 0.0 and 1.0. The maximum value 1.0 indicates that the measurements of $e$ and $\phi_{ce}$ are linearly related and without noise, whereas smaller values indicate the presence of nonlinear distortion and noise.[26]

# III. Design of Haptic Aid

A haptic aid was designed with the aim of helping pilots during the tracking task. The haptic aid was designed according to the Direct Haptic Aid approach(DHA).[29] Based on the tracking error, the haptic aid continuously generates forces on the stick that aim to reduce the roll tracking error. These forces suggests a possible control strategy to pilots, who can decide either to follow or to override them.

The interaction of the pilot with the haptic aid imposes some requirements on the haptic control signal.[30,31] The haptic force should be large enough to be felt by pilots, but at the same time it should leave full authority to pilots to take a different control action. Furthermore, the forces should induce pilots to adopt a force task, i.e. to be compliant with the forces.[31] If this does not happen, the haptic aid may make the control task even more difficult, instead of simplifying it.

A common approach that meets the previous requirements is to mimic the pilot behavior. The haptic forces are designed to be similar to those given by pilots during the tracking task without haptic aids.[20,31] According to Eq. (1), pilot dynamics $H_p$ change based on the dynamics of the controlled element $H_{ce}$. In our experimental setup, the dynamics $H_{ce}$ was chosen as a double integrator (as detailed in Section V):

$$H_{ce} = \frac{K_{ce}}{s^2} \tag{6}$$

where $K_{ce}$ represents the gain of the controlled element. The pilot response with these dynamics is given by:[24,32]

$$H_p = K_p(T_L s + 1)e^{-\tau_p s} \tag{7}$$

where $K_p$, $T_L$, and $\tau_p$ are the pilot gain, the lead time constant and the visual time delay, respectively. To obtain similar dynamics as in Eq. (7), the haptic aid was chosen as:

$$H_{hapt}H_{cd} = H_p \quad \Rightarrow \quad H_{hapt} = \frac{K_p(T_L s + 1)e^{-\tau_p s}}{H_{cd}} \tag{8}$$

where $H_{cd}$ represents the dynamics of the stick. The multiplication of $H_{hapt}$ with $H_{cd}$ in Eq. (8) is necessary because the output of the pilot response $H_p$ is the stick deflection $\delta$, while the output of the haptic aid is a force on the control stick.

The values for the parameters in Eq. (8) were chosen according the following criteria. The parameter $T_L$ approximated the lead time that pilots assume for a double-integrator control. The value for $T_L$ reported in previous works was 5 s.[23] The visual delay $\tau_p$ was set to zero, in order to obtain a haptic response slightly faster than the pilot response (typical values for pilots are $\tau_p = 0.3$ s). The dynamics $H_{cd}$ were approximated as a static gain, since $H_{cd}$ behaves like a gain at frequencies around $\omega_c$ where the model in Eq. (7) is valid (see Section V). The gain $K_p$ was tuned such that the haptic force could be felt by pilots, but at the same time could leave full authority to pilots. The chosen value was $K_p = 2$.

## IV. Design of Automation

The haptic systems are transparent to pilots, in the sense that they show their control strategy by means of forces on the stick. Showing the control action allows to overcome issues like lack of situational awareness, degradation of pilot skills, attention decrement, and over-reliance on automation.[30,33,34] However, the transparency introduces some drawbacks. The haptic forces are first processed by pilots before being fed into the aircraft, resulting in some delay before the haptic control action is actually applied to the aircraft. Furthermore, the interaction of the haptic feedback with the pilot puts some constraints on the forces that can be applied on the stick, as discussed in the previous section. The question arises as to how much these drawbacks influence the performance with respect to an automated system that interface directly to the aircraft.

To address this question, we compared the haptic aid to an "equivalent" automated system AUT. This means that, considering the pilot *out-of-the-loop*, the AUT provided the same control action $u$ to the aircraft as the haptic system. The system regulated the tracking error to zero with the same performance as the haptic system. With this mind, the AUT was obtained as:

$$H_{aut} = H_{hapt} H_{cd} = K_p(T_L s + 1) \tag{9}$$

The haptic aid and AUT provide low performance with the pilot out-of-the-loop. Thus, the pilot control action is still needed to perform the task.

A further analysis is required to investigate how the tracking task with automation is seen from the pilot's point of view. The pilot is not aware of the control command from the automation, since it is provided directly to the aircraft. Furthermore, the effect of the automation on the aircraft roll angle can not be deduced from the compensatory display, since the display does not show the roll angle but only the tracking error. Thus, the automated system is obscured from the pilot. Figure 3 shows the control loop in Figure 1 rearranged in the case when the automation is employed. The control task with the automated system results equivalent to a control task where:

- the target trajectory $\phi_{tar}$ is prefiltered with the filter $H_{tar}$

$$H_{tar} = \frac{1}{1 + H_{ce} H_{aut}} \tag{10}$$

- the aircraft has a modified dynamics $H_{ce-aut}$:

$$H_{ce-aut} = \frac{H_{ce}}{1 + H_{ce} H_{aut}} \tag{11}$$

Figure 4(a) and Figure 4(b) show the magnitude of $H_{tar}$ and $H_{ce-aut}$, respectively. The magnitude of $H_{tar}$ is lower than 1 at low frequencies, whereas it becomes slightly larger at frequencies around 1.5 Hz. Thus, the filter $H_{tar}$ reduces the power of $\phi_{tar}$ at low frequencies. Since most of the power of $\phi_{tar}$ is concentrated at low frequencies (see Figure 2), the filtered trajectory becomes less demanding for pilots. The modified dynamics $H_{ce-aut}$ is stable and behaves like a gain at low frequencies. The control of these dynamics is much easier compared to the double integrator. Thus, from the pilot point of view, the use of automation in the compensatory task drastically reduces the complexity of the task.

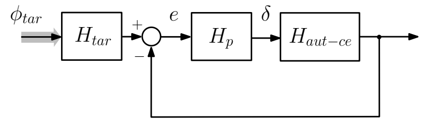
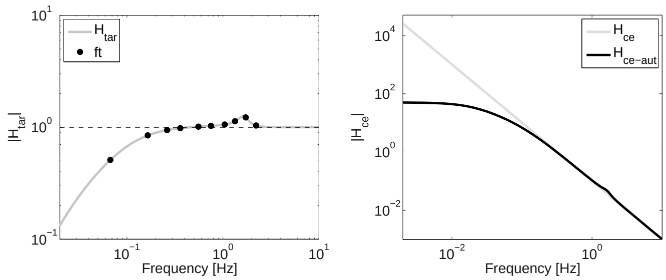



**Figure 3. Compensatory tracking task rearranged for the case when automation is employed.**




(a) $H_{tar}$. (b) $H_{ce-aut}$.

**Figure 4. Prefilter $H_{tar}$ and equivalent dynamics $H_{ce-aut}$ for the tracking task with automation.**

**Figure 5. Test station with high-resolution display and haptic sidestick.**

# V. Experiment Setup

To compare haptics and automation from a quantitative point of view, a human-in-the-loop experiment was performed that resembled control of an aircraft during a tracking task. In this section, the details of the experimental design are described.

### Task and Apparatus

The experimental task involved the tracking of a target trajectory of a roll angle. As illustrated in Figure 5, the tracking error $e$ was presented on a high-resolution display from VPixx Technologies Inc., Canada. The resolution of the display is 1920(H) x 1200(V) pixels, the refresh rate is 120 Hz. The error $e$ was shown as the angular difference between the moving horizontal line and the fixed aircraft symbol. The vertical offset between the horizontal line and the aircraft symbol, which indicates the pitch angle of the aircraft, was kept to zero. The refresh rate of the display was 120 Hz.

Participants controlled the roll angle of the aircraft with a control-loading sidestick from Wittenstein Aerospace & Simulation GmbH, Germany. The dynamics of the sidestick resembled a mass-spring-damper system, where the mass, the damping, and the stiffness can be set with different values. The stiffness of the stick was set to 1.1 N/deg in accordance with previous works dealing with similar control tasks.[32,35] The mass and the damping were set to the minimum available values. The resulting sidestick dynamics were:

$$H_{cd} = \frac{1}{0.0151\ s^2 + 0.0616\ s + 1.1} \qquad [deg/N] \tag{12}$$

Since the pitch axis of the sidestick was not used during the experiment, it was fixed in the zero position. An armrest was positioned close to the sidestick.

The aircraft roll attitude dynamics was chosen as:

$$H_{ce} = \frac{4}{s^2} \qquad [deg/deg] \tag{13}$$

The double integrator resembles the dynamics of a simplified roll attitude control of an aircraft.[36] The gain of $H_{ce}$ was chosen to give optimal control authority on the roll angle.[32]

A real-time computer running xPC Target (MathWorks, Inc.) was used to interface the primary flight display and the sidestick with the simulated aircraft dynamics. The update frequency of the real-time computer was 500 Hz.

### Target Trajectory

The target trajectory $\phi_{tar}$ was selected as the multisine signal in Eq. (2). The amplitudes $T_j$ were distributed according to the absolute value of a filter $H_T$:[28]

$$H_T(j\omega) = \frac{(T_1 j\omega + 1)^2}{(T_2 j\omega + 2)^2} \tag{14}$$

where $T_1 = 0.1$ s and $T_2 = 0.8$ s. To generate an integer number of periods in the measurement time, the base frequency $f_0$ was chosen as the inverse of the measurement time $T = 81.92$ s. The frequencies $f_{T_j}$ were logarithmically spaced multiples of the base frequency $f_0$. The phases $\psi_{T_j}$ were selected from a random set to yield an approximately Gaussian distribution of the values of $\phi_{tar}$.[28] The resulting time realization was scaled to give a power of 2 deg$^2$.

### Participants and Experiment Procedure

Six male participants between the age of 25 and 32 years were recruited for the experiment. All participants were affiliated to Max Planck Institute for Biological Cybernetics, three of them had previous experience with compensatory control tasks.

Before starting the experiment, participants were instructed to minimize the error shown in the compensatory display. They were informed about the possible presence of haptic forces on the control device, but no specific instructions were given on how to exploit the haptic force. All participants performed three tracking conditions: tracking task without aids (NoAID), with haptic aid (HAPT), and with automated system (AUT). The order of the conditions was randomized between participants according to a Latin Square Matrix. For each condition, participants performed some training trials until they reached a consistent level of performance. Then, four more trails were performed to collect the measurement data. Each trial lasted 90 s, with regular breaks in between the trials. The whole experiment lasted around three hours, split in two different sessions of 1.5 hours.

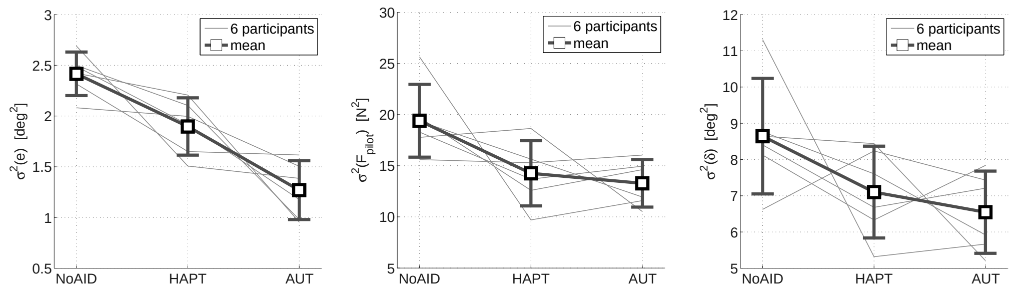
### Data Collection and Analysis

The time realizations of several signals were logged at 100 Hz during the experiment. These included the aircraft roll angle $\phi$, the human force $F_{hum}$, and the deflection of the stick $\delta$. Only the last T seconds of the measurements were considered for the data analysis. The time interval T was chosen as 81.92 s, which is a integer multiple of the period of $x_{tar}$. This allowed to remove transients at the beginning of the trials and to avoid the leakage bias in the estimation of pilot response.[26]

Several measures were calculated to investigate the influence of haptics and automation on the pilot performance and control behavior. The pilot performances in the three tracking conditions were evaluated from the variance of the tracking error $\sigma^2(e)$:

$$\sigma^2(e) = \frac{\sum_{k=1}^{N} (e(k) - \bar{e})^2}{N} \tag{15}$$

where N indicates the number of time samples and $\bar{e}$ the mean value of $e$. The variances of the stick deflection $\delta$ and of the human force $F_{pilot}$ were calculated as measures of the pilot control activity and the force needed




(a) Tracking error. (b) Pilot force. (c) Stick deflection.

**Figure 6. Mean and 95 % confidence intervals of $\sigma^2(\cdot)$ over all participants.**

**Table 1. Results of post-hoc tests with Bonferroni correction for $\sigma^2(\cdot)$ data.**

| Independent variables | Dependent measures | | | | | |
|---|---|---|---|---|---|---|
| | $\sigma^2(e)$ | | $\sigma^2(F_{pilot})$ | | $\sigma^2(\delta)$ | |
| Factor | p | Sig. [a] | p | Sig. | p | Sig. |
| NoAID *vs.* HAPT | 0.067 | * | 0.098 | * | 0.582 | – |
| NoAID *vs.* AUT | 0.003 | ** | 0.078 | * | 0.239 | – |
| HAPT *vs.* AUT | 0.086 | * | 1.000 | – | 1.000 | – |

a. *** : highly significant ($p < 0.050$)   * : marginally significant ($0.050 \leq p < 0.100$)*
*–: not significant ($p \geq 0.100$)*

to perform the task, respectively. To test statistical differences between the variances in the three tracking conditions, a one-way repeated measurement analysis of variance (ANOVA) was used. Post-hoc tests with Bonferroni correction were employed to perform pairwise comparisons between the tracking conditions.

Non-parametric estimates of pilot open-loop frequency response functions were calculated using Eq. (3). To reduce the variance of the estimates, the time signals were averaged over the four trials and the resulting estimates over two adjacent frequency points.[37] The reliability of the estimates was evaluated through the coherence function in Eq. (5). Then, the crossover frequency $f_c$ and the neuromuscular peak of the open-loop responses were calculated and statistically compared with ANOVA and post-hoc tests with Bonferroni correction. The crossover frequency $f_c$ represents the bandwidth of the pilot response. High values of $f_c$ imply a fast dynamic response and a higher ability to follow the tracking signal. On the other hand, high neuromuscular peaks should be avoided, since they can induce unstable oscillations on the aircraft.[38]

# VI. Results and Discussion

This section presents the results of the experimental comparison between haptics and automation. Pilot performance and control activity are contrasted between the experimental tracking conditions. Furthermore, differences in the pilot response are investigated.

## A. Performance and control activity

Pilot performance were evaluated using the variances of the tracking error $\sigma^2(e)$. Figure 6(a) shows the results from each participant (thin lines), together with the mean and the 95 % confidence interval (error bars). Results of ANOVA ($F(2, 10) = 10.627$, $p < 0.05$) and post-hoc tests with Bonferroni correction (Table 1) indicated that all the differences between conditions were statistically significant. Performance improved with haptic and automation compared with the baseline condition without aids. However, the haptic did not achieve the same performance as the automation, which reduced $\sigma^2(e)$ compared to NoHA with almost 50%.

Variances of pilot force $F_{pilot}$ and stick deflection $\delta$ were calculated as measures of the pilot effort. Figure 6(b) and Figure 6(c) depict the means and the 95 % confidence interval of $\sigma^2(F_{pilot})$ and $\sigma^2(\delta)$,

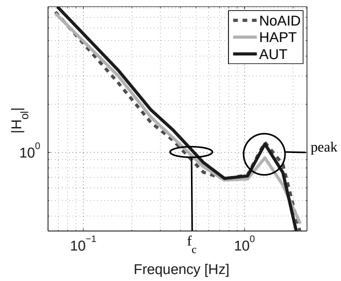
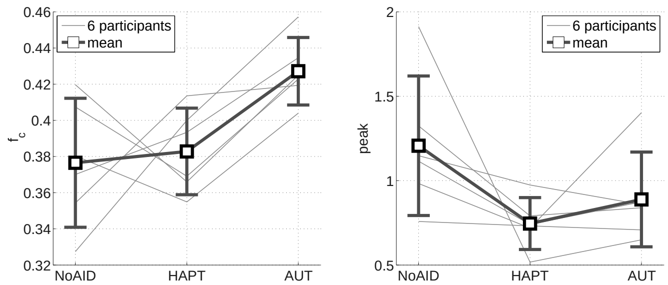



**Figure 7. Estimates of $H_{ol}$ for participant 4.**




(a) Crossover frequency $f_c$. (b) Neuromuscular peak.

**Figure 8. Mean and 95 % confidence intervals of $f_c$ and neuromuscular peak over all participants.**

respectively. The pilot force was affected by the external aids ($F(2,10) = 5.064$, $p < 0.05$). Post-hoc test with Bonferroni correction revealed a statistically significant difference between NoAID and the other two tracking conditions (Table 1). This indicates that the haptic aid allowed the pilot to significantly reduce the forces needed to control the aircraft. Furthermore, the forces applied with HAPT and AUT were found to be similar. The variance of the stick deflection was slightly lower for AUT and HAPT conditions compared with NoAID. However, no statistically significant difference was found between the three conditions ($F(2,10) = 2.876$, $p = 0.103$).

As discussed in Section IV, the tracking task with the automation is equivalent to a tracking task with a different and easier to control aircraft dynamics $H_{ce-aut}$. The lower performance in the HAPT condition compared to the AUT condition indicates that participants found easier to control $H_{ce-aut}$ rather than the double integrator $H_{ce}$ combined with the haptic forces. However, the variances of pilot control forces were similar between HAPT and AUT conditions. This indicates that the haptic forces allowed participants to control the double integrator with the same amount of control effort needed for the easier dynamics.

## B. Pilot response

An analysis was made to look for the influence of haptic and automation on the pilot open-loop responses. Figure 7 shows the open-loop responses of participant 4. High coherence values indicated reliability of the estimates ($\Gamma^2(f) > 0.8$ for all $f \in \{f_t\}$). These responses are representative for all participants. All the estimates closely follow an integrator-like dynamics at frequencies close to the crossover frequencies $f_c$ where $|H_{ol}(f_c)| = 1$. Thus, participants adapted their responses to the tracking error to yield an open-loop transfer function in line with McRuer theories.[36] This highlights that McRuer theories can still be applied when haptics or automation are employed in the control loop. The peak in the responses at high frequencies was related to the neuromuscular system of the pilot's arm,[36] see Figure 7.

The crossover frequency was found to be influenced by the presence of external aids ($F(2,10) = 5.122$, $p = 0.029$), see Figure 8(a). Post-hoc tests with Bonferroni correction revealed that AUT was statistically different from the other two conditions. This is in complete agreement with the higher performance found for the AUT system. The values of the neuromuscular peaks decreased with HAPT, as depicted in Figure 8(b). Although the ANOVA test revealed a marginally significant effect ($F(2,10) = 3.198$, $p = 0.084$), post-hoc

**Table 2. Results of post-hoc tests with Bonferroni correction for $\sigma^2(\cdot)$ data.**

| Independent variables | Dependent measures | | | |
|---|---|---|---|---|
| | $f_c$ | | *Peak* | |
| Factor | p | Sig. [b] | p | Sig. |
| NoAID *vs.* HAPT | 1.000 | – | 0.207 | – |
| NoAID *vs.* AUT | 0.131 | – | 0.659 | – |
| HAPT *vs.* AUT | 0.008 | ** | 0.807 | – |

b. *** : highly significant* ($p < 0.050$) ** : marginally significant* ($0.050 \leq p < 0.100$)
*–: not significant* ($p \geq 0.100$)

tests for pairwise comparisons did not result in statistically significant differences between the conditions due to the large variance on NoAID and AUT conditions.

# VII. Conclusions

To investigate the effects of haptics and automation on pilot performance and control behavior, two equivalent haptic and automated system were tested in a compensatory tracking task and compared with a baseline condition without external aids. Participants significantly improved their performance with the haptic aid and the automation. In particular, the automation outperformed the other two conditions. The control effort decreased with both external aids. This was indicated by the lower forces applied by pilots to perform the tracking task. Furthermore, participants modified their open-loop responses in different ways between the three tracking conditions. The automation lead to an increased crossover frequency, whereas the haptic system reduced the peak of the neuromuscular system.

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## 3. Interdependence of flight control performance and gaze efficiency

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**Abstract**

In this work, a descriptive study is reported that addresses the relationship between flight control performance and instrument scanning behaviour. This work was performed in a fixed-base flight simulator. It targets the ability of untrained novices to pilot a lightweight rotorcraft in a flight scenario that consisted of fundamental mission task elements such as speed and altitude changes. The results indicate that better control performance occurs when gaze is more selective for and focused on key instruments. Ideal instrument scanning behaviour is proposed and its relevance for training instructions and visual instrument design is discussed.

# A Fixed-Based Flight Simulator Study: The Interdependence of Flight Control Performance and Gaze Efficiency

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**Abstract.** Here, a descriptive study is reported that addresses the relationship between flight control performance and instrument scanning behavior. This work was performed in a fixed-based flight simulator. It targets the ability of untrained novices to pilot a lightweight rotorcraft in a flight scenario that consisted of fundamental mission task elements such as speed and altitude changes. The results indicate that better control performance occurs when gaze is more selective for and focused on key instruments. Ideal instrument scanning behavior is proposed and its relevance for training instructions and visual instrument design is discussed.

## 1 Introduction

Like driving a car, piloting a rotorcraft is a closed-loop motor control task that relies heavily on visual feedback. Visual feedback informs us on the outcome of our control inputs and whether it is necessary to change these inputs in order to arrive at our desired performance levels. Information such as velocity is available from the outside world, it can also be provided more precisely via instruments (eg., airspeed indicator).

Piloting a rotorcraft is, arguably, more difficult than driving a car for several reasons. First, it offers movement in more degrees of freedom. A rotorcraft pilot is required to control not only the vehicle's airspeed and heading, but also its altitude. Second, the control devices of a rotorcraft are not directly mapped to the direction of the vehicle's motion. In a car, accelerations and decelerations can be achieved by exerting pressure on the accelerator and braking pedal, respectively. Maintaining a constant velocity is achieved by determining the appropriate pressure to consistently apply to the accelerator. This connection between control

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device and vehicle control is direct and intuitive. In contrast, rotorcraft acceleration is achieved by tilting the rotor disc (and thus, the helicopter) forward. Lateral decelerations are effected by tilting the rotor disc in the opposite direction. Thus, flying at a constant airspeed requires continuous adjustments of the rotor disc's tilt. Last but not least, rotorcraft controls are coupled. Tilting the rotor disc forward will not only accelerate the rotorcraft in the same direction but will also reduce its upward thrust, hence causing a loss in altitude. Conversely, decelerating the rotorcraft by reducing the forward tilt of the rotor disc will increase the upward thrust, causing an increase in altitude.

Efficient monitoring of available visual feedback information can be expected to be relevant to effective rotorcraft control. By moving his eyes, the pilot is able to switch between monitoring several visual feedback cues (eg., airspeed, altitude, heading, etc.) and checking for any discrepancies between desired and actual values. This underlies his ability to manipulate the rotorcraft's controls appropriately, such as to reduce detected discrepancies. Scanning strategies have also been shown to differ across levels of control expertise. Recently, navigation accuracy was found to negatively correlate with the amount of time that pilots looked at the "outside" world [1]. Thus, expertise might be reflected in a decreasing reliance on outside world cues.

Gazetracking methods allow researchers to determine how visual feedback information is sought after during flight control. In the context of driving and aviation, gazetracking data can identify which visual cues and instruments are relied on the most. For example, the primary flight display was the cockpit instrument that pilots looked at the most during the approach and landing of a A330 fixed wing aircraft — namely, 40% of looking time [2]. Within this, attention was particularly dedicated to information relating to the attitude of the plane, its airspeed and altitude. Findings such as these can improve cockpit designs, by tailoring the visualization of information to fit the pilot's mission objectives.

To date, relevant eye-tracking research has predominantly addressed expert flight performance. Relatively little is known about the relationship between flight control performance and instrument gaze behavior in novices. Our research seeks to identify methods and technologies that will enable personal aviation transport, by allowing flying a personal aerial vehicle to be as easy as driving a car [3][4]. To do so, it is necessary to measure and model the behavior of untrained individuals that underlie their ability to control an aircraft.

In this study, we designed a flight scenario that reflected a daily commute from a suburban area to a city region. Novices were required to pilot a lightweight rotorcraft model in a helicopter flight simulator that was equipped with a remote eye-tracking system. The motivation of this work was to explore the relationship between flight control performance and scanning strategies of novices. Specifically, we investigated how novices with varying levels of control performance might differ in terms of how they looked at their flight instruments for control information. It should be mentioned that flight trainees are explicitly taught strategies on how to scan their flight instruments for flight control. In this paper, we investigate how novices are likely to monitor flight instruments without having received such instructions.

The remainder of this paper is organized as follows. Section 2 provides a detailed description of the flight mission and the fixed-base simulator environment. It also describes how data was collected for subsequent analyses. Section 3 presents the descriptive statistics of our current work and our interpretations. Section 4 discusses the implications of the current results and how that could influence training instructions and the interface design of visual instrumentation.

## 2 Methods

### 2.1 Participants

Four male participants were recruited for this study (age range: 29–34 years). They possessed normal or corrected-to-normal vision. None of the participants had formal flight training for rotorcraft. More importantly, they have never received any formal instructions for instrument scanning strategies.

### 2.2 Apparatus and Flight Model

The fixed-based flight simulator was based on a simulated model of a light-weight helicopter with a large bandwidth for control inputs [5] (Figure 1). Visualizations of the outside world were based on the topography of San Francisco, USA. These were presented via a large multi-panelled display that rendered a world environment (field-of-view: 105° x 100°).

A heads-down display consisted of eight standard flight instruments that indicated the rotor speed (RS), airspeed (ASI), attitude (AI; also referred to as the artificial horizon), altitude (AT), torque (TQ), compass (CO), heading (HI), vertical speed (VSI) — see Figure 1 (inset). These are arranged in the standard T-arrangement of ASI, AI, AT on the second to four position in the top row, and HI in the third position of the bottom row. Eye-movements on the instrument panel were recorded using a 60 Hz remote eyetracker (faceLAB; SeeingMachines). The users gaze vector was estimated up to an accuracy of 1.5°, which was sufficient for determining the specific flight instrument that was fixated by the user.

A cyclic stick, collective lever and foot-pedals comprised the control devices. The cyclic stick controls the tilt of the rotorcraft. Namely, the rotorcraft will tilt in the same direction as the cyclic stick. If the cyclic is moved forward, the rotorcraft tilts forward; if the cyclic is moved aft, the rotorcraft tilts aft, and so on. These changes are reflected in the attitude indicator (AI), which indicates the rotorcraft's relation to the horizon — that is, whether it is pointing below or above and whether it is level with the horizon. Tilting the rotorcraft such that it points below the horizon will increase airspeed (ASI). This forward tilt will induce a loss in altitude (AT) unless accompanied by an increase in thrust power (RS). Conversely, reducing airspeed (ASI) by decreasing the rotorcraft's forward

**Fig. 1.** Flight simulator with remote eye-tracking cameras (indicated in the white ellipse). Instrument panel is featured inset (From left to right. Top panel: RS, ASI, AI, AT. Bottom panel: TQ, CO, HI, VSI.)

tilt will induce an elevation in altitude if the thrust (RS) is not simultaneously reduced. Control of thrust is determined by the collective lever. The yaw of the rotorcraft can be controlled by the foot-pedals. This compensates for any undesired torque forces (TQ) on the fuselage that result from changes in the rotor speed (RS). The global bearing of the rotorcraft is indicated by the compass (CO) and its current heading relative to its destination by a heading indicator (HI).

### 2.3 Flight Scenario

Prior to experimentation, participants had at least 10 hours of experience in the flight simulator, which familiarized them with the dynamics of the simulated vehicle and the instrument layout. The participants were aware of how the controls were coupled and how to use them in combination to achieve simple maneuvers — such as to accelerate, decelerate, ascend and descend — without creating large instabilities.

Four experimental sessions were conducted per participant with a common flight mission. Our participants were to fly from a suburban airfield to the city area of San Francisco, USA. This reflects a daily personal aerial vehicle commuting scenario. Three classes of mission task elements (MTEs) comprised the entire flight scenario: straight and level flight, altitude change, and airspeed change. This flight scenario was designed, with the assistance of an experienced helicopter pilot (approx. 650 flight hours), to be within the control capabilities of a beginning trainee.

### 2.4 Data collection

The airspeed and altitude of the rotorcraft were recorded during each flight session, in tandem to our participants' gaze. This allowed us to characterize flight control performance (see Subsection 3.1)

Nine regions of interest (ROI) were designated. Namely, the eight instruments and the outside world. Dwells were defined as periods when the participants' gaze intersected with one of these ROIs. Gaze data across the flight mission were first classified into those that belonged to the heads-down instrument panel or the world environment. Dwells belonging to the instrument panel were further classified for the specific instruments using a k-nearest-neighbor filter. Thus, it was possible to derive the number of dwells per ROI as well as the likelihood that a ROI dwell follows from another ROI dwell (see Subsection 3.2).

## 3 Results and Discussion

### 3.1 Flight Control

The current flight scenario required our participants to demonstrate control over their airspeed and altitude. Figure 2 (upper half) illustrates the desired trajectory for these two attributes and how our participants deviated from them across their final flight mission. Performance in keeping altitude and airspeed was determined by calculating the root-mean-squared error (RMSE) between desired and actual value. For MTEs in which a change in altitude or airspeed was performed by the participants, the RMSE for altitude error or velocity error, respectively, was not determined.

All participants showed increased instabilities in keeping altitude with respect to straight-and-level flight after they performed changes in airspeed (acceleration and deceleration). Conversely, changes in altitude did not result in more airspeed instability with respect to straight-and-level flight.

Across the whole flight mission, our participants differed primarily on their ability to control airspeed, rather than altitude (see Fig. 2, lower half). Across all participants, a prominent increase in altitude control difficulty is observed in the later stages of the flight mission, especially when decelerating and descending.

We used the RMSE metric to rank-order the performance of our participants, such that we could evaluate their gaze behaviour for corresponding trends. Participant S4 performed worst in keeping airspeed and altitude, whereas participants S1, S2 and S3 had similar performance in keeping altitude, but showed decreasing performance in keeping airspeed, respectively. Henceforth, they will be referred to as S1, S2, S3 and S4 in increasing order of RMSE, and color-coded in the figures as dark-green, green, red and dark-red respectively.

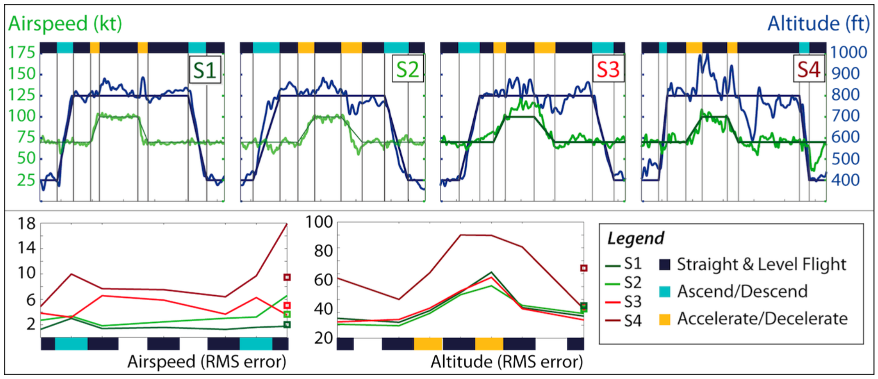


**Fig. 2. Upper half:** Control performance during a standard flight scenario. Participants are ranked according to decreasing control performance, from left to right. Nine mission task elements comprise the flight scenario: straight and level flight (dark blue), altitude change (light blue), airspeed change (yellow). Desired values for airspeed (green) and altitude (blue) across the flight scenario are indicated by the underlying straight lines and actual performance is overlaid. **Lower half:** Mean RMSEs of flight control performance of each participant. The mean RMSEs across flight mission are indicated on the right vertical axis.

### 3.2 Gaze behavior

**Gaze selectivity across instruments** Figure 3 illustrates the mean number of dwells on each instrument and the outside world (rows) for each MTE (columns) across the flight mission. Each grayscale histogram reflects the number of times each instrument was looked at; white denotes the maximum number of dwells within each individual histogram and black indicates that the instrument was never looked at.

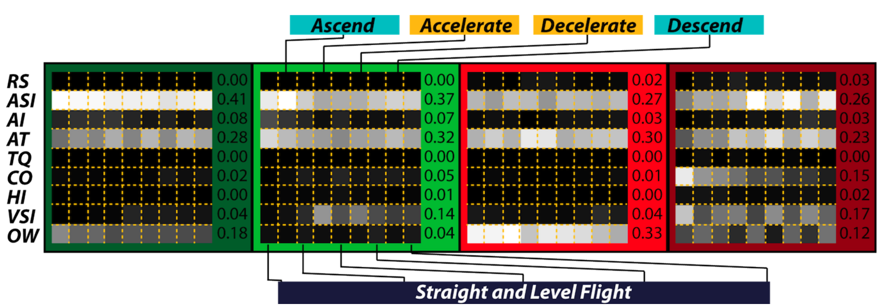


**Fig. 3.** Grayscale histogram for the mean number of dwells on each instrument and outside world (rows), for each maneuver (columns). The mean proportions of instrument dwells are reported on each histogram's right.

Every participant consistently demonstrated a gaze preference for the airspeed indicator (ASI) and altimeter (AT). This corresponds with the main determinants for flight control performance in our flight scenario. This instrument preference did not vary according to the changing mission task elements.

To reiterate, our participants primarily differed in terms of their ability to control airspeed, rather than altitude. A corresponding trend is noted in the gaze allocation to instruments. Mean proportion of dwells on ASI decreased from S1 to S4. Mean proportion of dwells on AT did not vary much between S1, S2 and S3 but was noticeably less for S4.

More than 85% of S1's dwells can be attributed to ASI, AT and the outside world (OW), in decreasing order of preference. This can be contrasted with S4's gaze, whereby the same three instruments only accounted for 61% of dwells. In comparison, S4 was less selective than S1 and looked at the compass (CO) and vertical speed indicator (VSI) more often than S1, at the expense of his monitoring levels of ASI and AT.

An interesting contrast can be observed between S2 and S3. S2 does not look at the OW as often as S3. In fact, S3 looks at the OW most frequently, relative to the other participants. Instead, S2 demonstrates a gaze preference for the VSI, especially during the middle of the flight mission from acceleration to deceleration, when control performance is most vulnerable across all participants (see Fig. 2).

**Looking at instruments versus outside world** Control performance in novice pilots is unlikely to be characterized by the relative distribution between looking at the instruments and the OW. About 90% of the dwells on instruments prior to looking at the OW could be accounted for by 8 or fewer dwells in S1's flight missions. And in S2, S3 and S4s' flight missions by 22, 3 and 15 dwells or fewer.

**Instrument scanning** Given that a particular instrument is being looked at, what are the other instruments that will be looked at next? Figure 4 illustrates these gaze relationships between instruments. Each column indexes an instrument and reflects the number of subsequent dwells on other instruments (rows).

The obvious relationship is that between ASI and AT. For S1, he is equally likely to look at AT and OW after looking at ASI when ascending and accelerating. When his control performance decreases during decelerating and descending, he looks at the OW less frequently and switches gaze primarily between AT and OW. Notably, S1 treats ASI as the primary reference point in instrument scanning. That is, S1's gaze consistently returns to this instrument after referencing AT and OW. Dwells in AT and OW tend to occur after ASI dwells (see column 2 for S1) and, reciprocally, dwells in AT and OW tend to be followed predominantly by ASI dwells (see columns 4 and 9 for S1).

A similar pattern is observed for S2. Unlike S1, however, S2 either switches gaze between ASI and AT almost exclusively (ascend, descend) or between ASI, AT and VSI (accelerate, decelerate). He does not exhibit a primary instrument

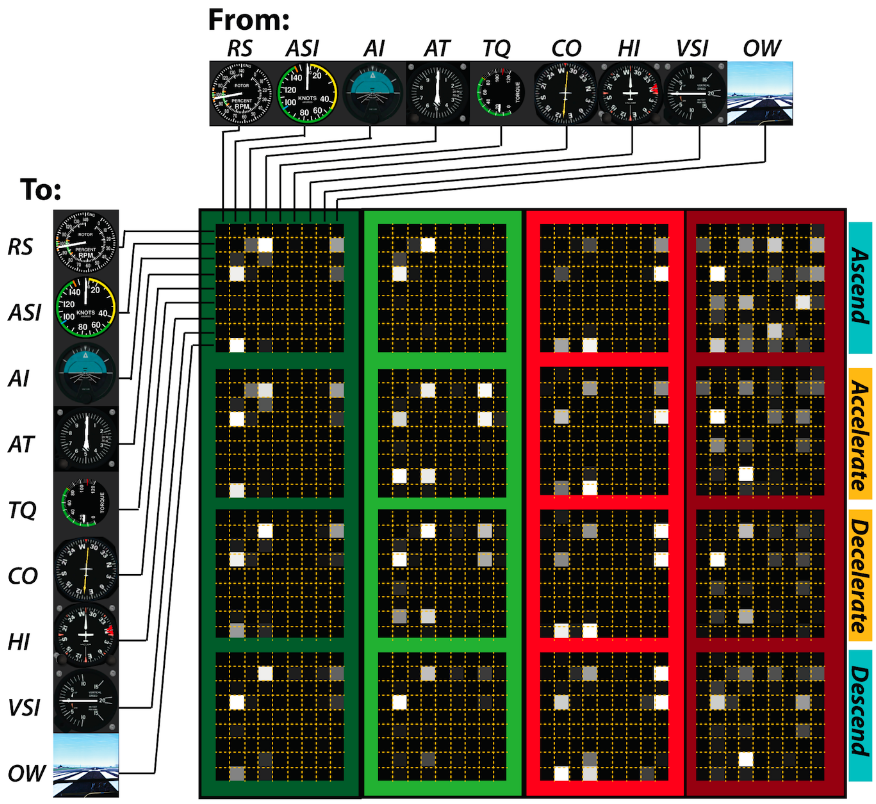


**Fig. 4.** Transition matrix of instrument dwells in grayscale, for the key maneuvers. Each column is indexed by an instrument. White denotes the maximum number of subsequent dwells within each matrix.

that he returns to preferentially after referencing other instruments, like ASI in S1's case.

S3's gaze alternates between ASI, AT and OW. Unlike S1, S3 relies on the OW instead of ASI as the primary reference point. In contrast to both S1 and S2, S3 demonstrates less turn-taking between ASI and AT. It is also interesting to note that this reliance on OW as a primary reference point increases when control performance deteriorates (ie., decelerate, descend).

There is no clear transitional pattern of gaze turn-taking across the instruments for S4. The lack of a consistent gaze strategy could underlie S4's poor control performance.

## 4 Conclusions

The current paper presents a descriptive study that was motivated to demonstrate and understand the relationship between flight control performance and gaze behavior. Our findings show that gaze behavior varies with control performance. In particular, participants with better control performance exhibited gaze behavior that was more selective for key instruments. Our best performer demonstrated a selective and ranked preference for different visual information, whilst our second and third performer distributed gaze equally across three different sources of visual information. The worst performer distributed his gaze across five sources of visual information.

The current findings do not allow us to conclude that selective gaze patterns generate good flight control performance (or vice versa). Nonetheless, we can recommend training instructions for novice pilots with regards to instrument scanning behavior. This can be expected to yield improvements given that gaze strategies are easier to be voluntarily controlled by novice pilots than flight control expertise. Fundamentally, instrument scanning should always be centered on the instrument that is key to control performance. This means that eye-movements should ideally return to one key instrument after referencing secondary sources of information. Distributing gaze evenly and across many instruments without such an underlying strategy is ill-advised. Indeed, such instructions are provided in formal flight training; the T-arrangement is intended to encourage such instrument scanning behavior.

The current work was intended to understand how novices without formal flight instructions would scan instruments. It is interesting to note that they generally prioritized the airspeed indicator, followed by the altitude indicator. This suggests that novice pilots intuitively react to changes in their airspeed and altitude and compensate accordingly. In formal training, pilots are instructed to treat the attitude indicator as the key instrument, given that it is the rotorcraft's attitude that dictates current airspeed and the need to adjust for changes in the altitude. In this regard, formal training serves the function of training novices to behave in a more anticipatory and less reactive fashion. This could account for better control performance and reduced workload.

A principled approach for diagnosing gaze selectivity in trainees could be useful in determining the skill levels of novices (cf. [1]). In fact, flight instructors sometimes rely on playbacks of eye-movements to identify inappropriate scanning strategy in trainee pilots [6]. The current analytical approach is one possible approach for quantifying gaze selectivity.

Finally, the spatial layout of visual instruments could be designed to encourage optimal scanning strategies. First, selective attention to relevant information could also be encouraged by removing the clutter of non-relevant instruments. Second, the spatial layout of instruments could emphasize the importance of a primary instrument by placing it in a central position. This could encourage users to return to it after referencing other instruments (cf., S1's scan pattern), rather than to treat every instrument equally.

Future work should be directed towards identifying effective scanning strategies for different maneuvers and key objectives. In the current work, constant airspeed and altitude control were emphasized above all other attributes (eg., flight path trajectory). It will be useful to determine whether the current principles for ideal instrument scanning are generalizable to different flight scenarios and maneuvers. A general model for ideal instrument scanning would be useful for training purposes as well as interface design.

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