

COMPARISON OF HELICOPTER PILOTS' GAZE BEHAVIOUR DURING DIFFERENT FLIGHT TASKS WITH DIFFERENT FLIGHT CHARACTERISTICS

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ABSTRACT

In order to perform a flight task successfully, in addition to the task-specific minimum performance helicopter pilots must provide a compensation performance. This compensation performance must remain below a critical limit to guarantee a safe flight condition at all times. This paper introduces the method known here as Visual Action, which enables a statement to be made about the pilot's compensation performance based on eye movement data. For this purpose, a simulator study was carried out, in which the flight dynamics were varied between the test points. Afterwards the pilots assessed the handling qualities using the Cooper-Harper rating. The Visual Action method presented here suggests a very good correlation with the handling quality ratings given by the pilots.

NOTATION

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List of Symbols

$A_{\alpha,N}$ Visual Attack Number, -

$A_{\alpha,R}$ Visual Activity Rate, s^{-1}

$\bar{A}_{\alpha,R}$ Mean Visual Activity Rate, s^{-1}

PCC Pearson Correlation Coefficient, -

R^2 Coefficient of Determination, -

$\vec{u}_{ref}$ Unit Reference Vector, -

$\vec{v}_{dir}$ Gaze Direction, -

z Standard score/z-score, -

$\bar{z}_{HQR=4}$ Average z-score at HQR = 4, -

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α Gaze Angle, $^{\circ}$

$\dot{\alpha}$ Gaze Angle Rate, $^{\circ}/s$

Λ_V Visual Action, -

μ Mean, -

σ Standard deviation, -

*

List of Abbreviations

ACT/FHS Active Control Technology/Flying Helicopter Simulator

ACAH Attitude Command, Attitude Hold

AOI Area of Interest

AVES Air Vehicle Simulator

COTS Commercial of the Shelf

DH Direction Hold

DLR German Aerospace Center

DVE Degraded Visual Environment

FoV Field-of-View

GVE Good Visual Environment

HH Height Hold
hor horizontal
HQR Handling Qualities Rating
ITC Inside-the-Cockpit
LE Left Eye
MTE Mission Task Element
OTW Out-the-window
PCCR Pupil Centre Corneal Reflection
PFD Primary Flight Display
POI Point of Interest
RCAH Rate Command, Attitude Hold
RE Right Eye
TRC Translational Rate Command
vert vertical

INTRODUCTION

To perform a flight task successfully, a helicopter pilot must always achieve a certain performance. If it is the same task, the performance to be achieved can be influenced by the environment (e.g. wind and visibility conditions) and the helicopter itself (e.g. type and flight controller). In this respect, the pilot's overall performance is made up of a task-specific minimum performance, which the pilot must provide in any case, and a compensation performance in addition to the optimum case. It is important for the pilot to not only successfully complete the flight task, but above all, to ensure a safe flight condition at all times as well as to keep an eye on the surroundings so as not to endanger himself or the helicopter (Ref. 1). The compensation performance must therefore not exceed a critical level above which the flight task is no longer feasible and the helicopter is uncontrollable. For that, the key concept of pilot compensation is of particular importance in the assessment of helicopter handling qualities (Ref. 2). A change in the applied pilot compensation can also be understood as a change in pilot behaviour, such as control behaviour (Ref. 3).

A better understanding of pilot compensation is the key to a better understanding of human-machine interaction with the aim of constantly expanding the possible uses of helicopters and further increasing safety in flight. One way of analysing human-machine interfaces is e.g. eye tracking. In recent decades, numerous advances have been made in analysing eye movements (Ref. 4). In addition to the development of high-performance and easy-to-use Commercial of the Shelf (COTS) eye trackers, the methods for analysing eye tracking data have also been

continuously developed (Ref. 5). This is the main reason why human-machine interfaces have been successfully investigated in many different domains such as, e.g. automotive (Refs. 6, 7) or trains (Refs. 8, 9). Due to the high level of integration required in aviation and the particularly complex environment in a helicopter (Ref. 10), there have only been a few studies on the eye movement of helicopter pilots to date (e.g. (Refs. 11–13)). In recent years, the German Aerospace Center (DLR) has intensified its research activities on this topic, which is why the sensible use of eye tracking in helicopters has now been successfully demonstrated in several studies. In addition to its use in real flights (Refs. 14, 15), studies have also been carried out on helicopter ship deck landings (Ref. 16) and air-to-air refuelling (Ref. 17) in the simulator. A further study (Ref. 18) provided evidence that although the gaze behaviour in real flight and simulator is similar, differences could also be identified, which is why direct transferability of the results obtained in the simulator is only possible to a limited extent.

Memon et al. (Ref. 3) discussed in their research the development of a metric aimed at quantifying and predicting the extent of pilot control compensation required across a wide range of Mission Task Elements (MTEs). They explored the utility of various time- and frequency-domain measures to examine pilot control activity during hover, low-speed, and forward flight tasks performed by test pilots. Utilising both the National Research Council (Canada)'s Bell 412 Advanced Systems Research Aircraft and the University of Liverpool's HELIFLIGHTR simulator, they assigned Handling Qualities Rating (HQR) for each task and compared these ratings to a newly developed weighted adaptive control compensation metric based on discrete pilot inputs, demonstrating a strong correlation. Moreover, their study highlighted the relationship between the pilot's subjective assessments and measured control activity as well as task performance through a time-varying frequency-domain exposure. The findings proposed compensation boundaries that predict and verify subjective assessments from the Cooper-Harper HQR scale.

The Cooper-Harper Handling Quality Scale (Ref. 19) is a standardised pilot rating system, ranging from 1 (excellent, minimal pilot effort) to 10 (uncontrollable, intense effort), used to subjectively assess aircraft handling qualities during specific tasks. It is based on a non-linear decision tree, which is shown in Figure 18 in the appendix. The ADS-33 standard (Ref. 20) determines handling quality levels (1-3) for military rotorcraft by evaluating pilot compensation effort and performance in Mission Task Elements, such as Hover, Slalom, Pirouette or Acceleration/Deceleration, ensuring compliance mission handling qualities requirements.

The aim of this study is to investigate the gaze behaviour of helicopter pilots for various maneuvers that differ primarily in terms of flight dynamics. It is to be investigated whether these flight dynamics have a particular

influence on the pilots' gaze behaviour. Furthermore, the hypothesis is to be evaluated as to whether the pilot compensation to be applied has a similar influence on gaze behaviour as on control behaviour. For this purpose, the method presented in (Ref. 3) is transferred to eye movement data and compared with the subjective ratings given by the pilots.

This paper is structured as follows: At the beginning, following the motivation for this study, the method of quantifying gaze activity is derived. The structure of the simulator study, the participating pilots and the eye tracking system used are then described. After the presentation of the results, these are critically discussed. Finally, conclusions are going to be drawn, and an outlook for future work is given.

METHODOLOGY

The main hypothesis of this study is that a pilot's handling qualities rating, measured using scales like the Cooper-Harper Rating Scale, correlates systematically with their Visual Activity during flight. The Cooper-Harper Rating Scale is a standardised tool used to evaluate the handling qualities of an aircraft based on pilot feedback, ranging from 1 (excellent) to 10 (major deficiencies) (Ref. 19). Visual behavior, particularly gaze allocation and fixation patterns, is assumed to reflect underlying cognitive effort and task engagement.

In the context of flight operations, the pilot engages with the system through three primary output channels: auditory (e.g., radio communications), visual (e.g., attention shifts and gaze behavior), and muscular (e.g., cyclic and collective stick inputs). Among these, Visual Activity plays a dual role: it is both a channel for environmental perception and a potential indicator of mental workload and compensation strategy. As such, analysing visual dynamics offers a non-invasive and continuous means to infer pilot state and performance.

This approach is particularly valuable in highly dynamic or safety-critical flight scenarios where traditional performance metrics alone may be insufficient to capture the nuances of pilot-system interaction.

The following section describes the proposal and derivation of the "Visual Action" metric that is designed as a means to capture this relationship.

Visual Attack Number The "Visual Attack Number", denoted as $A_{\alpha,N}$, is defined as the total number of discrete gaze shifts—characterised by changes in gaze angle α that exceed a predefined angular threshold α_{lim} —within a specified task time window. This metric is intended to quantify visually driven activity, particularly the frequency of intentional redirection of gaze between Points of Interest (POIs). A detailed discussion on the appropriate selection of the angular threshold α_{lim} is provided later in this section.

Conceptually, each Visual Attack represents a significant redirection of attention from one Area of Interest (AOI) to another. By introducing a minimum threshold, small oscillatory eye movements around a point of fixation (e.g., micro-saccades or stabilisation movements) are excluded from analysis, as they are interpreted as bio-mechanical noise rather than deliberate scanning behavior.

The calculation of $A_{\alpha,N}$ is based on gaze angle data. First, zero-crossings of the gaze angle rate $\dot{\alpha}(t) = 0$ are identified, which correspond to local reversal points in the direction of eye movement. These reversal points define the boundaries of individual gaze shifts. For each pair of adjacent reversal points, the magnitude of the angular change $\Delta\alpha_{rev}$ in gaze is computed. If the angular difference exceeds the threshold $\Delta\alpha_{rev} \geq \alpha_{lim}$, the shift is classified as a valid or intentional Visual Attack. Otherwise, the algorithm continues to the next reversal point, ignoring minor fluctuations.

Figure 1 presents the gaze angle and rate data α and $\dot{\alpha}$ for a representative run of the Hover MTE, a specific helicopter flight test technique defined in the ADS-33E standard (Ref. 20), which is discussed in detail later in this paper. In contrast, Figure 2 provides a zoomed-in view of the same run, highlighting the process of gaze angle reversal and the identification of intentional POI shifts.

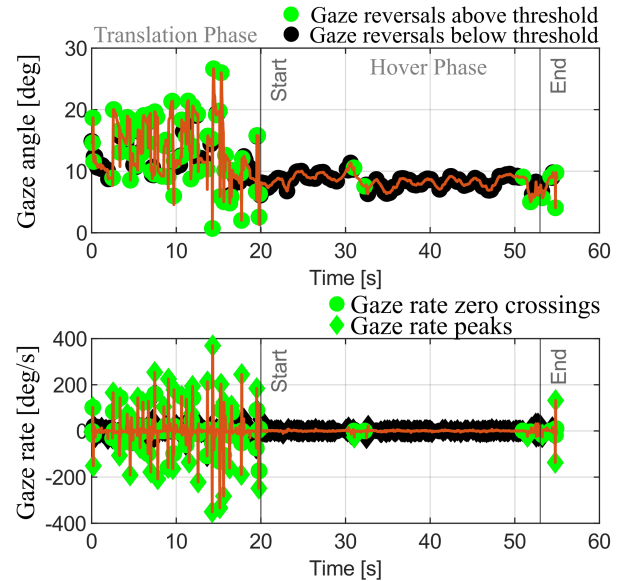


Figure 1. Gaze angle and rate evolution over a Hover MTE run.

The resulting event count of valid Visual Attacks is accumulated over fixed time intervals Δt throughout the entire duration of the task. In this study, a time window of $\Delta t = 5$ seconds is chosen. This duration is grounded in prior literature (Ref. 21) and reflects the minimum time typically required for a pilot to perceive visual cues and

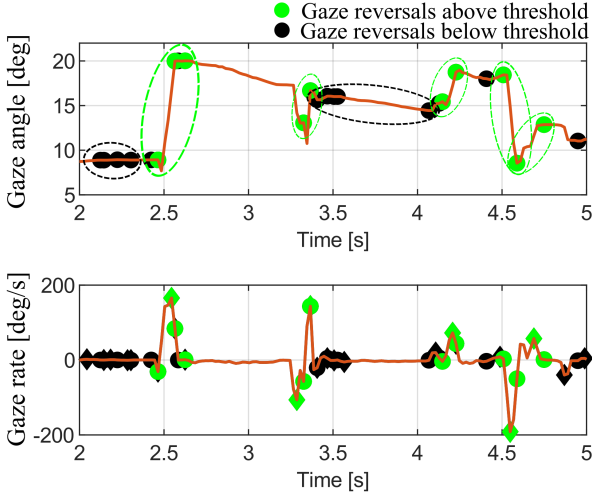


Figure 2. Zoomed-in gaze angle and rate evolution over a Hover MTE run.

respond with a compensatory action during a MTE.

The objective of this metric is to localise periods of peak visual POI shifts during the MTE, thereby identifying phases of elevated pilot compensation and attentional demand. It provides a time-resolved view of visual POI shifts, enabling correlation with task phases, control inputs, and subjective ratings during specific phases of a flight task.

Visual Attack Activity Rate The Visual Attack Activity Rate, denoted as $A_{\alpha,R}$, is defined as the frequency of Visual Attack events per second. It is calculated by dividing the Visual Attack Number $A_{\alpha,N}$ by the moving time window Δt with a 2.5 s overlap. The resulting metric $A_{\alpha,R}$ represents the rate of significant gaze shifts — interpreted as attentional redirections — per second.

From the time-resolved sequence of $A_{\alpha,R}$ values, a single summary statistic — namely the Critical Mean Visual Attack Activity Rate during the critical sub-phase, denoted as $\bar{A}_{\alpha,R}$ — is extracted. This average is computed over the critical time segment T_{crit} , which corresponds to the most demanding sub-phase of a given MTE. The critical segment is determined post-flight based on pilot self-reports and handling quality debriefings.

This approach is grounded in the understanding that subjective handling quality ratings typically reflect the phase of the MTE that required the highest level of compensation. Consequently, $\bar{A}_{\alpha,R}$ serves as a representative measure of a pilot's average visual workload during the most effort-intensive portion of the task.

In summary, $\bar{A}_{\alpha,R}$ quantifies the visual "busyness" of a pilot during the critical sub-phase of an MTE and is intended to serve as a proxy for visually mediated compensation effort.

Figure 3 illustrates the evolution of the Visual Attack Number $A_{\alpha,N}$ across consecutive 5-second intervals and

the resulting Visual Attack Activity Rate $A_{\alpha,R}$ during a Hover MTE run, revealing periods of intensified and lowered Visual Attack Numbers. During the translation phase of the MTE, numerous POI shifts are observed, primarily due to the cross-referencing of airspeed displayed on the primary instrument cluster and external cues that are utilised to maintain an optimal approach to the hover point, considering lateral and longitudinal positioning as well as altitude. Once the pilot transitions into the hover point, the visual focus shifts almost exclusively to the hover board cue directly in front of them, allowing the detection of minor positional deviations indicated by the hover board setup. This enables the pilot to execute immediate corrective control inputs, ensuring precise closed-loop position control. Consequently, $\bar{A}_{\alpha,R}$ during the critical hover sub-phase is characterised by a very low number of POI shifts, indicating a high degree of visual focus.

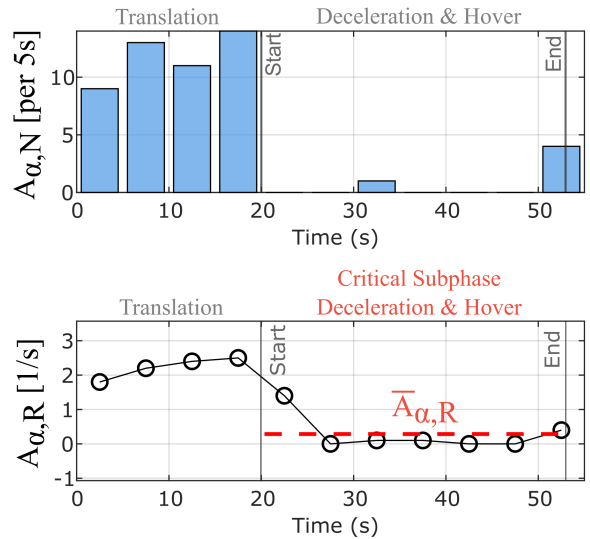


Figure 3. Visual Attack Number $A_{\alpha,N}$, Visual Attack Activity Rate $A_{\alpha,R}$ and Critical Mean Visual Attack Activity Rate during the critical sub-phase $\bar{A}_{\alpha,R}$ over a Hover MTE run.

Eye-Specific Weighting The eye-tracking device separately records the gaze angles for the Left Eye (LE), $\alpha_{total,LE}$, and the Right Eye (RE), $\alpha_{total,RE}$. While averaging the data streams from both eyes could provide a combined gaze angle α_{total} , this approach assumes identical behavior between the left and right eyes, which may not necessarily be the case. For example, a shift of the visual focus from the left to the right hemisphere can already mean a difference in the gaze movement of the individual eyes. To account for potential differences, this analysis treats the two eye channels independently.

A weighted-adaptive formulation, originally proposed by (Ref. 3) for control channels, is adapted to weight the

individual eye channels based on their respective contributions to the total Visual Attacks. The weighting factor for each eye - LE and RE - is defined as $A_{\alpha,N,i}/A_{\alpha,N,Tot}$, where $A_{\alpha,N,i}$ represents the Visual Attacks for eye i (LE or RE), and $A_{\alpha,N,Tot}$ is the total Visual Attack Number across both eyes. The combined, weighted-adaptive metric, $A_{\alpha,R}$, is then computed as:

$$A_{\alpha,R} = \sum_{i \in \{LE, RE\}} A_{\alpha,R,i} \cdot \frac{A_{\alpha,N,i}}{A_{\alpha,N,Tot}} \quad (1)$$

Although significant differences between the left and right eye gaze angles are not typically expected, this formulation ensures that any discrepancies are captured and appropriately weighted in the analysis.

Standardisation In this study, a comparative analysis of pilots' gaze behavior is conducted using standardisation techniques. By applying z-scoring to each pilot's $\bar{A}_{\alpha,R}$ metric, the data are transformed into a common scale, adjusting for differences in means and variances across individual data sets (Ref. 22). This allows relative performance comparisons without the influence of inherent variability within each pilot's data. The z-score represents the number of standard deviations an observed value deviates from the dataset's mean, with positive and negative scores indicating values above and below the mean, respectively.

The standard score, or z-score, is calculated by subtracting the mean μ from a raw score and dividing it by the standard deviation σ , a process known as standardisation. Applying this standardisation procedure to the data-set of $\bar{A}_{\alpha,R}$, will be denoted as $z(\bar{A}_{\alpha,R})$:

$$z(\bar{A}_{\alpha,R}) = \frac{\bar{A}_{\alpha,R} - \mu(\bar{A}_{\alpha,R})}{\sigma(\bar{A}_{\alpha,R})} \quad (2)$$

Normalisation and Visual Action To enable meaningful comparisons across pilots, an additional normalisation procedure is applied to the metric $\bar{A}_{\alpha,R}$. The metric is based on z-scoring each pilot's dataset individually. This transformation centers the data around zero and expresses deviations in units of each pilot's standard deviation. However, since each data-set is pilot-specific, differences in individual gaze compensation strategies, bio-mechanical characteristics, and subjective interpretation of the task result in varying mean values across pilots.

To account for these inter-pilot offsets, an individualised baseline reference is defined by identifying a HQR value on the Cooper-Harper scale that serves as a common anchor point. The authors select a rating of HQR = 4 for this purpose, as it represents a transitional region between Level 1 and Level 2 handling qualities (Ref. 19). This point is considered the most reliable rating value

across pilots: a downward misrating (e.g., HQR = 5 despite good performance) is unlikely due to task performance objectively being either desired or adequate. Upward misratings are mitigated by the clear distinction in compensation levels between HQR = 3 and HQR = 4. It is assumed that well-trained experimental pilots are capable of reliably identifying this transition.

For each pilot, the average value of $z(\bar{A}_{\alpha,R})$ across all trials rated as HQR = 4 is computed and denoted as $\bar{z}_{HQR=4}(\bar{A}_{\alpha,R})$. The pilot-specific offset is then defined as:

$$\Lambda_V = z(\bar{A}_{\alpha,R}) - \bar{z}_{HQR=4}(\bar{A}_{\alpha,R}) \quad (3)$$

The Λ_V metric will be referred to as the *Visual Action* from here on out, and represents the gaze-derived compensation effort relative to the HQR = 4 anchor point.

The subtraction of the pilot-specific HQR = 4 baseline offset in the calculation of Λ_V preserves the standard deviation of the data, ensuring that the axis remains interpretable in terms of standard deviations. Consequently, Λ_V values represent standardised deviations relative to each pilot's HQR = 4 baseline. The resulting Λ_V metric is expressed in units of each pilot's individual standard deviation, with the HQR = 4 performance centered at zero. For example, a $\Lambda_V = +1$ indicates that a pilot's gaze activity is one standard deviation above their HQR = 4 baseline, reflecting increased Visual Activity, while a $\Lambda_V = -1$ indicates one standard deviation below, suggesting reduced Visual Activity. When plotting Λ_V values for multiple pilots on a single x-axis, each pilot's Λ_V remains tied to their individual standard deviation, not a global standard. The x-axis provides a common scale in terms of standard deviations relative to each pilot's HQR = 4 baseline, but the magnitude of a standard deviation varies across pilots due to differences in their gaze behavior variability. This approach enables relative comparisons of visual effort across pilots while preserving the unique characteristics of their individual data distributions.

A critical caveat in computing Λ_V is the requirement of at least one trial rated as HQR = 4 to establish a pilot-specific baseline. While measurements from both high- and low-activity tasks are not necessary, the absence of an HQR = 4 rating prevents the normalisation of a pilot's gaze activity data under the presented method.

The following outlines the defined visual metrics and their interrelationships:

1. Visual Attack Number $A_{\alpha,N}$: the total number of times that the pilot shifts the gaze within a given time frame where the change in gaze angle magnitude is higher than a specified gaze angle threshold value.

2. Visual Attack Activity Rate $A_{\alpha,R}$: the ratio of $A_{\alpha,N}$ to a given time interval. It can be defined as the instantaneous ‘busyness’ metric.
3. Critical Mean Visual Attack Activity Rate $\bar{A}_{\alpha,R}$: the mean value of $A_{\alpha,R}$ during the critical sub-phase of the MTE.
4. Visual Action Δ_V : Standardised and Normalised Critical Mean Visual Attack Activity Rate ($\bar{A}_{\alpha,R}$) relative to the HQR = 4 anchor point. A measurement for deviations of Visual Activity from HQR = 4-rated conditions.

STUDY DESIGN

Simulator Facility

The simulator study was conducted at the Air Vehicle Simulator (AVES), which is DLR’s research flight simulation facility in Braunschweig (Ref. 23). The cockpits, which are replicas of e.g. the A320 ATRA, the EC135 Active Control Technology/Flying Helicopter Simulator (ACT/FHS) or a generic single aisle passenger cabin, are interchangeable via a roll-on/roll-off system. For the ACT/FHS replica the Field-of-View (FoV) is about -53° to 40° vertically and 240° horizontally. The total resolution was measured to be at least 4.9 arc-min/OLP with a resolution per projector about 2560×1600 px. In total nine projectors of the type Barco FL40 MKII were installed. The brightness of the projection system is about 35 cd/m^2 and the contrast ratio is about 9:1. According to the requirements for helicopter full flight simulators by (Ref. 24), a Level-D certification of AVES would be possible. Especially the FoV is far above the certification requirements of 176° horizontally and 56° vertically. No motion simulation was used for the simulator study. The helicopter cockpit at AVES, which was used for the simulator test series, is a replica of DLR’s research helicopter ACT/FHS and is further described in (Ref. 25). It is a highly modified EC135 that features a full authority fly-by-wire/fly-by-light flight control system, which offers the opportunity for in-flight simulation. All flight test data are stored at the experimental system that is duplicated at AVES. During the simulator study the real time non-linear helicopter model HeliWorX was used to calculate the helicopter flight dynamics. It is based on the helicopter model SIMH (Ref. 26) and has been adapted to represent the ACT/FHS that is further described by (Ref. 27).

Test matrix

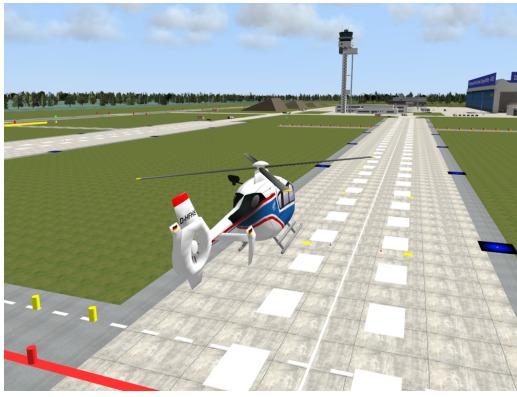
Based on the anticipated influence of visual dynamics on pilot ratings, a series of ADS-33E MTEs have been specifically selected for the piloted study to encompass a wide range of eye dynamics. The detailed task descriptions can be found in the Appendix and in (Ref. 20).

The chosen tasks aim to address various aspects of visual cueing associated with piloting performance:

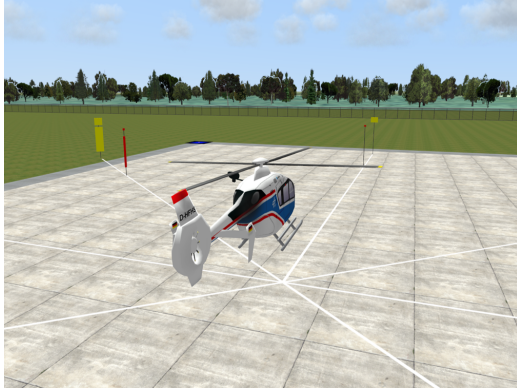
- **Hover:** This task focuses on executing a precision hover, requiring pilots to concentrate on a few small visual cues to obtain the required information to maintain positional accuracy. The objective is to verify the ability to transition from translational flight to a precise, stabilised hover and maintain position, heading, and altitude.
- **Acceleration/Deceleration:** This task emphasises high vertical eye movements where pilots must effectively manage changes in speed while maintaining vehicle control. The high expected vertical eye movements arise by the pilot being forced to check the airspeed in the primary flight display, while simultaneously having to monitor the outside surroundings during high pitch angle attitudes. The objective is to verify pitch and heave axis handling qualities for aggressive maneuvering near rotorcraft performance limits, ensuring minimal longitudinal/lateral-directional axis coupling, harmony between heave and pitch controllers, adequate rotor response to aggressive collective inputs, and simple power management requirements.
- **Slalom:** This task addresses high lateral eye movements, requiring pilots to navigate through a series of alternating lateral gates, thereby testing the dynamic situational awareness and control responsiveness. The objective is to verify the ability to maneuver aggressively in forward flight relative to ground objects, ensure proper turn coordination, and check for objectionable inter-axis coupling during moderately aggressive forward flight maneuvers.
- **Pirouette:** This task evaluates a pilot’s ability to achieve simultaneous precision control of the vehicle across all axes, integrating both lateral and vertical eye movements. The objective is to verify precise simultaneous control of the rotorcraft in pitch, roll, yaw, and heave axes, ensuring accurate control.

Together, these tasks comprehensively cover a variety of eye dynamics, ensuring that both specific and combined cueing areas are effectively represented in the study. For all selected MTEs, the performance limitations refer to the Cargo/Utility Aircraft category with conditions for Good Visual Environment (GVE) (clear daylight & adequate visual cues) and no-wind. The visualisation of the MTEs according to the test course description shown in the Figures 14 to 17 at AVES facility is shown in Figure 4.

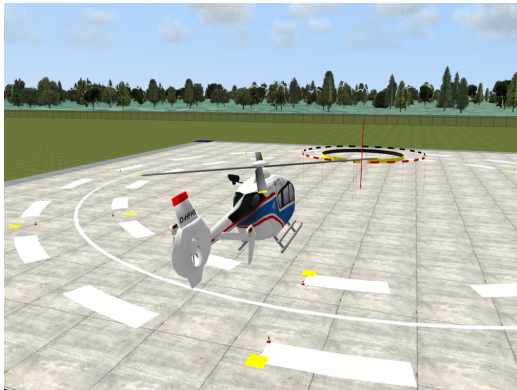
Three different basic controller modes were used for the simulator study as shown in the test matrix in



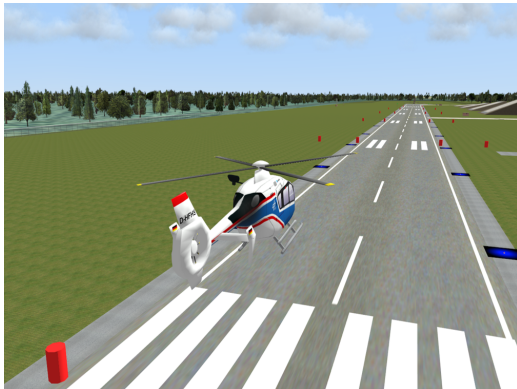
(a) Accel/Decel MTE



(b) Hover MTE



(c) Pirouette MTE



(d) Slalom MTE

Figure 4. MTE Visualisation at AVES facility

Table 1. Test Matrix of the Simulator Study

MTE	ACAH	RCAH	TRC
Hover	X		X
Pirouette	X		X
Slalom	X	X	
Accel/Decel	X	X	

Table 1: Attitude Command, Attitude Hold (ACAH), Rate Command, Attitude Hold (RCAH) and Translational Rate Command (TRC). These controllers are briefly described in the following section. A detailed description of the controller structures can be found in (Ref. 28).

In ACAH command mode, the deflection of the longitudinal and lateral sticks directly corresponds to the aircraft's pitch and roll attitudes. The pedals control yaw rate, incorporating a Direction Hold (DH) feature. Meanwhile, the collective stick commands vertical speed, working in conjunction with a Height Hold (HH) function.

In RCAH mode, the helicopter responds similarly to direct mode. The control inputs for the longitudinal and lateral axes are directly proportional to the commanded angular rates. Yaw rate is controlled through the pedals, while vertical speed is controlled through the collective axis.

The TRC mode allows the stick deflections to be proportional to the aircraft's longitudinal and lateral velocities. Pedals control yaw rate and collective axis control vertical speed, both incorporating a DH and a HH, respectively.

Pilots

Table 2. Pilot Experience

Pilot	A	B	C
Pilot license (years)	28	32	28
Test pilot (y/n)	y	y	y
Flight hours, total	2900	4000	3000

Three military pilots of the Wehrtechnische Dienststelle WTD 61 took part in the simulator study (see Table 2). All pilots are well-trained experimental test pilots (flight hours above 1000 h) and are therefore very familiar with research flight tests including MTEs and the subjective rating techniques. At least all pilots are familiar with the helicopter type EC135 (flight hours below 1000 h).

The pilots repeated each test point at least three times. Only when the pilots were convinced that they had achieved the best possible reproducible performance, a hot run was carried out. This was used as the basis for the subsequent handling quality assessment. The pilots completed the study alternately in several runs. Test points were selected at random. Each run lasted a maximum of 2 hours.

Eye Tracking Device



Figure 5. Headworn Eye Tracker Pro Glasses 3 by Tobii

Eye Tracker Pro Glasses 3 by Tobii (see Figure 5) were used to record the pilots' eye movements. They consist of a body-worn recording unit, that is not depicted, and the glasses themselves. For the eye movement recording Tobii uses an improved Pupil Centre Corneal Reflection (PCCR) (Ref. 29) eye tracking technique. The pilot's eyes are illuminated by 16 infrared illuminators and recorded by 4 infrared cameras in a stereo geometry, dark pupil tracking process. In combination with the scene camera the glasses cover a FoV of about 106° diagonal and 95° horizontal with a sampling rate of 50 Hz and an accuracy of 0.6° according to general information of the manufacturer (Ref. 30). According to Onkhar et al. (Ref. 31) the angular resolution of the Tobii Pro Glasses 3 is at least worse than 1.2°. However, the authors cited numerous differences in the experimental setup compared to the test report by Tobii that may have led to a degradation of their results.

The eye movement data was further processed using a Matlab routine developed in-house. First, the total gaze angle α_{total} was calculated separately for the left and the right eye with one of the direction vectors $\vec{v}_{dir}$ and the corresponding reference vector $\vec{u}_{ref,total}$ using equation 4. The total angle α_{total} results from the arc-cosine of the scalar product of the two vectors divided by the product of the magnitudes of the two vectors. In addition, equations 5 and 6 were used to calculate the vertical and horizontal gaze angles α_{vert} and α_{hor} . The calculation of the two gaze angles α_{vert} and α_{hor} is comparable to the total gaze angle α_{total} , whereby the arc-sine is calculated instead of the arc-cosine so that the two angles α_{vert} and α_{hor} are equal to 0° when the direction vector $\vec{v}_{dir}$ is aligned with the z-axis.

$$\alpha_{total} = \arccos \left(\frac{\vec{v}_{dir} \cdot \vec{u}_{ref,total}}{|\vec{v}_{dir}| \cdot |\vec{u}_{ref,total}|} \right) \quad (4)$$

$$\alpha_{vert} = \arcsin \left(\frac{\vec{v}_{dir} \cdot \vec{u}_{ref,vert}}{|\vec{v}_{dir}| \cdot |\vec{u}_{ref,vert}|} \right) \quad (5)$$

$$\alpha_{hor} = \arcsin \left(\frac{\vec{v}_{dir} \cdot \vec{u}_{ref,hor}}{|\vec{v}_{dir}| \cdot |\vec{u}_{ref,hor}|} \right) \quad (6)$$

$$\vec{u}_{ref,total} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad \vec{u}_{ref,vert} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \quad \vec{u}_{ref,hor} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad (7)$$

Missing data points, such as blinks or corrupted data points, were linearly interpolated to obtain a continuous data set. The data was smoothed using the moving median method (window size = 3) and derived to obtain the total gaze rate $\dot{\alpha}$. The pre-processed data was then used to determine the Visual Action Λ_V .

RESULTS

The results of the study are presented in the following section. Since points can be missing in the data set not only due to blinks but also due to incorrect calibration or problems with the infrared-based measurement methodology of the eye tracker, the valid data points for the left and right eye were determined first. Table 3 shows the valid data points of the respective pilot averaged over all test points. On average, between 89% and 99% of all gaze points were recorded. As a measure of data quality, this is rated as good, so that the missing sample points can be interpolated.

Table 3. Valid Eye Tracking Samples

Pilot	Left Eye, Mean	Right Eye, Mean
A	89.1%	94.6%
B	96.3%	99.0%
C	98.9%	98.1%
Total	94.8%	97.3%

The sequence diagrams in Figures 6 to 9 show the temporal course of the eye movements for the respective MTEs of Pilot A. The different flight phases were emphasised, all significant AOIs were differentiated and a distinction was made between Out-the-window (OTW) and Inside-the-Cockpit (ITC) gaze points. The OTW AOIs have been highlighted in the Figures 14 to 17.

During the Hover MTE, the pilot only looked ITC during the translation in order to determine the ground speed on the Primary Flight Display (PFD) (see Figure 6). The ground speed is a limit of the Hover MTE. Between the translation and hover flight phases, the pilot increasingly shifts his attention from the right target to the front target. During the deceleration, a single fixed point in the environment was recorded, with the pilot using a tree behind the hover board as a visual reference.

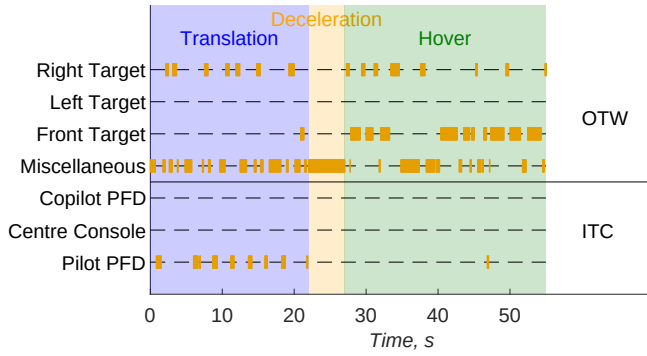


Figure 6. Sequence Diagram of Pilot A during Hover MTE with ACAH

No viewpoints within the cockpit were recorded during the Pirouette MTE (see Figure 7). In the flight phase Pirouette, the pilot constantly switches between the front target and the ground marks. Similar to the Hover MTE, a fixed reference point can be observed during deceleration. In this case, the pilot used the front target. The pilot showed similar behaviour during the final hover phase, when a fixed point slightly below the hover board on the concrete surface as a visual reference was used.

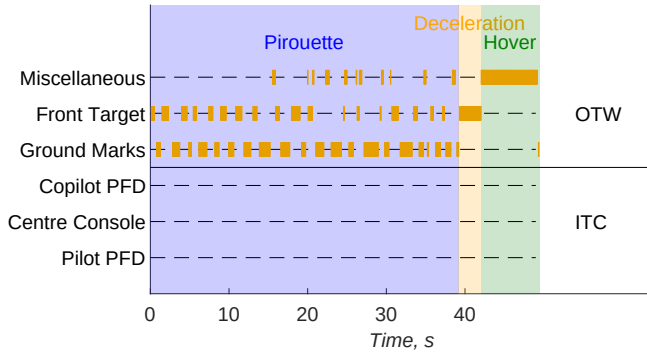


Figure 7. Sequence Diagram of Pilot A during Pirouette MTE with ACAH

During Accel/Decel MTE, the pilot used the instruments ITC a few times during acceleration to check whether the required pitch attitude had been reached (see Figure 8). In addition, the pilot mainly looked at the ground marks. During deceleration, the pilot increasingly looked at objects in the vicinity to check the longitudinal position of the helicopter and not to exceed the holding line.

During the Slalom MTE, the pilot mainly switched between the gates, which had to be passed, and the instruments ITC (see Figure 9). Here it was again necessary to check whether the required speed could be maintained. Towards the end of the MTE, the pilot used objects in the vicinity, as there were no more gates that the pilot could have used as a reference.

The gaze behaviour of Pilot A is qualitatively transferable to Pilot B and Pilot C. Summarised for all pilots and

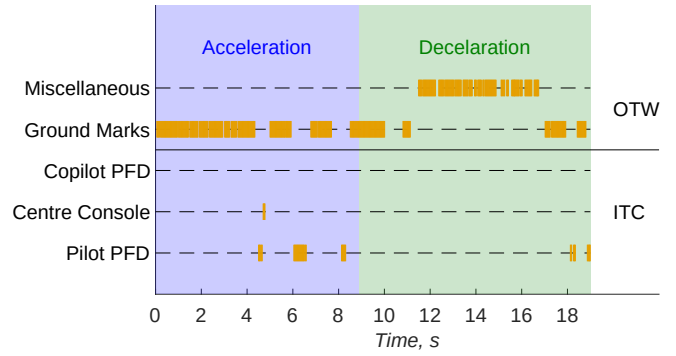


Figure 8. Sequence Diagram of Pilot A during Accel/Decel MTE with ACAH

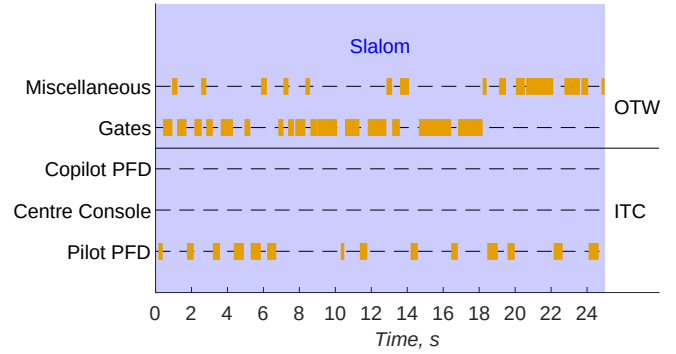


Figure 9. Sequence Diagram of Pilot A during Slalom MTE with ACAH

all test points, information from ITC is rarely used. On average, the pilots looked ITC for 4.6% of the entire duration of the test. The maximum ratio between ITC and OTW gaze points was 26.2%. The standard deviation is 6.5% and is therefore rated as low.

After each test point, the pilots submitted a HQR and indicated the most critical flight phase for which the HQR applies. The comments provided by the pilots are consistent to the extent that the critical flight phase can be defined for each MTE. These critical sub-phases are listed in Table 4 and are used to calculate the Visual Action or the Visual Activity Rate.

Table 4. Critical Sub-phases of the MTEs

MTE	Critical Sub-phase
Hover	Deceleration & Hover
Pirouette	Deceleration & Hover
Slalom	Complete
Accel/Decel	Deceleration

To determine the Visual Attack Number $A_{\alpha, N}$, it is necessary to identify all intentional changes between different POIs. The threshold value α_{lim} required for this is determined empirically using the present data set, in which the correlation between the HQRs and the Visual Ac-

tion Δ_V is determined for different threshold values α_{lim} . These threshold values were systematically varied and the results were presented in Figure 10 using the coefficient of determination R^2 and the Pearson correlation PCC. Assuming that the previous effort that a pilot had to make has an influence on the effort at the current point in time, the influence of smoothing the Visual Attack Number $A_{\alpha,N}$ using a moving average including different window sizes and weighting functions was investigated. In addition to the results for the un-smoothed raw data, Figure 10 also shows the results of the data smoothed with the moving average. Different weighting functions (simple, quadratic, exponential, linear) and window sizes between 2 and 5 were considered. In addition to the raw data, Figure 10 also shows the results for the individual weighting methods with the best window size in each case. As can be seen, a better correlation can generally be achieved by using the moving average compared to the un-smoothed raw data. The influence of the different weighting methods and window sizes is rated as low here. The best results were achieved with a simple weighting with window size 2 at a threshold value of $\alpha_{lim} = 6.58^\circ$. This is used in the following to determine the Visual Attack Number $A_{\alpha,N}$. It should be emphasised that there are similarly good correlations in a range between $5^\circ \leq \alpha_{lim} \leq 9^\circ$. The authors therefore assume a robust solution for the empirically determined threshold value α_{lim} .

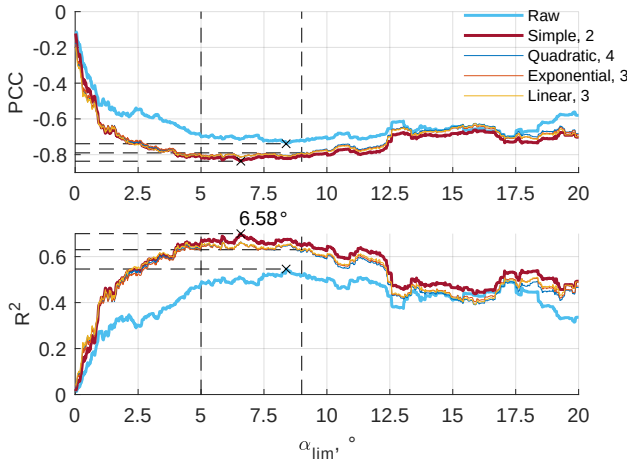


Figure 10. Comparison of coefficients R^2 and PCC across different thresholds α_{lim} for raw and smoothed data

Figure 11 shows the HQR given by the pilots via the Visual Action Δ_V . All test points with $HQR \geq 7$ were discarded, as by definition the pilot compensation is only used to maintain a safe flight condition and not for the successful and best possible execution of the flight task. The critical limit described in the introduction, which the pilot compensation performance must not exceed, is therefore assumed to be exceeded here. The data

recorded in this study suggest a linear relationship between the HQR and the Visual Action Δ_V with a correlation of $R^2 = 0.70$ and $PCC = -0.84$. The regression line was fitted using ordinary least squares, which minimizes the sum of squared residuals to model the relationship between HQR values and Δ_V . The fundamental nature of this relationship shows an increase in Visual Action with a lower HQR. Accordingly, the Visual Action is low when the required pilot compensation is high, whereas the Visual Action is high when the pilot compensation is low. The distribution of the test points is not MTE specific.

Although the Visual Action metric has been normalised using the mean values of HQR = 4 rated runs for each pilot, a considerable spread remains within the HQR = 4 group, with Δ_V values ranging approximately between ± 1 . This suggests that pilots tolerate a significant range of Visual Action while still assigning an HQR = 4 (moderate compensation), indicating a transition region between minimal pilot compensation and considerable pilot compensation. Conceptually this means that an individual pilot tolerates a variation of $\pm 1\sigma$ of individual standard deviations in Visual Action to still be considered moderate pilot compensation effort.

Excursions below $\Delta_V \leq -1$ are associated with a clear increase in perceived compensation effort (considerable), as expected during the transition into Adequate task performance. Conversely, values of $\Delta_V \geq 1$ correspond to noticeably reduced compensation efforts (minimal), resulting in the associated Level 1 ratings. The selection of the HQR = 4 anchor point appears to be appropriate, as only one data point within the $\Delta_V = \pm 1$ range did not receive the corresponding rating. This outlier occurred for Pilot A during the Accel/Decel MTE task under the ACAH configuration.

For the comparison with HQR, the total gaze angle α_{total} was used to determine the Visual Action Δ_V . In order to describe the gaze behaviour of the pilots in more detail, the vertical and horizontal gaze movements are now considered. To evaluate possible differences between the MTEs and the pilots, the horizontal and vertical gaze movements are specified as the Visual Activity Rate. Figures 12 and 13 show the vertical over the horizontal Mean Visual Activity Rate. In Figure 12, all test points of an MTE are summarised by an enveloping ellipse, whereas in Figure 13 all test points of a pilot are described by an enveloping ellipse. In general, the Mean Visual Activity Rate in the vertical direction is usually greater than in the horizontal direction.

For the Hover MTE and the Pirouette MTE, the ratio between the horizontal and vertical Mean Visual Activity is similar, so that the vertical Mean Visual Activity is around 1.5 times greater. However, a higher vertical Mean Visual Activity Rate was measured for the Hover MTE, which at around 1.8 s^{-1} was approximately twice as high as that of the Pirouette MTE. Similar flight phases were

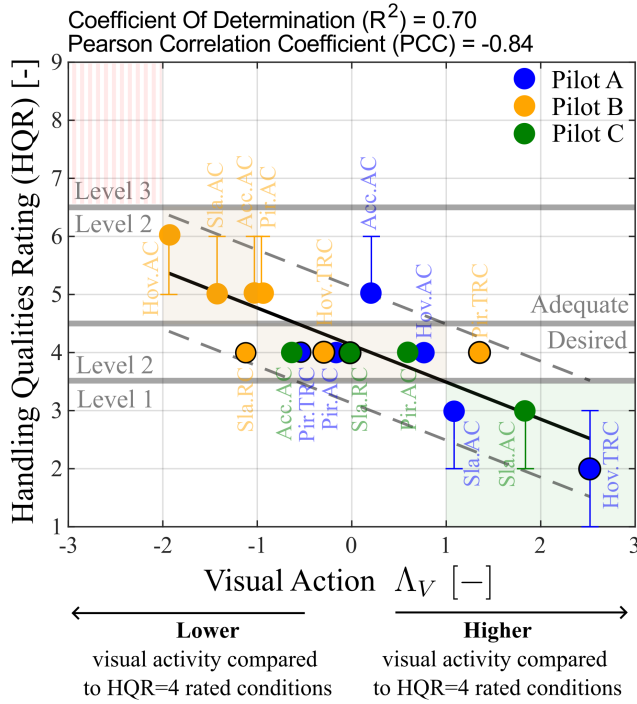


Figure 11. Visual Action over HQR for all Test Points and Pilots. Error bars, representing the expected rating error of ± 1 HQR are provided, given there is no crossing of HQ levels or task performance thresholds.

analysed for both MTEs with the deceleration and hover flight phase. The highest horizontal Mean Visual Activity Rate was measured for the Slalom MTE at around 1.5 s^{-1} . In general, no major differences between the MTEs were found. The overlapping areas of all ellipses for the respective MTEs are large.

When looking at the pilot-specific representation in Figure 13, the horizontal and vertical Mean Visual Activity Rate can be used to describe a certain pilot gaze behaviour. Pilot B shows the lowest Mean Visual Activity Rate of all pilots. Regardless of the MTEs, all test points of Pilot B lie in a range between 0.5 s^{-1} horizontal and 0.9 s^{-1} vertical. Pilot C has a slightly higher vertical Mean Visual Activity Rate in comparison. In comparison to Pilots B and C, Pilot A has the greatest Mean Visual Activity Rate in both horizontal and vertical directions. The Mean Visual Activity Rate ranges up to 1.5 s^{-1} horizontally and 1.8 s^{-1} vertically. In addition, the dependency on the MTEs is greatest for Pilot A, as the emphasised area is larger than that of the other pilots.

DISCUSSION

A flight phase-specific distribution of the pilots' attention can be derived from the sequence diagrams. The limits and visual cues of the MTEs define the tasks so precisely that a very specific need for information arises.

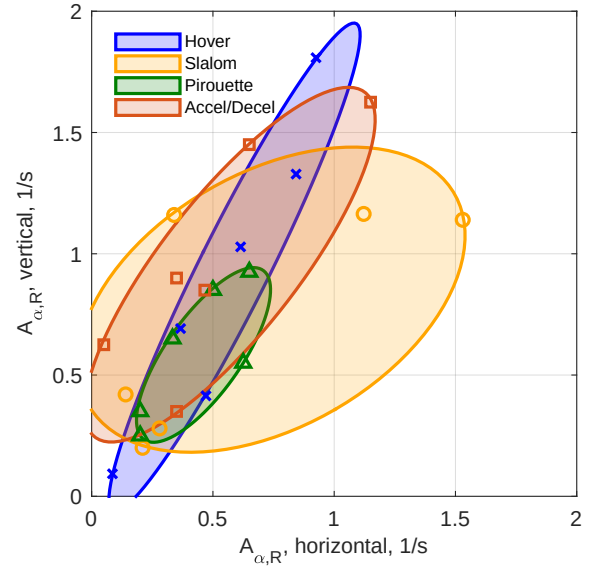


Figure 12. Horizontal over Vertical Mean Visual Activity Rate $A_{\alpha,R}$ for all Test Points summarised according to MTEs

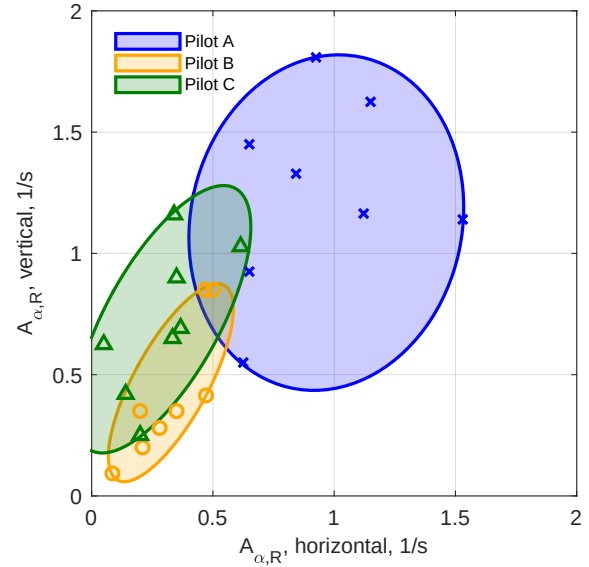


Figure 13. Horizontal over Vertical Mean Visual Activity Rate $A_{\alpha,R}$ for all Test Points summarised according to Pilots

The pilot's receipt of all relevant visual information is essential for successful task performance and achieving the desired level of performance. This leads to a strong correlation between the expected and the recorded distribution of attention. In the case of precisely defined flight manoeuvres, sequence diagrams offer the potential to provide initial indications as to whether a pilot has deviated from an expected distribution of attention and whether it is therefore possible to optimise human-machine interaction e.g. with flight training or pilot assistance systems.

Sequence diagrams use AOIs to visualise a distribution of attention. As just described, it is possible to determine deviations from an ideal distribution of attention using this type of visualisation method. However, prior investigations did not reveal a significant correlation between the frequency of alternation between the AOIs and the HQR. The reason for this lies in the definition of the AOIs. AOIs can be freely selected so that a certain type of information is contained within a single AOI. So, if the pilot looks at an AOI, it can be assumed that precisely this specific information has been retrieved. Each AOI change represents a qualitative shift in visual attention. However, this also means that there is no geometric similarity between AOIs and they can differ greatly depending on the test setup.

The comparison of HQR and Visual Action suggests a strong correlation. This is shown not only by the correlation coefficients, but also by the fact that all points lie within the expected spread of ± 1 rating point. Compared to the results in (Ref. 3), an opposite trend can be observed for gaze behaviour than for control inputs. When pilot compensation is low, the spare capacity is utilised to switch between POIs more frequently, resulting in increased gaze activity. This might indicate a connection between situational awareness and attentional tunnelling, which should be investigated in further studies.

Due to the further development in comparison to (Ref. 3), different pilots can be compared with each other through standardisation. The anchor point at HQR = 4 appears to be very well suited for this, although the pilots certainly have individual gaze behaviour and differ from each other, as it can be seen in Figure 13.

Smoothing the Visual Activity with the moving average method led to a better correlation between HQR and the Visual Action. The method only considers the current and past sample points. Based on a time window of $\Delta t = 5$ seconds to determine the Visual Attack Number $A_{\alpha,N}$ and a window size of 2 to 5 for smoothing Visual Attack Rate $A_{\alpha,R}$ with the moving average method, the influence of a time range of 10 to 25 seconds on the current Visual Action Δ_V was analysed. Accordingly, the improved correlation suggests that pilot compensation efforts within a 25-second time window have an impact on current pilot compensation. Longer past stress states,

which can manifest themselves as fatigue or exhaustion, e.g., were not considered in this study.

The recorded data enable estimation of two threshold values for fixed-seat simulators. The limit between Level 1 and Level 2 (transition between minimal and moderate pilot compensation) is proposed to be a Visual Action of $\Delta_V \approx 1$, whereas the limit between Desired and Adequate performance (transition between moderate and considerable pilot compensation) is proposed to be a Visual Action of $\Delta_V \approx -1$. For the Control Attack Activity Rate, it could be shown in (Ref. 3) that there is a correlation to HQR not only in the fixed-seat simulator but also in real helicopter flight. However, differences were found between the real helicopter flight and the simulator with regard to the specified limits between Level 1 and Level 2. It is therefore essential to check whether a similar correlation also exists for the Visual Action Δ_V for the motion simulation and the real helicopter flight and whether the estimated limits also exist or need to be adjusted.

CONCLUSION & FUTURE WORK

In this paper, a piloted study was conducted in the simulator, whereby the influence of different flight dynamics on the pilots' gaze behaviour was investigated for 4 different MTEs and 3 different flight controllers. In addition, a new evaluation method, namely the Visual Action Δ_V , was derived and applied.

The following conclusions can be drawn:

- A flight phase-dependent gaze behaviour could be identified based on the attention distribution of the pilots. A visualisation using a sequence diagram was helpful for this. No further dependencies between flight dynamics and gaze behaviour were identified in this study.
- For the majority of the observed test points, the vertical Visual Activity was greater than the horizontal Visual Activity. In addition, pilot-specific gaze behaviour could be attributed to the pilots based on their horizontal and vertical Visual Activity.
- The recorded eye tracking data suggest a strong correlation ($R^2 = 0.70$, $PCC = -0.84$) between Visual Action Δ_V and the HQR given by the pilot. Thus, helicopter pilots react to a change in the required pilot compensation by also adjusting their gaze behaviour.
- The study suggests that the correlation already found between helicopter pilots' control inputs and HQR can be transferred to gaze behaviour. The method was further developed through standardisation and normalisation so that a comparison between pilots with different gaze behaviour is still possible.

- The correlation between the Visual Action and the HQR shows no dependency between the different MTEs. The Visual Action therefore represents a measure of pilot compensation independent of different flight dynamics.

At this point in time, the paper provides an initial approach with the Visual Action method regarding a correlation between the pilots' gaze activity and compensation performance. In order to further develop this method into a metric and, e.g., to confirm the threshold values for Level 1 and Level 2 or α_{lim} defined here, further data is required. In addition, other possible correlations must first be investigated in order to make the method more reliable. These include possible influences of good and poor visibility conditions on visual activity, as well as differences between a fixed-based simulator, the motion simulation and real helicopter flight. Further studies should examine whether the approach presented here can be generalised and whether similar correlations can be established wherever human-machine interactions occur in a cockpit, such as in a car, train or aircraft.

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REFERENCES

1. G.D. Padfield. Rotorcraft handling qualities engineering: Managing the tension between safety and performance. *Journal of the American Helicopter Society*, 58(1):1–27, 2013.
2. G. E. Cooper and R. P. Harper. The use of pilot rating in the evaluation of aircraft handling qualities, 1969. Technical Note NASA-TN-D-5153, Advisory Group for Aerospace Research & Development, North Atlantic Treaty Organization, Rue Ancelle, France, April 1969.
3. W. A. Memon, M. D. White, G. D. Padfield, N. Cameron, and L. Lu. Helicopter handling qualities: A study in pilot control compensation. *The Aeronautical Journal*, 126(1295):152–186, 2022.
4. M.G. Glaholt. Eye tracking in the cockpit: a review of the relationships between eye movements and the aviator's cognitive state, 2014. Technical Report DRDC-RDDC-2014-R153, Defence Research and Development Canada - Toronto Research Centre, Toronto, December 2014.
5. K. Holmqvist, M. Nyström, R. Andersson, R. Dewhurst, H. Jarodzka, and J. de van Weijer. *Eye tracking: A comprehensive guide to methods and measures*. Oxford University Press, Oxford, New York, Auckland, 2011.
6. M. Akamatsu, M. Okuwa, M. Funakawa, M. Kitajima, M. Onuki, Q. Life, and M.P. Co. Whole-view driving simulator for measuring driving behavior in town environment, 2001. Paper presented at DSC 2001: Driving Simulation Conference, Sophia Antipolis (Nice), France, September 2001.
7. B. Kapitaniak, M. Walczak, M. Kosobudzki, Z. Jóźwiak, and A. Bortkiewicz. Application of eye-tracking in the testing of drivers: A review of research. *International journal of occupational medicine and environmental health*, 28(6):941–954, 2015.
8. R. Madlenak, J. Masek, L. Madlenakova, and R. Chino-racky. Eye-tracking investigation of the train driver's: A case study. *Applied Sciences*, 13(4):2437, 2023.
9. P. Wegrzyn, M. Kepski, and I. Grabska-Gradzińska. Eye tracking measurement of train drivers' attention based on quasi-static areas of interest. In José Manuel Ferrández Vicente, José Ramón Álvarez-Sánchez, Félix de La Paz López, and Hojjat Adeli, editors, *Bio-inspired Systems and Applications: from Robotics to Ambient Intelligence*, volume 13259, pages 3–12, Cham, 2022. Springer International Publishing.
10. M.-J. Maibach, D.H. Greiwe, and M. Müllhäuser. Helicopter in-flight eye tracking: System integration aspects and first results, 2023. Paper presented at Vertical Flight Society International 79th Annual Forum & Technology Display, West Palm Beach, Florida, 16–18 May 2023.
11. C.E. Kirby, Q. Kennedy, and J.H. Yang. Helicopter pilot scan techniques during low-altitude high-speed flight. *Aviation, space, and environmental medicine*, 85(7):740–744, 2014.
12. M. Robinski and M. Stein. Tracking visual scanning techniques in training simulation for helicopter landing. *Journal of Eye Movement Research*, 6(2):1–17, 2013.
13. G. Rainieri, F. Fraboni, G. Russo, M. Tul, A. Pingitore, A. Tessari, and L. Pietrantoni. Visual scanning techniques and mental workload of helicopter pilots during simulated flight. *Aerospace medicine and human performance*, 92(1):11–19, 2021.
14. M.-J. Maibach. In-flight evaluation of pilot gaze patterns during ship deck landings, 2024. Paper presented at 50th European Rotorcraft Forum, Marseille, France, 9–11 September 2024.
15. D.H. Greiwe and M. Friedrich. A comparison of helicopter pilots' gaze movements during hover flight in a real helicopter and a full flight simulator, 2022. Paper presented at 72nd Deutscher Luft- und Raumfahrtkongress, Stuttgart, Germany, 19–21 September 2023.
16. A. Kalra and D.H. Greiwe. Impact of control augmentation on pilot workload during shipboard helicopter hover operation, 2025. Paper to be presented at 51th European Rotorcraft Forum, Venice, Italy, 9–12 September 2025.

17. S.O. Schmidt, D.H. Greiwe, and T. Jusko. Pilots' gaze behavior during simulated helicopter air-to-air refueling, 2024. Paper presented at Vertical Flight Society International 80th Annual Forum & Technology Display, Montreal, Quebec, Canada, 7–9 May 2024.
18. D.H. Greiwe and M. Friedrich. Gaze movements of helicopter pilots during real and simulated take-off and landing maneuvers. *Aerospace*, 11(6):429, 2024.
19. George E. Cooper and Robert P. Harper. The use of pilot rating in the evaluation of aircraft handling qualities. Technical Report NASA TN D-5153, National Aeronautics and Space Administration, Washington, D.C., April 1969.
20. Anon. Ads-33e-prf aeronautical design standard, performance specification, handling qualities requirements for military rotorcraft.
21. G. D. Padfield, G. Clark, and A. Taghizad. How long do pilots look forward? prospective visual guidance in terrain-hugging flight. 52:134–145.
22. William M. Mendenhall and Terry L. Sincich. *Statistics for Engineering and the Sciences, Sixth Edition*. Taylor & Francis.
23. H. Duda, S.K. Advani, and M. Potter. Design of the dlr aves research flight simulator, 2013. Paper presented at the AIAA Modeling and Simulation Technologies Conference, Boston, Massachusetts, 19–22 August 2013.
24. European Union Aviation Safety Agency. Certification specifications for helicopter flight simulation training devices, 2012.
25. J. Kaletka, H. Kurscheid, and U. Butter. Fhs, the new research helicopter: Ready for service. *Aerospace Science and Technology*, 9(5):456–467, 2005.
26. M. Rohlfs, W. von Grünhagen, and J. Kaletka. Nonlinear rotorcraft modeling and identification, 1998. Paper presented at the RTO Systems Concepts and Integration Panel (SCI) Symposium, Madrid, Spain, 5–7 May 1998.
27. A. Štrbac, T. Martini, D.H. Greiwe, F. Hoffmann, and M. Jones. Analysis of rotorcraft wind turbine wake encounters using piloted simulation. *CEAS Aeronautical Journal*, 12(2):273–290, 2021.
28. A. Kalra, A. Štrbac, and M.-J. Maibach. Evaluation of helicopter ship deck landing control laws in piloted simulations. *Journal of the American Helicopter Society*, 69(1):1–15, 2024.
29. J. Elvesjo, M. Skogo, and G. Elvers. Method and installation for detecting and following an eye and the gaze direction thereof, 2009. U.S. Patent No. 7,572,008.
30. Anon. Tobii pro glasses 3: User manual, 2022.
31. V. Onkhar, D. Dodou, and J. de Winter. Evaluating the tobii pro glasses 2 and 3 in static and dynamic conditions. *Behavior Research Methods*, 2023.
32. T. Schönenberg. Flugeigenschaftskriterien zur hubschraubersteuerung mit aktiven sidesticks (engl.). Dissertation 2012/23, Technische Universität Braunschweig, 2012.

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APPENDIX

This section describes the MTEs used in the study in detail. The subsections “Objectives” , “Description of the maneuver” and “Description of the test course” are direct extracts from ADS-33E-PRF (Ref. 20).

Hover MTE

Objectives. Assess the ability to transition from translating flight to a stabilised hover with precision and reasonable aggressiveness, as well as maintain position, heading, and altitude in moderate wind during GVE and calm winds in Degraded Visual Environment (DVE).

Description of the maneuver. Initiate the maneuver at a ground speed of between 6 and 10 knots, at an altitude less than 20 ft. For rotorcraft carrying external loads, the altitude will have to be adjusted to provide a 10 ft load clearance. The target hover point shall be oriented approximately 45 degrees relative to the heading of the rotorcraft. The target hover point is a repeatable, ground-referenced point from which rotorcraft deviations are measured. The ground track should be such that the rotorcraft will arrive over the target hover point. In the GVE, the maneuver shall be accomplished in calm winds and in moderate winds from the most critical direction. If a critical direction has not been defined, the hover shall be accomplished with the wind blowing directly from the rear of the rotorcraft.

Description of the test course. The suggested test course for this maneuver is shown in Figure 14. Note that the hover altitude depends on the height of the hover sight and the distance between the sight, the hover target, and the rotorcraft. These dimensions may be adjusted to achieve a desired hover altitude.

Performance standards. Detailed performance standards are given in (Ref. 20).

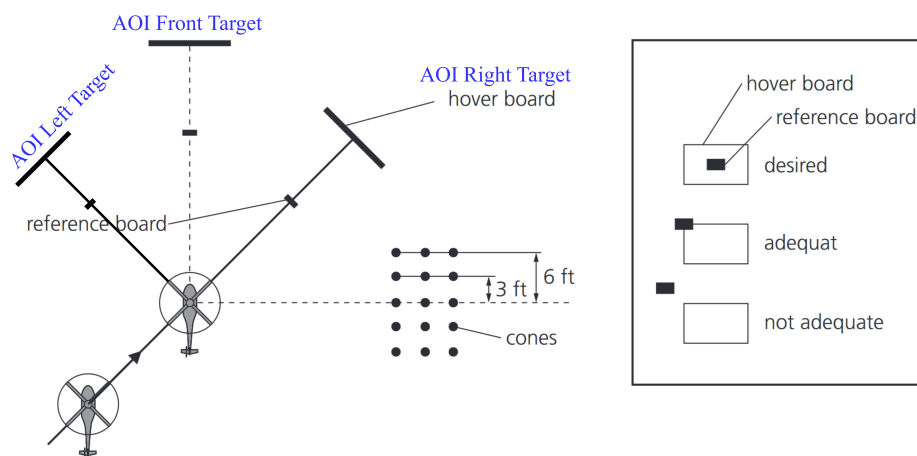


Figure 14. Test course for Hover MTE adapted from (Ref. 32)

Slalom MTE

Objectives. Assess the ability to maneuver aggressively in forward flight relative to ground objects, evaluate turn coordination during moderately aggressive maneuvers, and check for objectionable interaxis coupling in similar conditions.

Description of the maneuver. Initiate the maneuver in level unaccelerated flight and lined up with the centerline of the test course. Perform a series of smooth turns at 500 ft intervals (at least twice to each side of the course). The turns shall be at least 50 ft from the centerline, with a maximum lateral error of 50 ft. The maneuver is to be accomplished below the reference altitude. Complete the maneuver on the centerline, in coordinated straight flight.

Description of the test course. The suggested test course for this maneuver is shown in Figure 15.

Performance standards. Detailed performance standards are given in (Ref. 20).

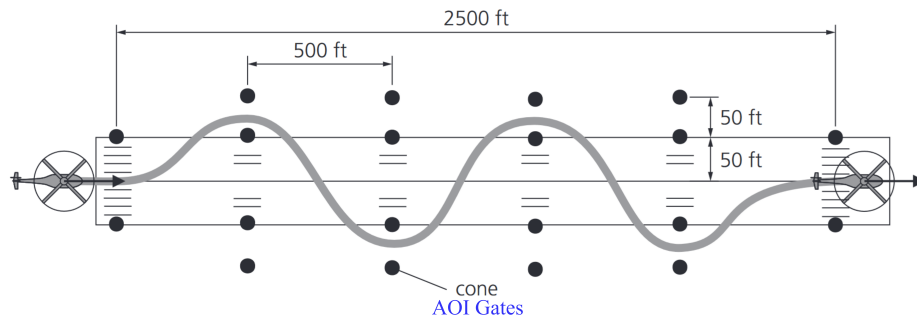


Figure 15. Test course for Slalom MTE adapted from (Ref. 32)

Acceleration/Deceleration MTE

Objectives. Evaluate the handling qualities of pitch and heave axes during aggressive maneuvers, assess coupling between longitudinal and lateral-directional axes, ensure harmony between heave and pitch controllers, verify rotor response to collective inputs, and check for power management complexity.

Description of the maneuver. Start from a stabilised hover. In the GVE, rapidly increase power to approximately maximum, maintain altitude constant with pitch attitude, and hold collective constant during the acceleration to an airspeed of 50 knots. Upon reaching the target airspeed, initiate a deceleration by aggressively reducing the power and holding altitude constant with pitch attitude. The peak nose-up attitude should occur just before reaching the final stabilised hover. In the DVE, accelerate to a groundspeed of at least 50 knots, and immediately decelerate to hover over a defined point. The maximum nose-down attitude should occur immediately after initiating the maneuver, and the peak nose-up attitude should occur just before reaching the final stabilised hover. Complete the maneuver in a stabilised hover for 5 seconds over the reference point at the end of the course.

Description of the test course. The test course shall consist of a reference line on the ground indicating the desired track during the acceleration and deceleration, and markers to denote the starting point and endpoint of the maneuver. The distance from the starting point to the final stabilised hover position is a function of the performance of the rotorcraft, and shall be determined based on trial runs consisting of acceleration to the target airspeed, and decelerations to hover as described above. The course should also include reference lines or markers parallel to the course centerline to allow the pilot and observers to perceive desired and adequate lateral tracking performance. A suggested test course is shown in Figure 16.

Performance standards. Detailed performance standards are given in (Ref. 20).

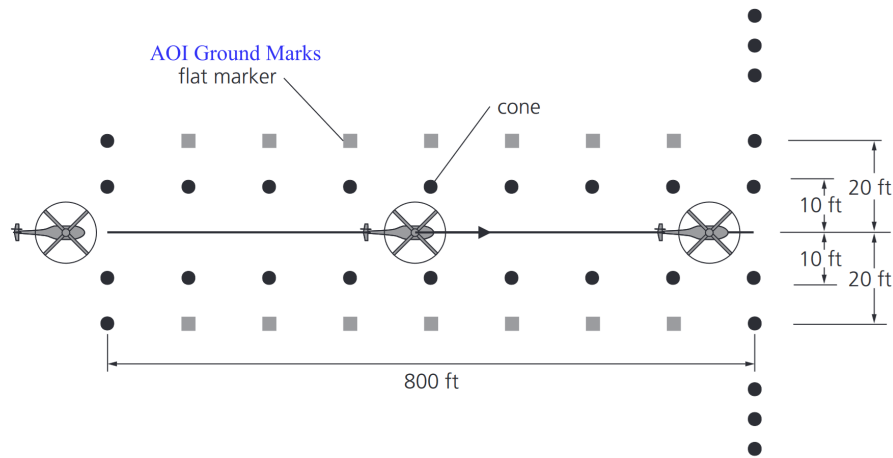


Figure 16. Test course for Acceleration/Deceleration MTE adapted from (Ref. 32)

Pirouette MTE

Objectives. Evaluate the ability to achieve precise control of the rotorcraft in pitch, roll, yaw, and heave axes, manage control during continuously varying moderate winds in GVE, and check for degraded display symbology and dynamics during multi-axis maneuvering in DVE.

Description of the maneuver. Initiate the maneuver from a stabilised hover over a point on the circumference of a 100 ft radius circle with the nose of the rotorcraft pointed at a reference point at the center of the circle, and at a hover altitude of approximately 10 ft. Accomplish a lateral translation around the circle, keeping the nose of rotorcraft pointed at the center of the circle, and the circumference of the circle under a selected point on the rotorcraft. Maintain essentially constant lateral groundspeed throughout the lateral translation (note: nominal lateral velocity will be approximately 8 knots for the 45-sec and 6 knots for the 60-sec time around the circle). Terminate the maneuver with a stabilised hover over the starting point.

Description of the test course. The test course shall consist of markings on the ground that clearly denote the circular pathways that define desired and adequate performance. The suggested test course for this maneuver is shown in Figure 17. It may also be useful to add objects to assist the pilot with vertical cueing, such as a post at the center of the circle.

Performance standards. Detailed performance standards are given in (Ref. 20).

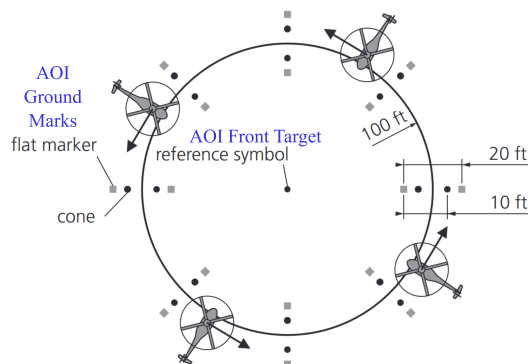


Figure 17. Test course for Pirouette MTE adapted from (Ref. 32)

Cooper-Harper Rating Scale

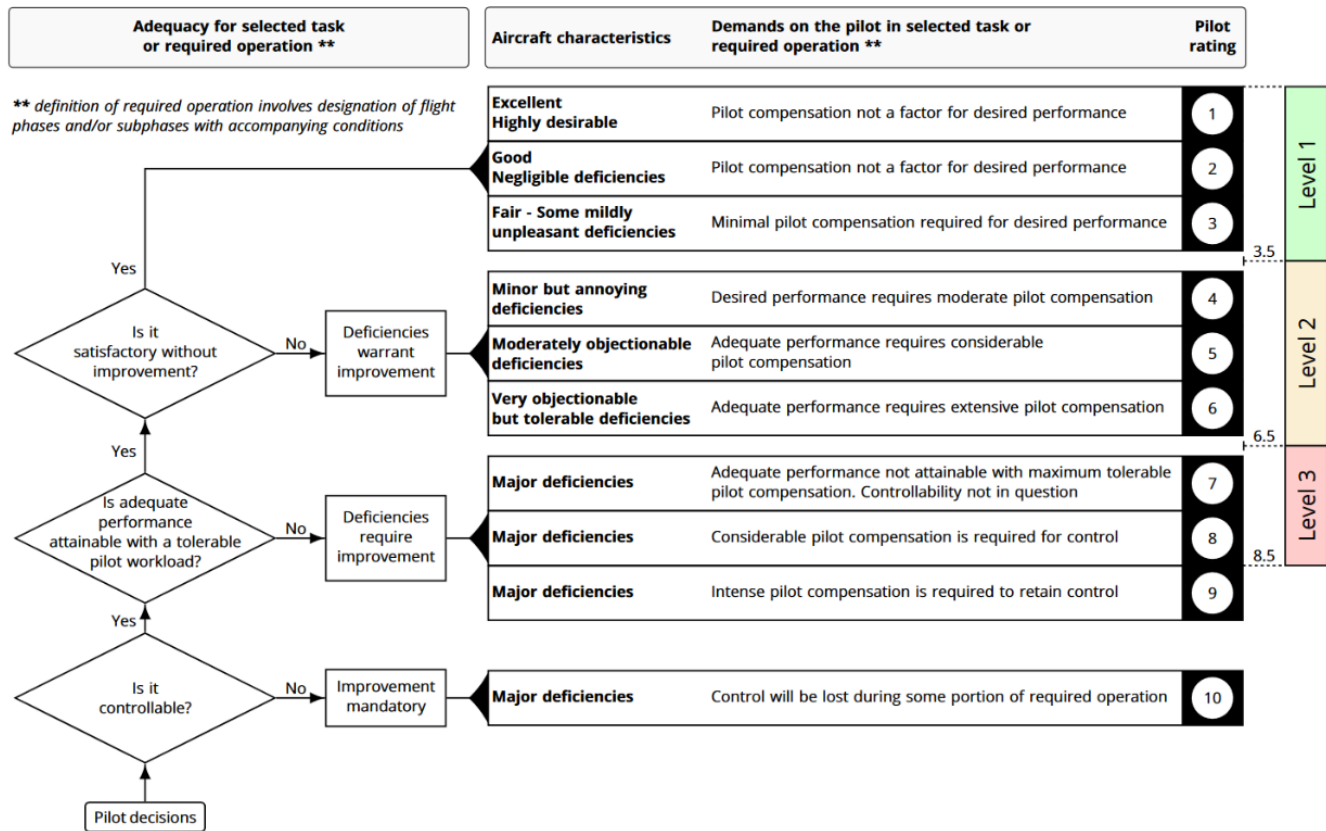


Figure 18. Cooper-Harper Handling Qualities Rating Scale (HQR) (Ref. 19)