EFFECT OF A HAPTIC TORQUE PROTECTION WITH AN ACTIVE SIDESTICK ON PILOT'S EYES-OUT CAPABILITY DURING A HELICOPTER TAKEOFF

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Abstract

Tactile limit cueing with active inceptors can reduce limit exceedances and workload. The often stated assumption, that it would enable the pilots to look more outside and less on the instruments, was not verified yet. In a simulator study the pilots' gaze during a high performance takeoff maneuver with and without a *haptic torque protection* system was now measured. It confirmed the assumption. Also, the pilot's workload was less and the accuracy of limit tracking higher with the *haptic torque protection* system.

NOTATION

Symbols:

Q	eng. Engine Torque / Torque-%
TCoff	Configuration without *Tactile cue*
TC^{STOP}	Configuration with stop-cue
$\text{TC}^{\text{STOP}}_{\text{INFO}}$	Configuration with stop-cue and info-cue
v_y	Velocity of best climb, here 65 kt
δ_0	Collective deflection
$\delta_{0,INFO}$	Position of the info-cue
$\delta_{0,STOP}$	Position of the stop-cue

Acronyms:

ACAH	Attitude Command / Attitude Hold
ACS	Active Controller Software
AOI	Area-of-Interest
fbw	fly-by-wire
fcs	flight-control-system
ACT/FHS	Active Control Technology / Flying Helicopter Simulator
AVES	Air Vehicle Simulator
CDF	Cumulative Distribution Function
DVE	Degraded Visual Environment
FLI	First Limit Indicator
ITC	inside-the-cockpit, compare OTW
MCP	Maximum Continuous Power
MTP	Maximum Takeoff Power
OTW	out-the-window, compare ITC
TOP	Takeoff Power
TLX	NASA-Task-Load-Index, workload rating scheme

1. INTRODUCTION

Helicopters operate close to obstacles and ground and land and takeoff on unprepared sites. High system complexity with various limits and gauges to keep in focus increases the risk of collisions or limit exceedances especially in DVE, e.g. during rain or fog or rotor induced whiteout. In fact, the former "European Helicopter Safety Team" (EHEST), which analysed 311 accidents of the years 2000 to 2005 (Ref. 1), and an analysis of the EASA for 824 accidents of the years 2010-2020 (Ref. 2) concluded that the main causes for more than 70 % of all analysed helicopter accidents were "Human Factors" and "Perceptional Errors". Also the US Army stated, that "Loss of Situational Awareness" was responsible for 70 % of all accidents during several missions in the near east, that most often resulted in "Controlled Flight Into Terrain" (CFIT) in DVE (Ref. 3). Among the identified adverse conditions, were "*situations where power required exceeded power available*" during hover and low speed operation and without inadvertent transition to instrument meteorological conditions (IMC). This is another hint for the difficulty to continuously perceive both, the relevant information from the outside, or out-the-window (OTW), like here height above ground and obstacles and relative sinkrate and from inside-the-cockpit (ITC), like current and available torque and prioritize accordingly. As ITC information are mostly presented visually there is a permanent conflict of where to put the visual focus. That urges the pilot to permanently switch the focus between ITC and OTW.

In order to mitigate this conflict, research developed the concept of *tactile cueing* for limit protection using active inceptors: The active inceptors contain actuators that can be used to generate force patterns to inform, warn or even guide the pilot via his or her haptic perception. Within a system, that properly calculates the control limits, the *tactile cues* allow to avoid unintended inputs that would lead to unintended limit exceedances and thus, enable "carefree" handling: The pilot does no longer need to check the instruments visually. The gained visual resources could then be used to observe the world OTWs.

Various applications were evaluated experimentally with pilots in simulator and real aircraft. The most mentioned function was *tactile cueing* for drivetrain limit protection, including *engine performance* limits, like torque, temperature, but also mast and hub torque, here referred to as *haptic torque protection*. It provided a *tactile cue* at the control position that corresponded with the current drivetrain limit. The often selected force pattern *softstop*, i.e. a local force gradient with limited amplitude, not only made the limit perceivable to the pilot, but also literally stopped the stick, avoiding unintentional limit exceedance, as long as the pilot kept the control forces low. What makes this stop "soft", is the force threshold limitation, allowing the pilot to intentionally exceed it and the corresponding (torque) limit, maintaining pilot authority. It could be shown, that such a system can reduce pilot workload, limit exceedances and increase system performance by others (Ref. 4–15 and by the author (Ref. 16, 17). That principle was also demonstrated for other applications, like obstacle avoidance cueing (Ref. 18–22). Today, more and more helicopters and also other aircraft are going to be equipped with active inceptor systems, e.g. the *CH-47F Block II* (Ref. 23), the *CH-53K* (Ref.24) or the civilian *Bell 525 - "relentless"* (Ref.13), the fixed-wing aircraft *Gulfstream 500 and 600* and *Embraer KC 390* (Ref. 25, 26) and the F-35 Joint-Strike-Fighter (JSF) (Ref.27).

However, the pre-assumption that *tactile cueing* would allow the pilots to look more outside and less on the instruments was not quantified yet. It was only confirmed by subjective pilots, who commented after testing such system, that they liked the "ability to look more outside" (compare Ref. 9, 10, 12, 19). A quantification of this assumption could verify the pilots' subjective impression and provide evidence and numbers for flight deck system designers and deciders whether and were to use *tactile cueing* best. This lead to the following main scientific question, addressed in this paper: "Can a *haptic torque protection* increase pilot's eyes out-the-window (OTW) time during helicopter flight and if, how much?" Additionally also the correct functionality of the *haptic torque protection* in terms of accuracy, i.e. the levels of torque limit exceedances and usage of available torque should be analyzed. Finally, subjective data, as the influence of a *haptic torque protection* on pilot workload and system acceptance were of interest.

2. METHOD

In order to estimate the influence of a *haptic torque protection* on the pilot's visual attention, or distribution between ITC and OTW, a simulator experiment with helicopter pilots using an eye tracking system to estimate the visual gaze with and without a *haptic torque protection* during a standardized maneuver was selected as research method. This section gives insight on the number of the participants and their experience, the apparatus, including the description of simulator, the *haptic torque protection* and the eye tracking system, the maneuver and acquired data and finally the data analysis.

2.1. Participants

Three experienced military test pilots participated in the evaluation. Their aliases and individual piloting experience is defined in Table 1. Each pilot had flown a multitude of helicopters, including conventional, like CH-53 and glass cockpits, like NH90. Only pilot 3C had flown the Active Control Technology / Flying Helicopter Simulator (ACT/FHS) before.

2.2. Apparatus

This section describes the flight simulator and the *haptic torque protection* system as well as the eye tracking system. The evaluation was conducted in the helicopter simulator of DLR's AVES Simulation

Table 1: Participants and experience

Pilot	3A	3B	3C
License	each military testpilot		
Types	each various types with conventional and glass cockpit		
ACT/FHS	no	no	yes
Years	18	34	23
Hours	2000	5000	4000

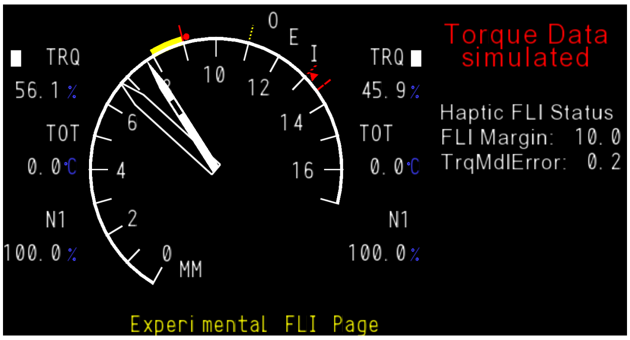


Figure 1: Torque displayed on (experimental) First Limit Indicator (FLI) (here the markers are dislocated representing 1 FLI unit margin that was actually 0 in the experiment)

Center. It replicates the "ACT/FHS" research helicopter cockpit, that is based on a H-135 helicopter (Ref. 28). The simulation provides a realistic, non-linear flight dynamics model. Like the real ACT/FHS, it is equipped with a pair of active sidesticks for the experimental pilot on the right seat, a prototype from Liebherr aerospace for the left and a Stirling Dynamics Goldstick for the right hand (Ref. 29).

The ACT/FHS drivetrain limits correspond to the original limits of its platform, the H135 T2+. They are displayed on the so called First Limit Indicator (FLI), compare Fig. 1, that shows the here used replica of original FLI. This display combines engine torque (TRQ), temperature (TOT) and turbine speed (N1) in one indicator for each of the two engines in a normalized way. It indicates the relative usage of the available range towards different limits and operation areas of that parameter which is closest or "first" to the limit. Here, the relevant limit and operation area are the Maximum Takeoff Power (MTP), indicated by a red line at 10 FLI, and the Maximum Continuous Power (MCP) at 9 FLI, that corresponds to the beginning of a yellow arc at 9 FLI. The MTP can be used only at speeds below $v_y = 65\,\mathrm{kt}$, mainly for takeoff, that is why the "yellow" range between MCP and MTP

Figure 2: *eye tracking*-Glasses with headtracker "antennas"

is also known as Takeoff Power (TOP).

For simplification in the simulator only the torque, and not the temperature or turbine speed, was simulated. That is why here only the torque limits are of interest: $Q_{MTP} = 78\,\%$ and $Q_{MCP} = 69\,\%$.

Usually the FLI is located in the center of the cockpit front panel, at about the location of the number 2 in Fig. 3. Here an experimental version of the FLI, located on the right panel, directly in front of the experimental pilot, was used, that, other than the original FLI, allowed adding a safety margin, which was used in a previous in-flight evaluation with the ACT/FHS (Ref. 16). Nonetheless, as now the experiments were conducted in a simulator, the margin was set to 0. The original FLI was here turned dark during the simulator experiments to avoid confusion.

The *tactile cues* of the *haptic torque protection* were presented on the left-hand active sidestick, which controlled the collective axis. The positions where the *tactile cues* needed to become effective, in order to maintain the helicopter just below the current limit were calculated based on an approximation, using the current airspeed, air density, collective and pedal position. The system actively selected the current limit based on the flight state using a state-machine. The inverse of that model was used to drive the experimental FLI, added by some lag. Further details of that *haptic torque protection* system described in previous publications (Ref. 16, 17). In contrast to the previous system the *tactile cueing*-Design has evolved, see section "Configuration" below.

In order to collect the gaze movement data, an eye tracking system was used. Eye tracking systems are more and more used also for helicopter research, like

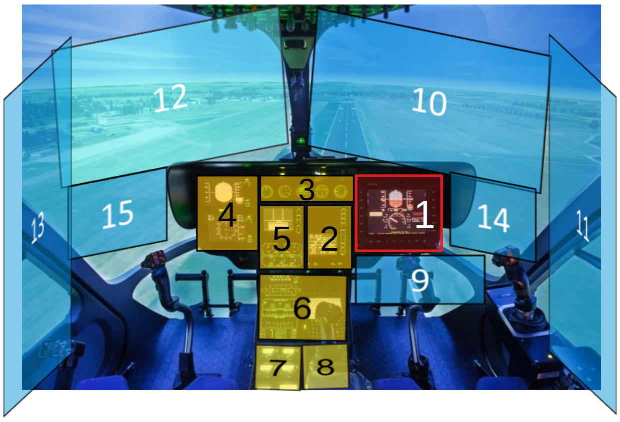
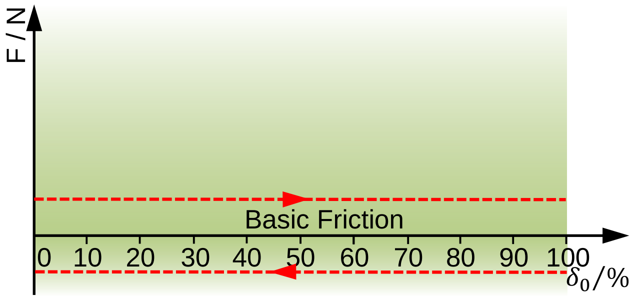


Figure 3: Areas-of-Interest (AOI) in the AVES ACT/FHS simulator cockpit (illustration)

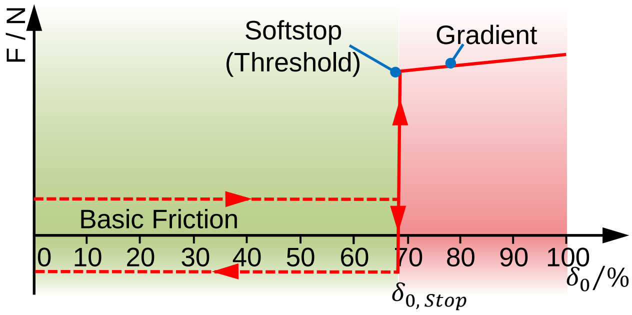
in References 30–32. Here, the SMI Eye Tracking Glasses 2 Wireless (SensoMotoric Instruments, Germany), was integrated into the cockpit. It consisted of a head-worn eye-tracking device in the form of binocular glasses (Figure 2), that was combined with a cockpit fixed head-tracker. According to Reference 33 it is capable of tracking and recording the visual gaze with an accuracy of 0.5° and an angular range of 80° horizontally and 60° vertically at a sampling rate of 60 Hz. A definition of eye tracking terminology is given in Reference 34. Here the so called "dwell times" were of interest, i.e. the duration of consecutive gazes on a specific object, or Area-of-Interest (AOI). For this experiment, the AOI were predefined according to (Figure 3), distinguishing between AOIs ITC, like the front panel with primary flight display and torque display, and OTW, i.e. the windows. The AOI OTW are here colour-coded blue, whereas ITC are coded yellow, except the main instrument (AOI no 1), where the experimental FLI is located, which is coded red.

2.3. Configurations

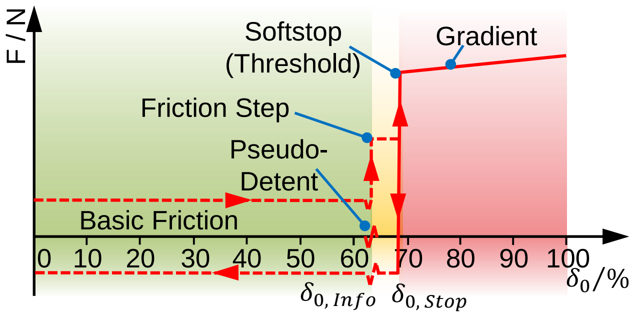
Three different configurations were defined, based on prior simulator testing with pilots, see Figure 4: (a) A benchmark without *tactile cue*: TCoff. (b) A single *tactile cue* shape variant only for the MTP, named TC^{STOP}, as it had the intention to stop the pilot from inadvertently exceed the limit. (c) A compound *tactile cue* shape variant, that in addition to configuration 2 also indicated the TOP, just below the *tactile cue* for the MTP. As this additional cue was intended to just inform the pilot, that the torque is inside that range it was named TC^{STOP}_{INFO}. In all configurations friction was present as basic force-feel setting, like in conventional collective controls. It was as much as required for the stick to maintain its position when hands-off, see value definition in label of Figure 4. In the TC^{STOP}_{INFO} configuration, the info-range was represented by increased friction. In pre-tests a detent was used to indicate the transition between lower torque and the info-range. The pilots liked that idea to highlight the transition, however, the downside of the used detent function was, that it was not possible to reduce its effectiveness-range, i.e. the area, where it starts to affect the stick and tries to pull it into the detent's centre, to a tolerable level. That is why here it was tried to find a realization that provided the information of a



(a) TCoff



(b) TC^{STOP}



(c) TC^{STOP}_{INFO}

Figure 4: *Tactile cue*-Designs: Basic Friction, 4 N, stop-cue: steep *softstop*, 50 N, info-cue: Friction Step, 10 N and Pseudo-Detent

detent, but without affecting the stick position or fine control. It was realized by activating the built-in sine-shaped shaker function for the duration of just one sine-wave at a shaking frequency of about 20 Hz, with an amplitude just big enough to be perceivable. That pseudo detent was only activated in the moment the stick passed the corresponding position. The stop-cue in both *tactile cue*-configurations consisted of a steep *softstop*. It was realized using the sticks built-in *hardstop*-function. The pilot could deliberately exceed it by applying more than its set force-threshold, here 50 N. Therefore the system deactivated the *hardstop* and commanded a *softstop* when the force-threshold was reached. It was continued by a spring gradient, in order to allow fine control after exceeding the force threshold. Also, in both *tactile cueing* configurations, as the airspeed approached v_y the stop-cue position $\delta_{0,STOP}$ automatically moved from the collective position corresponding with MTP to the one corresponding with MCP.

In all configurations a flight-control-system (fcs) was active with an attitude command/hold (ACAH) response type in the pitch- and roll axes and a rate command (RC) in the yaw axis. The collective or heave axis was not controlled.

2.4. Evaluation maneuver and conduct

The basic requirement for the evaluation maneuver was to motivate the pilot to apply maximum power and also to pass v_y, in order to include the limit transition from MTP to MCP, as demanded by the flight manual, see above. As the evaluation was part of a military funded project it should also reflect a plausible military use case. Based on a previous maneuver (Ref. 35), a high performance takeoff maneuver, the *Small Arms Takeoff Maneuver* was developed, see Figure 5 and Table 2, which required the pilot to takeoff from cover, here a forrest clearing, and gain a safe altitude as quickly as possible. It consisted of three phases: 1. Takeoff from the ground to hover, 2. acceleration to just above v_y, here 70 kt, while staying below the tree tops (about 40 ft above ground) of the surrounding forest and 3. climb to a safe altitude, maintaining that velocity. The pilot was briefed to target a height above ground of 1000 ft, but in order to save time the experimenter ended the run earlier, the earliest after passing 450 ft.

Each pilot conducted a test points (TP), one for each of the defined configurations. The order was TP1

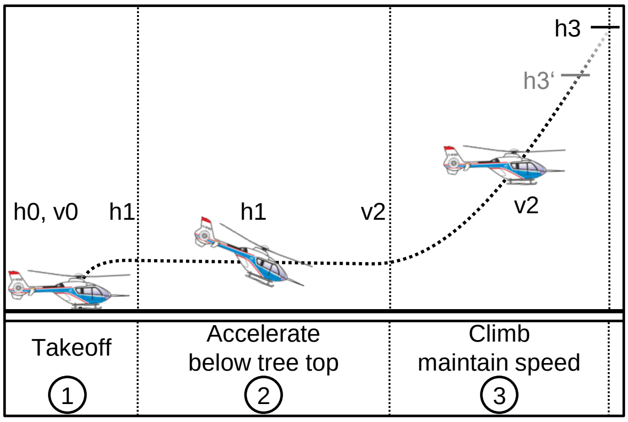


Figure 5: Small Arms Takeoff Maneuvre

Table 2: Maneuver Parameters

Parameter	Value	Description
h0/ft	0	on ground
v0/kt	0	
h1/ft	40	below tree line
v2/kt	70±2	
h3/ft	1000	target height
h3'/ft	450	here experimenter may skip

TCoff, TP 2 TC^{STOP}, TP 3 TC^{STOP}_{INFO}, TP 4 TC^{STOP}_{INFO}.[1] For each test point the pilot flew the maneuver one time for training. After that followed at least one evaluation-run. Each pilot was offered to repeat the evaluation-run as often as he desired to improve performance and reduce the influence of training effect on the results.

2.5. Data acquisition

During the evaluation the pilots wore eye-tracking glasses, that were calibrated for each pilot at the beginnings of the sorties. The calibration was checked regularly during the conduct and repeated whenever necessary. The eye tracking data were recorded for each evaluation run, as well as other quantitative data, like simulated sensor data, control deflections and forces, as well as the *tactile cueing* configuration for the active sidestick.

The pilots were asked to comment on their experience "thinking aloud" and notes were taken accord-

[1] There were additional test points, that dealt with effects on the control forces, that are not part of this paper and only mentioned here for transparency: After TP 2, the pilot was asked to fly the maneuver very aggressively in TC^{STOP}, and after TP 4 the pilot was surprised by a sudden engine failure in configuration TC^{STOP}_{INFO}.

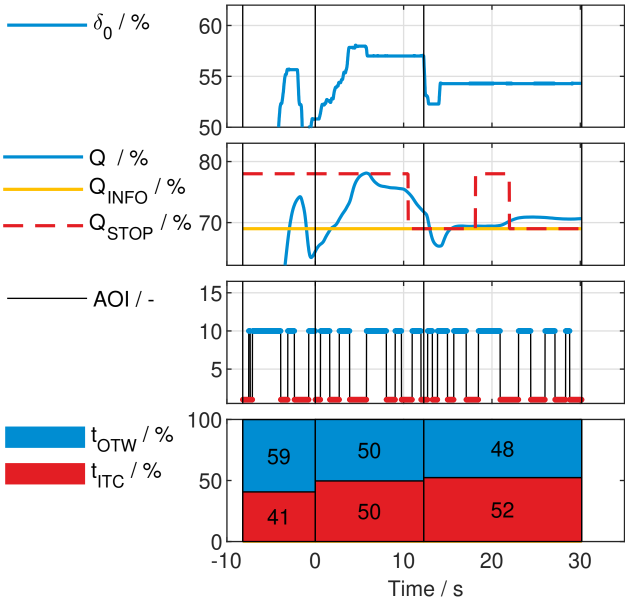


Figure 6: Small of Arms Takeoff, Pilot 3A, TCoff

ingly during the maneuver. After finishing a test point, or configuration respectively, the pilots filled in a questionnaire. It included the NASA-TLX form for the workload self-assessment (Ref. 36) and the "van der Laan" system acceptance questionnaire (Ref. 37).

2.6. Data handling

The best runs of each test point and pilot in terms of maneuver accuracy and data quality were selected for data analysis. The time histories of the here relevant data are plotted exemplarily for pilot 3A for configurations TCoff (Figure 6), TC^{STOP} (Figure 7) and TC^{STOP}_{INFO} (Figure 7). Row 1 shows the collective side-stick control deflection δ_0 and, for TC^{STOP}_{INFO} also the position of the stop-cue $\delta_{0,STOP}$. The torque Q, torque-limit and beginning of the torque-info-range is shown in the second row.

The eye tracking system provided an automatic AOI detection. But, due to quite extreme gaze-angles the AOI could not be detected continuously. That is why the eye tracking data were processed manually. Therefore, first the gaze-point was made visible in the videos taken by the scene camera of the eye tracking device. Then these videos were used to manually detect the dwells, i.e. the visual gaze in relation to the predefined AOIs of Figure 3, see row 3. Row 4 shows the relative accumulated dwell times for all AOIs ITC, t_{ITC}, and OTW, t_{OTW}, for all three maneuver phases, i.e. takeoff, acceleration and climb. The maneuver phases are depicted by vertical lines. Their start and

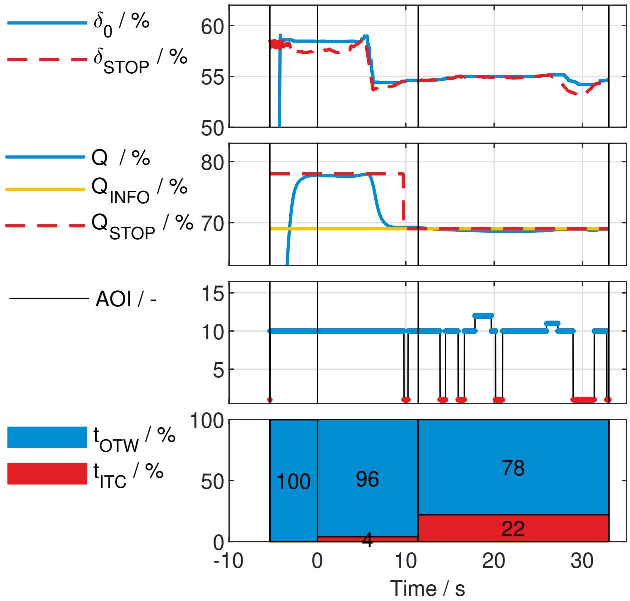


Figure 7: Small Arms Takeoff, Pilot 3A, TC^{STOP}

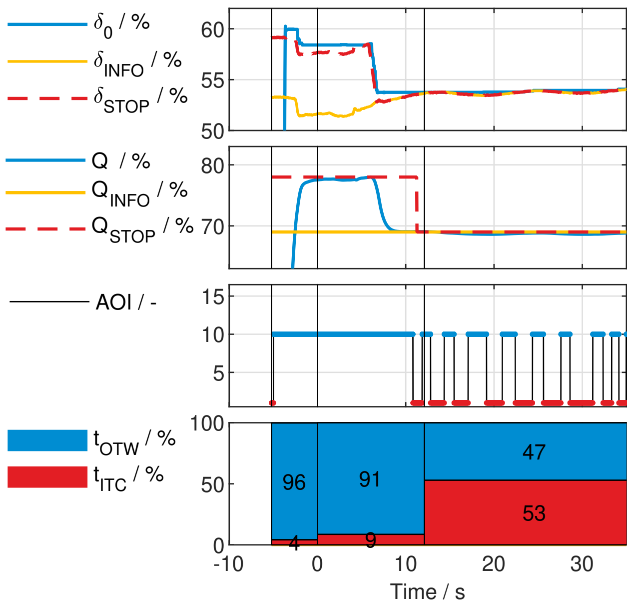


Figure 8: Small Arms Takeoff, Pilot 3A, TC^{STOP}_{INFO}

end times were estimated post-flight according to the predefined maneuver phase criteria, see section 2.4.

3. RESULTS AND DISCUSSION

The results include an overview over the accuracy, the eye tracking evaluation as well as qualitative data like the perceived workload and system acceptance.

3.1. Accuracy

The estimation of the accuracy serves to quantify the effectiveness of the different configurations, i.e. how good each configuration is at avoiding exceedances and how good it enables to use the available resources, or how close to the limit it allows to operate. The accuracy can be expressed by the difference ΔQ between measured torque Q and current torque-limit Q_{STOP}, see time histories of the torque in Figures 6 to 8.

For quantification and better visibility, the Cumulative Distribution Function (CDF) of ΔQ was estimated, see Figure 9. Negative values indicate an under usage and positive values an exceedance. The vertical axis shows the accumulated time. A_n and A_p are the integrals of the under-usage and exceedance.

At the beginning of the maneuver the pilots required different times for the transition from the take-off to the acceleration phase, i.e. before really pulling the collective to reach the torque limit. For example one pilot first hovered in the TC^{STOP}-configuration for a relatively long time, using only the hover power, before starting the acceleration. In order to mitigate this influence on the degree of utilisation, only torque values above a selected threshold value of here 59 %-torque were processed.

There was only one relevant exceedance. This was caused by pilot 3A in the reference configuration, i.e. without tactile cueing (TCoff), see also Figure 6. The pilot was too late in reducing the torque below the limit. In the *tactile cueing*-configurations there were negligible overshoots of very short durations, with an order of magnitude of 0.1 %-torque and 1 s.

The degree of utilisation was better for all pilots in all tactile cueing configurations than in the reference configuration without tactile cueing. With the exception of pilot 3B in the configuration TC^{STOP}, the utilisation with tactile cueing was always at least twice as good than without. Pilot 3B, in the first tested configuration with tactile cueing, did not go to the limit during the hover phase. In average, the pilots achieved better use of the available torque in the configuration TC$^{STOP}_{INFO}$. This may result from training effect and increased trust in the function. Since there was only one test point without versus two test points with *tactile cueing*, the here observed improvement may be biased, as also without *tactile cueing* the performance might have improved with more training. To eliminate this possible effect, the order of the test points should be varied in future studies.

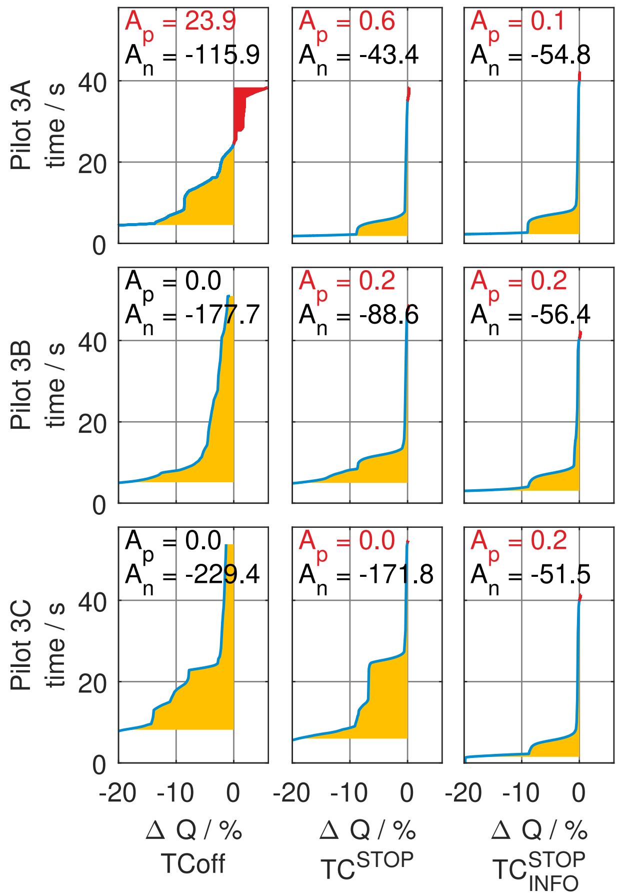
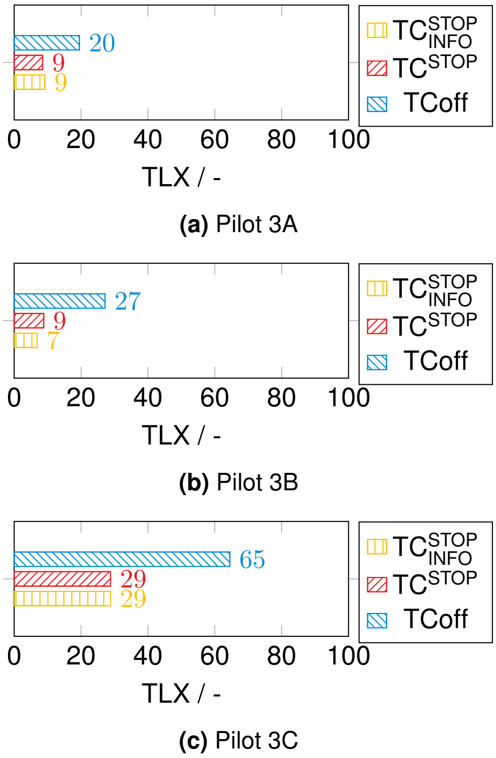


Figure 9: CDF and integrals of under-usage (A_n) and exceedance (A_p) of the available Torque (starting at $\Delta Q > -19\,\%$)

What is salient is the characteristic shape of the "bump" in all the configurations with active Tactile Cueing, see bottom right in each case. This has the same shape and size for all pilots. These result from a) the system dynamics of the torque and b) the too early reduction of the valid torque limit from MTP to MCP before passing $v_y = 65$ kt based on a speed predictor. Nonetheless, the reoccurrence of the "bump" shape can be seen as evidence, that in the *tactile cue*-configurations the system was taking care of the



(a) Pilot 3A

(b) Pilot 3B

(c) Pilot 3C

Figure 10: NASA TLX Small Arms Takeoff

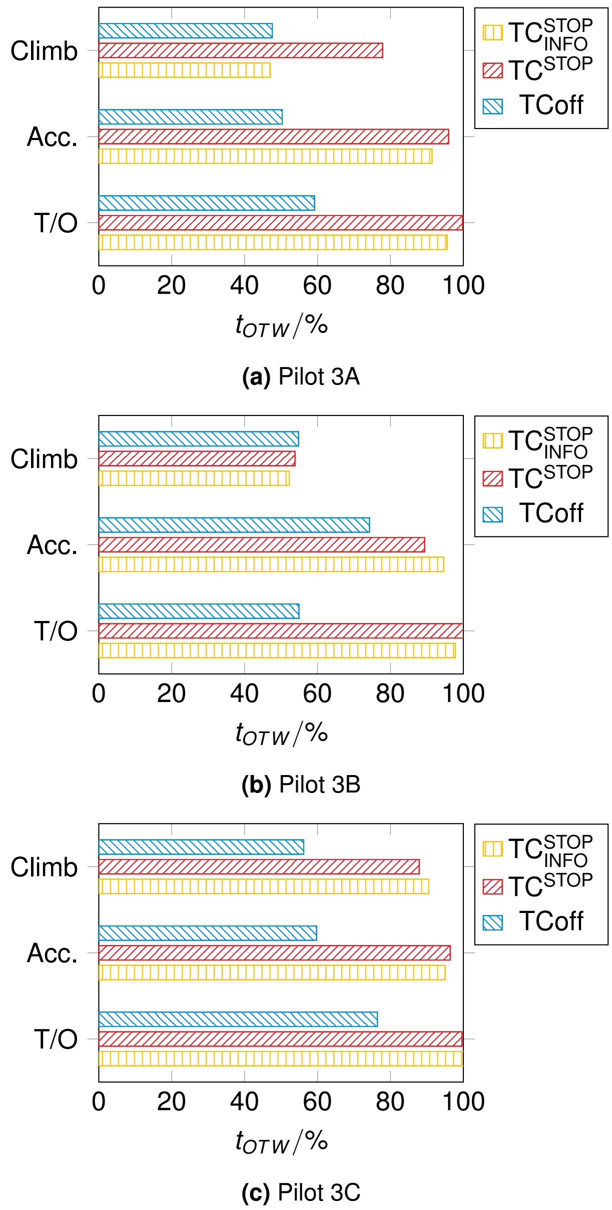
torque, while the pilots only needed to maintain contact to the *softstop*.

In the data, there was some evidence, that the pilots could eventually have lost contact with the *softstop* when it moved away. They might have perceived the basic friction as *softstop*, that here had a very steep gradient, providing a similar force-feel, when the stick is static. Nonetheless more evidence is needed to understand the correlation between *softstop*-gradient and perceptibility of its motion.

3.2. Workload

Figure 10 shows the workload self-assessment of all three pilots based on the NASA-Task-Load-Index (TLX) rating scale for each configuration. The overall workload level was relatively low, with maximum TLX values of 65 for pilot 3C and only 20 and 27 for the other pilots, all for configuration TCoff. The *tactile cueing*-configurations received one third to one half of the TCoff-ratings. There was no difference between both *tactile cueing*-ratings $\mathrm{TC}^{\mathrm{STOP}}$ and $\mathrm{TC}^{\mathrm{STOP}}_{\mathrm{INFO}}$. In absolute values, the *tactile cueing* could reduce the workload by 11 to 36 TLX.

3.3. Eye Tracking Data



(a) Pilot 3A

(b) Pilot 3B

(c) Pilot 3C

Figure 11: Accumulated relative gaze time "out-of-the-window" (OTW) for each pilots and configuration

It can be seen in both time histories Figure 6 and Figure 7 that the pilot's gaze switched between the primary flight display, AOI number 1, colored red and the front window, AOI number 10, colored blue. Figure 11 shows the relative accumulated dwell times per maneuver phaseOTW for all three pilots and configurations.

The number of gaze switches between the AOIs is lower in the *tactile cueing* configurations $\mathrm{TC}^{\mathrm{STOP}}$ and $\mathrm{TC}^{\mathrm{STOP}}_{\mathrm{INFO}}$than in 1 TCoff. In the phases takeoff (T/O) and acceleration (Acc.), all pilots had more time OTW

(t_{OTW}) in both *tactile cue*-configurations (≈ 90-100 % OTW-time) than in the benchmark configuration TCoff (≈ 50-77 % OTW-time). During the takeoff phase the pilots did not look into the instruments at all with *Tactile cueing*. During the climb phase the OTW-time was less than in the first two phases, for all configurations and pilots. Also, during this phase, two pilots had more OTW-time in configuration $\mathrm{TC}^{\mathrm{STOP}}$ than in configuration TCoff.

The general reduction of gaze time OTW for all configurations in the climb phase matches very well with findings of Greiwe in two later performed experiments, which dealt with the estimation of pilot gaze behaviour during real and simulated helicopter flight. In (Ref. 30) he describes that during a vertical climb maneuver, the OTW time decreased with height for two of three participating pilots. In a consecutive experiment (Ref. 31), he estimated, that during flying a simplified mission profile in the simulator, the OTW-time was higher for the takeoff than for the departure phase and higher for the landing than for the approach phase for each of the three pilot. The in-flight-evaluation did not show that consistent trend of the simulator evaluation. A possible reason is, that the pilot's interest to look outside is higher when closer to the ground and obstacles, correlating with the higher collision risk. And also, here the briefed test maneuver asked the pilots to maintain a specific flight speed during climb, which made it necessary to control the speed on the flight instruments. In future analysis it should be distinguished which instruments were used when the gaze was on the instrument panel to verify that assumption.

3.4. System Acceptance

All pilots stated high usability of and satisfaction with the tested system and *tactile cueing*-configuration, see Figure 12. Pilot 3A said, it was "more comfortable [than without *tactile cueing*]" and "fun". Pilot 3B found it "Quite close to perfect, brilliant" and "intuitive, very nice" and finally stated Pilot 3C "Can look outside more, better SA [situational awareness]". The here new idea to also provide a *tactile cue* to indicate the info-range was generally rated as adequate and "never disturbing". Two pilots added, that for the flown takeoff task it was not obligatory, but would generally help, e.g. to understand the torque margin. Nonetheless, it was argued, that with a constant friction as info-cue it was not possible to estimate the relative position inside the info-range. Instead it was proposed to use a force gradient, i.e. a *softstop*, even at the cost, that it would require a force to keep the stick inside that range. But the pilot added, that this would only be necessary for helicopter types, which had a wider info-range than the H-135. As the H-135 had a relatively short info-range, i.e. TOP-range, a friction-step would "probably be sufficient".

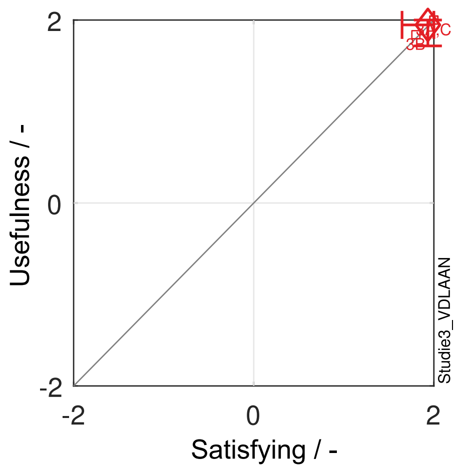


Figure 12: System Acceptance: Usability over Satisfaction, scale according to Ref. 37

4. CONCLUSIONS AND OUTLOOK

The following conclusions can be drawn:

1. With the *haptic torque protection* the available torque was used better, i.e. the pilots operated longer and closer to the limits. With *tactile cue* there were no exceedances, without there was one.
2. In comparison to the reference case without *tactile cue*, there was more out-the-window (OTW) time during the used takeoff maneuver in all phases with the *haptic torque protection*. Nonetheless, there were differences between the phases.
3. During the initial phase, i.e. takeoff from the ground to hover, with *tactile cueing*, the pilots did not look into the instruments at all with the simple *tactile cue*.
4. During the climb phase there was less OTW-generally and the effect of *tactile cue* towards more OTW-time was also less strong.
5. When adding complexity to the *tactile cue* to indicate an additional torque range just below the max. torque limit, the pilots looked slightly more

into the instruments, than with the simpler *tactile cue*, that only indicates the max. limit. However, also here the OTW-time is still higher than for the benchmark with no *tactile cue*.

6. With the *haptic torque protection* all pilots perceived half the workload, i.e. at least 11 to 36 TLX less than without.
7. The system acceptance, or usability ratings showed high appraisal for the *haptic torque protection*.

In future *tactile cueing*experiments the eyes-out-time estimated by eye tracking could serve as a metric for *tactile cue* optimization. It should also be distinguished which instruments were in focus and how *tactile cueing* influences the gaze distribution between the instruments to help understanding, to which extent a *tactile cue* can replace an instrument.

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