WORKLOAD REDUCTION THROUGH STEERING WHEEL CONTROL FOR ROTORCRAFT

B.I. Schuchardt
DLR Institute of Flight Systems, German Aerospace Center
Lilienthalplatz 7, 38108 Braunschweig, Germany
bianca.schuchardt@dlr.de

ABSTRACT

This paper reports on the development and investigation of a novel steering wheel control concept for highly augmented rotorcraft with fly-by-wire control. The main idea is to use a steering wheel as primary inceptor instead of the conventional centre stick. The existing yaw pedals are reprogrammed to function similar to accelerator and brake pedal in a car. The height can be controlled either via a conventional collective lever or via switches behind the wheel. An additional 8-way switch in the centre of the wheel is used for horizontal precision manoeuvres in the low speed regime. A fixed-base simulator study was performed in order to compare conventional and steering wheel control with respect to pilot workload. Three different user groups participated in the study, namely helicopter pilots, car drivers and test candidates with no experience in either driving or flying. The study showed that, especially for the car drivers, the perceived workload could be reduced when flying a helicopter with steering wheel.

NOMENCLATURE

Acronyms

AC	Attitude Command
AcC	Acceleration Command
ACT/FHS	Active Control Technology Flying Helicopter Simulator
ATPL(H)	Air Traffic Pilot Licence (Helicopter)
AVES	Air VEhicle Simulator
CPL(H)	Commercial Pilot Licence (Helicopter)
DLR	German Aerospace Center
GLM	General Linear Model
NASA	National Aeronautics and Space Administration
PPL(H)	Private Pilot Licence (Helicopter)
RC	Rate Command
TC	Turn Coordination
TLX	Task Load Index
TRC	Translational Rate Command
βC	Sideslip Angle Command
γC	Flight Path Angle Command

Symbols

df	Degree of Freedom
F	Test Size for Analysis of Variance
M	Mean
p	Level of Significance
SD	Standard Deviation
T	Test Size for T-Test
α	Error Probability
η^2	Effect Size

1. INTRODUCTION

Flying a rotorcraft requires special skills and intensive training. In contrast to that, almost everybody is able to learn how to drive a car. Already in 1987 Drees [1] aimed at changing this prejudice by proposing an “easy-to-fly” rotorcraft that would feature a car-like control and advanced control laws. Gazda [2] had tried to build a helicopter with steering wheel control long before that in the 1940s but could not successfully finish his project.

Today’s development of fly-by-wire architectures has removed the constraints of control devices that have to be mechanically linked to the rotorcraft’s actuators [3]. This offers new possibilities of freely redesigning the conventional pilot controls for more comfort and efficiency. Sidesticks are the most popular competitors to conventional controls and constantly under research [4]. But also totally new pilot interceptors can be implemented and tested. This allows taking up the ideas of Gazda and Drees and finally equipping a rotorcraft with a steering wheel. The expected outcome is an intuitive pilot interface that can be comfortably used by professional pilots as well as by novice pilots who can profit from their – often extensive – experience in car driving.

This paper documents research conducted at DLR that has its origins in the European project myCopter [5]. The development of the applied steering wheel control concept for rotorcraft has been described in details in [6]. In a first piloted study in DLR’s AVES simulation centre [7], the concept has already demonstrated its viability and led to equally good or even improved handling qualities compared to conventional helicopter controls [8]. In addition to the ground-based investigations, the underlying control laws have been flight tested successfully on DLR’s research helicopter ACT/FHS in combination with conventional controls [9].

The current paper reports on a second ground-based study that was again conducted at the AVES simulation centre. The goal was to investigate the usability of the steering wheel control concept for users with different levels of experience. Helicopter pilots, car drivers and inexperienced candidates with no experience in either flying or driving were asked to compare the steering wheel control concept to conventional helicopter controls.

Following this introduction, the paper first describes the layout of the novel control concept. Next, an overview is given on the experimental setup before the study’s results are presented. Finally, the paper is concluded with discussion and summary.

2. STEERING WHEEL CONTROL CONCEPT

The starting point for the development of the steering wheel control concept is formed by a set of control laws that were originally developed as “easy-to-fly” response types within the myCopter project. They offer a very high level of stabilization and augmentation such that minimal training is required even for flight-naïve users [10]. Test candidates with no flying experience could safely handle the simulated rotorcraft within a few hours.

Figure 1 shows the control laws for conventional helicopter controls. In the longitudinal and lateral axes a Translational Rate Command (TRC) is implemented for the low speed flight regime. This response type relates the control deflections of the pilot’s centre stick (cyclic) linearly to commands for the longitudinal and lateral ground speed. When the stick is returned to the neutral position, the rotorcraft returns to hover condition. Above 15 kn, linear blending starts towards the forward flight control mode which is fully active at 25 kn forward speed. The forward flight mode is of Acceleration Command (AcC) type in the longitudinal axis which means that the rotorcraft’s acceleration command is proportional to the pilot’s inceptor deflection. Thus, the current airspeed is held when the inceptor is returned to neutral. In the lateral axis an Attitude Command (AC) with attitude hold is implemented for speeds above 25 kn. Therefore, a lateral control input results in a proportional roll angle command.

The yaw control is designed as Rate Command (RC) response type in hover condition and for low speed. The yaw rate command is proportional to the pilot’s pedal input. In fast forward flight the response type changes to a Sideslip Angle Command (βC) with Turn Coordination (TC). This allows flying coordinated turns (free of sideslip) in forward flight without additional pilot inputs.

The altitude is controlled with the collective lever via a vertical TRC response type in hover mode and changes to a Flight Path Angle Command (γC) in forward flight. Inter-axis coupling is not present in the selected response type configuration apart from the turn coordination.

The mode change is designed one-directional such that the blending is active between 15 and 25 kn when accelerating. In order to return from the fast forward mode to the slow mode, the pilot must bring the rotorcraft back to hover while AcC is active until hover is achieved. Then, in hover, TRC is activated. The respective hysteresis prevents unintended mode changes while being in the transition phase.

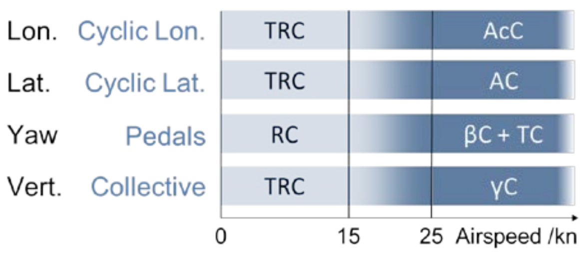

Figure 1. Control laws as originally designed for conventional helicopter controls.

As described in reference [6], the central idea of the novel control concept is to use a steering wheel as primary control interface that takes the place of the conventional cyclic stick. Turning the wheel results in flying coordinated turns in forward flight as depicted in the schemes in figures 2 and 3.

The existing conventional helicopter yaw pedals are repurposed for longitudinal acceleration and deceleration.

Two different inceptors were investigated for height control: a conventional collective lever (pulling up for ascending and pushing down for descending) and rocker switches that are located behind the wheel (right switch for ascending and left switch for descending).

The inceptors described so far do not yet allow commands for lateral or backwards translational movements. Therefore, an additional 8-way switch in the centre of the wheel is provided for precision manoeuvers, namely flying horizontally forward, backward, sideward, or diagonally at low speeds up to 5 kn.

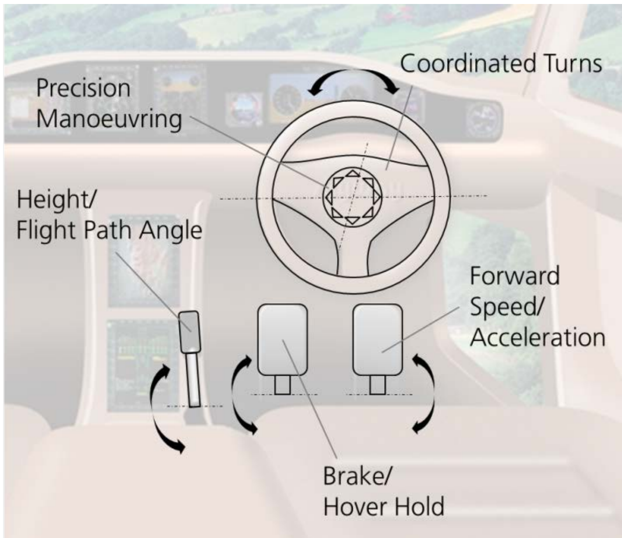

Figure 2. Steering wheel control concept including collective lever.

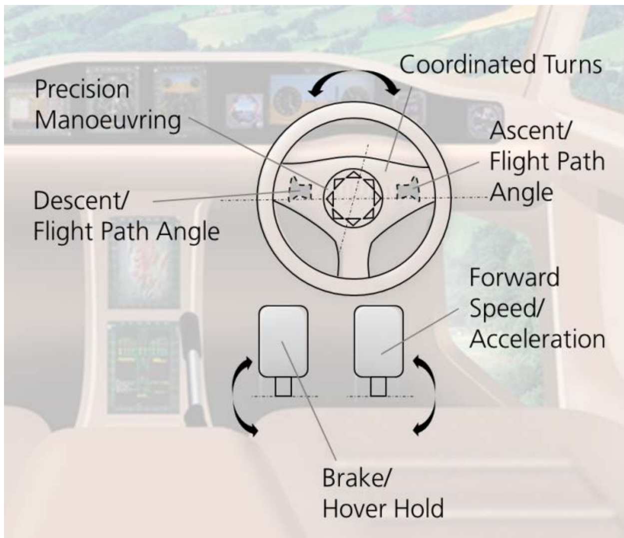

Figure 3. Steering wheel in combination with rocker switches for height control.

Figure 4 shows the necessary changes in the control laws. Differences to the previous control law design for conventional inceptors are marked in green. (In references

[6] and [8] a slightly different setup had been described that was improved for this study based on pilot feedback from the first study.)

The dynamics of the longitudinal axis remain unchanged compared to figure 1 but are now controlled via pedals. The steering wheel controls both lateral and yaw axes with a turn coordination being implemented over the complete speed range. For low speeds the wheel is primarily used for yaw commands. These are linearly blended over into roll attitude commands between 15 and 25 kn. The vertical axis response remains the same as for the conventional inceptor arrangement but can now be controlled either via collective lever or switches. The precision manoeuvres that can be commanded via the 8-way switch are implemented as additional TRC in the longitudinal and lateral direction for speeds up to 5 kn.

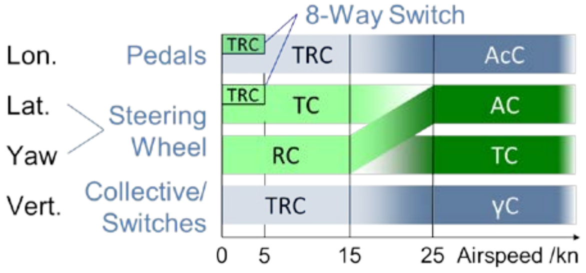

Figure 4. Speed dependent control laws for steering wheel usage.

3. EXPERIMENTAL SETUP

DLR's AVES (Air VEhicle Simulator) centre [7] features an experimental environment that is flexible enough to investigate also unconventional control concepts. It offers two reconfigurable flight simulators for rotorcraft and fixed-wing aircraft. The two cockpits represent DLR's research aircraft EC135 ACT/FHS and A320 ATRA. They are interchangeable and can either be operated on a fixed-based or an electro-mechanically driven motion platform. The visual system contains 15 LED projectors that produce a field of view of 240° x 95°.

Figure 5. AVES EC135 cockpit featuring conventional and steering wheel inceptors.

For the study described in this paper, the helicopter cockpit on the fixed-base platform was used and extended with a steering wheel prototype as shown in figure 5. For fast interchangeability (and later experimental flight certification), the wheel was not attached to the airframe but rested on the pilot's knees. When the steering wheel was active, the cyclic stick was automatically deactivated and could be trimmed to the most forward position such that it did not hinder the pilot in his movements.

The control laws were implemented as MATLAB/Simulink models and integrated into the AVES simulation environment via automated 2Simulate [11] scripts. Details on the mathematical definition of the control laws can be found in references [8] and [12].

Three different test groups were selected for the investigation of the novel control concept: helicopter pilots, car drivers and test candidates with no experience in either flying or driving. Each group consisted of five to six candidates, summing up to a total of 17 test candidates. Table 1 contains statistical data regarding the level of experience of the test candidates.

Table 1: Experience of test groups (*M* – mean, *SD* – standard deviation).

	Pilots		Drivers		Inexperienced	
	M	*SD*	*M*	*SD*	*M*	*SD*
Age	40.2	8.5	36.8	9.3	26.4	6.3
Years with driver's licence	22.2	8.6	19.0	9.1	-	-
Weekly driving time	3.7	1.6	10.3	3.7	-	-
Years with helicopter licence	14.1	11.1	-	-	-	-
Total helicopter flight hours	1843	1856	-	-	-	-
Number	6		6		5	

Among the helicopter pilots were one with PPL(H) licence, three with CPL(H), one with ATPL(H) and one military pilot. Three of them were also experienced test pilots. Their previous helicopter flight hours reached from 60 to 5,400 and their age from 34 to 58 years. The car drivers were 27 to 52 years old, were holding their driver's licenses for over ten years and drove 2 to 20 hours in the weekly average. Finally, the candidates in the inexperienced group were 16 to 33 years old. Four of the test candidates were women, two of them car drivers and two inexperienced. All test candidates were right handed.

In the previous handling qualities study [8] helicopter pilots were asked to fly mission task elements derived from ADS-33E-PRF [13]. As this study included test candidates with no flying experience, more practical and less abstract flight tasks were selected. One task was similar to the slalom mission task element but was extended by an ascending starting phase. Instead of ground markings the test candidates had a tunnel-in-the-sky display [14] as guidance reference. This display showed the three-dimensional flight path and the target speed.

The second task was a city scenario. The test candidates had to start from a street, fly several turns between houses and finally land on a roof-top helipad. Again, the tunnel-in-the-sky display was used as navigation aid.

Three different steering configurations were investigated in the study:

- Conventional helicopter controls as reference,
- Steering wheel control and car-like pedals combined with a conventional collective lever, and
- Steering wheel control and car-like pedals combined with rocker switches for height control.

In order to minimize learning effects, the order of the configurations as well as the order of the flight tasks was varied between the test candidates.

Before the actual measurements were started, each candidate had one hour for familiarization with the configurations, the control laws and the flight tasks. Due to the high stabilization characteristics of the simulated rotorcraft, this time was sufficient for all of the candidates in order to acquire the necessary skills for handling the rotorcraft and completing the required flight tasks.

The perceived workload was examined with the first part of the NASA Task Load Index (TLX) questionnaire [15]. This questionnaire contains scales for rating the subjectively experienced workload in the categories mental demand, physical demand, temporal demand, performance, effort and frustration. The total workload was calculated as average of the scales with final values in the range of 0 to 100 where higher values correspond to higher perceived workload.

Performance and system usability were also measured in the study. These results will be reported on in a separate publication.

4. RESULTS

In order to analyse the suitability of the three different control concepts, the mean (*M*) workload was calculated for each task, configuration and group of test candidates. In tables 2 and 3 the standard deviation (*SD*) can also be found.

Table 2: City scenario: Descriptive statistics of the perceived workload.

	Pilots		Drivers		Inexperienced	
	M	*SD*	*M*	*SD*	*M*	*SD*
Conventional	25.0	10.6	44.3	24.0	42.0	11.1
Wheel + Collective	28.8	12.4	23.3	19.2	32.0	10.9
Wheel + Switches	28.0	9.0	21.3	21.4	34.8	8.6

Table 3: Slalom scenario: Descriptive statistics of the perceived workload.

	Pilots		Drivers		Inexperienced	
	M	*SD*	*M*	*SD*	*M*	*SD*
Conventional	39.3	18.4	63.5	26.7	55.2	14.6
Wheel + Collective	37.8	13.3	49.0	29.4	41.4	16.9
Wheel + Switches	45.5	17.4	44.3	25.5	42.8	15.4

Apparently, for both, drivers and inexperienced candidates, there is a remarkable difference in the mean values in both tasks. While the conventional helicopter controls are associated with higher workload, both steering wheel configurations received ratings of similarly lower TLX values.

In contrast to that, for the helicopter pilots the differences between the control concepts are lower with a slightly lower TLX rating for the conventional control concept in the city scenario. For the slalom, the configuration with steering wheel + collective lever received the lowest mean TLX ratings, followed by the conventional controls and the steering wheel + switches.

Following the evaluation of the descriptive statistics, an analysis of variance was conducted for determining the statistical significance of the findings. The analysis was perfomed using the statistics software SPSS [16]. The implemented GLM (General Linear Models) repeated measures procedure with mixed design was used as an overall statistical test. A correction of the degrees of freedom according to Greenhouse-Geisser was conducted whenever the Mauchly test of sphericity was significant. Pairwise comparisons after Bonferroni were conducted afterwards and post hoc t-tests showed pairwise differences for significant interferences between configurations and groups of test candidates (see also [17]).

The error probability α was initially set to 0.05. When the level of significance p is smaller than α, results are statistically significant. Trends were taken into account up to values of 0.1. For completeness not only the level of significance p is given for the results but also the test sizes $F(df_1, df_2)$ (for the analysis of variance) and $T(df)$ (for t-tests) in dependence of the degrees of freedom df. The effect size η^2 can take values between 0 and 1 with higher values representing higher strength of the investigated effect.

Figure 6 shows the overall workload experienced in the city scenario. The workload is depicted in boxplots, sorted by user group and configuration. (The bold horizontal line shows the median; the coloured box contains the upper and lower quartiles of the data; minimum and maximum ratings are shown by vertical antennas, outliers by dots and extreme outliers by stars. Outliers are numbered according to the number of the test candidate in the respective group).

As can be seen from the boxplot in figure 6, the configuration had an effect on the workload but with differences between the groups. This is confirmed by a statistically significant interference between configuration and group (F [2.77, 19.37] = 5.58, p = 0.007, η^2 = 0.44). Post hoc t-tests proved that the car drivers experienced significantly lower workload when flying with steering wheel + collective or steering wheel + switches compared to conventional controls (T [5] = 4.31, p = 0.008 and T [5] = 3.47, p = 0.018 respectively). No significant difference between the two steering wheel configurations could be found (p > 0.100).

The descriptive differences between the configurations for the groups of helicopter pilots and inexperienced candidates were statistically not significant (p > 0.100).

In Figure 7 the workload is plotted for the slalom scenario. The tendency is the same as in the city scenario: drivers and inexperienced test candidates perceived lower workload when flying with steering wheel compared to conventional inceptors. Though, due to wider spreading of the data, the differences in variance are statistically not significant ($p > 0.100$).

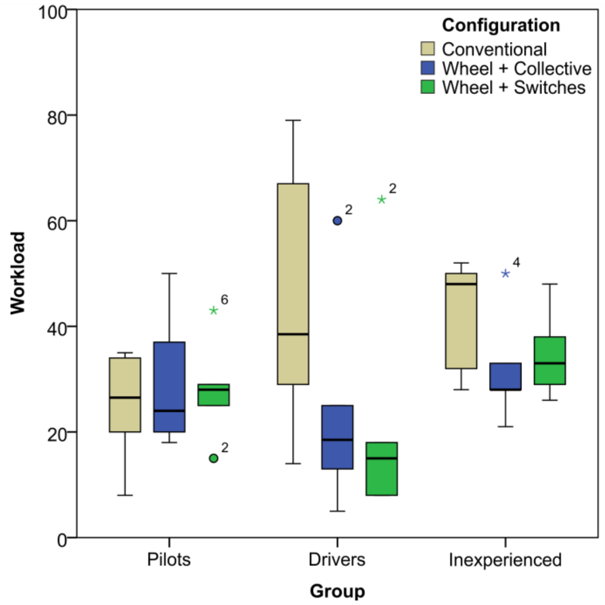

Figure 6. Perceived overall workload for the city scenario.

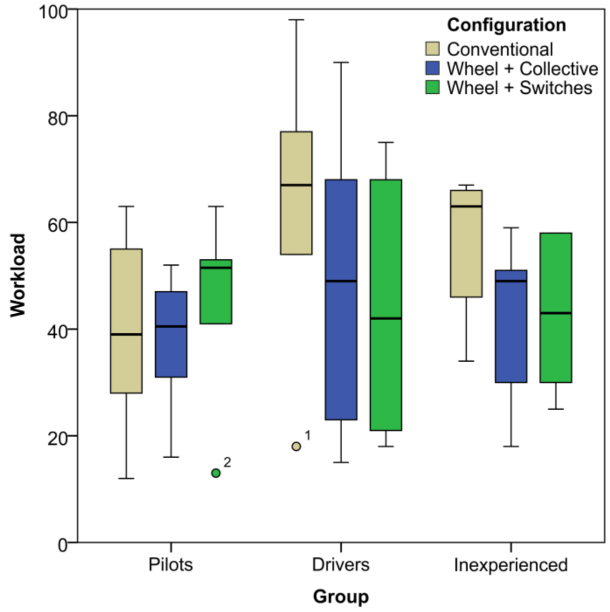

Figure 7. Perceived overall workload for the slalom scenario.

The analysis of the overall workload shows that especially for car drivers the workload could be reduced with both of the steering wheel configurations compared to conventional helicopter controls. In contrast to that, helicopter pilots experienced similar workload levels with all of the configurations.

Following the examination of the overall workload, subscales of the TLX questionnaire are presented that led to statistically significant findings. Figure 8 shows the physical demand perceived in the slalom scenario. This was significantly influenced by the configuration (F [2, 28] = 7.71, p = 0.002, η^2 = 0.36). When flying with conventional controls, the demand was higher than with steering wheel + switches (p = 0.009). The usage of steering wheel + collective lever resulted in higher workload than the steering wheel + switches (p = 0.049) but still less than the conventional controls.

The resulting conclusion is that the centre stick as well as the collective lever were associated with higher physical demand. This reflects the comments of two of the participating pilots who mentioned high control forces and displacements in the debriefing. A factor that increased this perception was that the pilots were asked not to use the trim functions of the conventional controls.

Table 4: Descriptive statistics of the perceived physical demand in the slalom scenario.

	Pilots		Drivers		Inexperienced	
	M	*SD*	*M*	*SD*	*M*	*SD*
Conventional	40.0	13.8	56.7	33.9	57.0	18.2
Wheel + Collective	30.0	13.8	50.8	34.3	48.0	25.6
Wheel + Switches	30.8	22.0	35.8	29.4	37.0	11.5

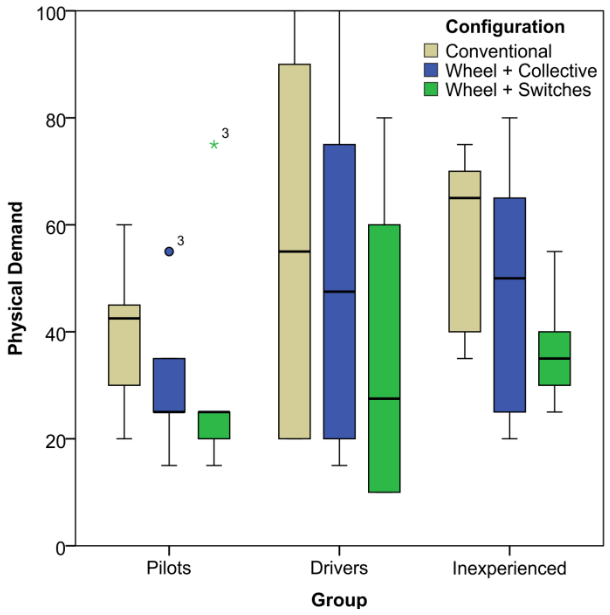

Figure 8. Physical demand during the slalom.

The following Figure 9 shows the temporal demand during the city scenario. The mean temporal demand was highest when flying with conventional helicopter controls (F [1.29, 17.99] = 7.49, p = 0.009, η^2 = 0.35). Compared to the steering wheel + collective and the steering wheel + switches, the difference is statistically significant with (p = 0.043) and (p = 0.032) while both steering wheel configuration show no significant difference ($p > 0.100$).

Although the objective temporal demand, influenced by the displayed route and target speed, was obviously the same for all three configurations, the test candidates experienced measurable differences in the subjective temporal demand. This finding allows the conclusion that the usage of the steering wheel was intuitively better understood by the test candidates than the conventional controls and therefore led to a lower demand.

Table 5: Descriptive statistics of the perceived temporal demand in the city scenario.

	Pilots		Drivers		Inexperienced	
	M	*SD*	*M*	*SD*	*M*	*SD*
Conventional	20.8	12.4	39.2	30.7	41.0	14.3
Wheel + Collective	19.2	7.4	17.5	14.4	27.0	24.9
Wheel + Switches	18.3	7.5	17.5	19.4	28.0	20.8

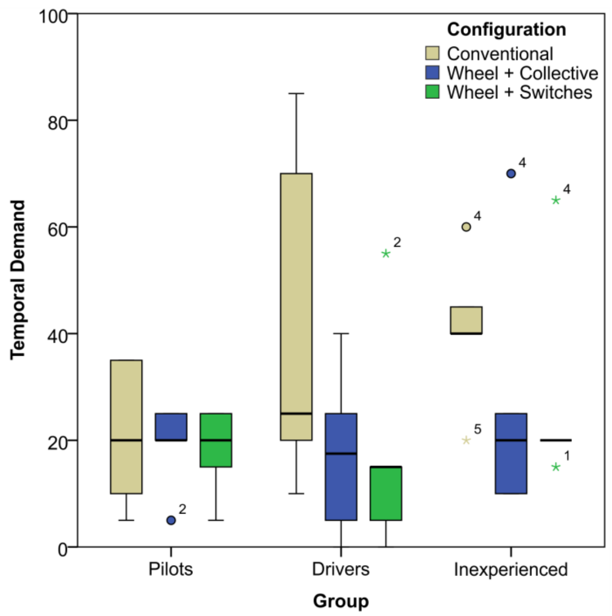

Figure 9. Temporal demand for the city scenario.

Finally, in figure 10 the frustration during the city scenario is plotted. Here, an interference between configuration and group can be observed (*F* [4, 28] = 6.98, $p < 0.001$, $\eta^2 = 0.50$). The pilots experienced different frustration levels than the other two groups. For them, the mean frustration level was lowest when flying with conventional inceptors. In the post-hoc t-test, the differences were not statistically significant ($p > 0.100$). The results are opposite for the drivers. For them, the conventional controls go along with the highest frustration level compared to the steering wheel + switches (*T* [5] = 5.32, $p = 0.003$) and to the steering wheel + collective (*T* [5] = 3.57, $p = 0.016$). The differences between both steering wheel configurations are not significant ($p > 0.100$). The frustration of the inexperienced test candidates is comparable to that of the car drivers with the conventional controls being more frustrating than the steering wheel + switches (*T* [4] = 2.26, $p = 0.087$) or the steering wheel + collective (*T* [4] = 2.41, $p = 0.074$). Again, both steering wheel configurations show no significant difference ($p > 0.100$).

Table 6: Descriptive statistics of the perceived frustration level in the city scenario.

	Pilots		Drivers		Inexperienced	
	M	*SD*	*M*	*SD*	*M*	*SD*
Conventional	15.0	7.8	35.0	17.3	38.0	18.2
Wheel + Collective	25.8	22.7	14.2	9.7	17.0	5.7
Wheel + Switches	28.3	23.8	12.5	10.8	24.0	11.9

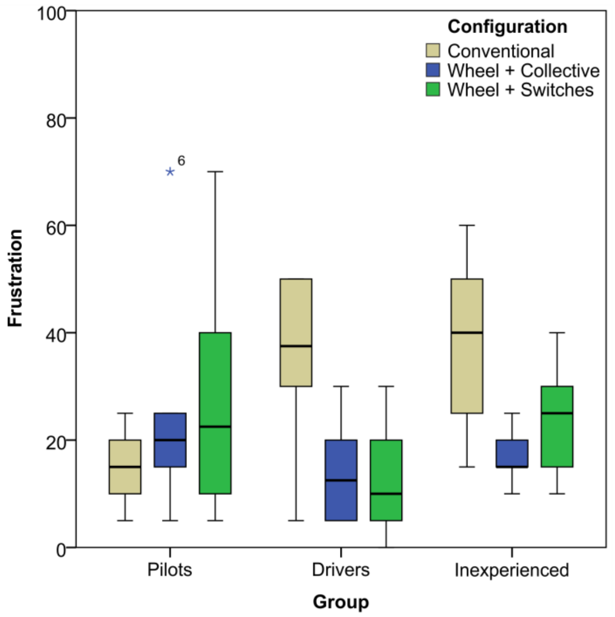

Figure 10. Frustration level for the city scenario.

5. DISCUSSION

When looking again at the perceived frustration levels, it is interesting to see that the helicopter pilots stated to be most frustrated by the steering wheel configurations. On the first look this might be surprising as in the other workload subscales as well as in the overall performance, the steering wheel was not rated worse than the conventional inceptors. These subjective results can be explained by the typical conservativeness of professional pilots. They have been flying helicopters conventionally for most to all of their previous flying hours. Even if a new control concept might offer objective advantages, they tend to hold on to the well-known control concept that they are familiar with.

The situation is completely different for users without flying experience. Car drivers clearly prefer a steering wheel over conventional helicopter controls and inexperienced users also gave best ratings for the steering wheel. This proves how intuitive this control concept is.

Regarding height control when flying with the steering wheel, both collective lever and switches received similar workload ratings from non-pilots. Comments in the debriefing showed that each test candidate had a personal preference for one of the concepts. The advantage of the collective lever is the intuitive direction of movement (up means up and down means down) but the steering wheel must be operated one-handed during height changes.

When flying with switches, the user can keep both hands on the wheel but has to remember that the right switch is for ascending and the left switch for descending. Especially in emergency situations, confusion might occur. More demanding scenarios regarding height control could be used in future studies to further investigate differences between the two options. Additionally, the mechanical characteristics of the switches should be redesigned. The current travel range of only few millimetres is very low and even led to a digital feeling for some of the test candidates. This was the main reason for the helicopter pilots' high frustration with this control concept.

6. CONCLUSION

This paper describes the development and investigation of a steering wheel control configuration for rotorcraft. Previous studies had already shown that the handling qualities of a rotorcraft with advanced control laws could be improved with the novel steering wheel concept. The current study investigates the workload perceived by different user groups when flying with conventional or steering wheel control. The following findings were made:

- The overall workload could be reduced for car drivers, when flying a steering wheel controlled helicopter.
- Test candidates with no experience in driving or flying could also intuitively use the steering wheel.
- Helicopter pilots gave similar overall workload ratings for all investigated control concepts. Their frustration level was higher when flying with the steering wheel compared to conventional helicopter controls.
- Both alternatives for height control (collective lever or switches) received similar workload ratings in combination with the steering wheel.

Although several of the helicopter pilots were initially sceptical regarding the steering wheel control, the reported study could show that this control concept is a viable alternative to conventional controls for highly augmented rotorcraft. It can be intuitively used by a wide range of users, receives equally good or even improved handling qualities and offers a possible workload reduction, especially for users without prior pilot training.

ACKNOWLEDGEMENTS

This research activity has received funding from the European Commission's Seventh Framework Programme for the project myCopter – Enabling Technologies for Personal Aerial Transportation Systems under grant agreement no. 266470.

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