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Direct Comparison of Eye Tracking Data Loss Between Systems Utilizing Three Common Camera Mounting Configurations in a UH-60M Black Hawk Simulator

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14. ABSTRACT

Performance comparison of eye tracking camera systems, by mounting configuration, in the UH-60M cockpit layout.

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Eye tracking, UH-60M cockpit, pupillometry

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Introduction

The U.S. Army's Future Vertical Lift program is supporting the development of new utility aircraft with advanced sensors, autonomous systems, and expanded capabilities. Integrated operator state monitoring systems are being developed to monitor both the physical and mental state of pilots to inform both initial design decisions and provide a safety net when pilots become disabled or overwhelmed while operating the aircraft. The unique enervation of the pupillary muscles allow them to reflect changes in autonomic tone, cognitive state, neurological condition, and arousal (e.g., Glick et al., 2019; Guyton, & Hall, 2016). This, accentuated by the ease of use, and the non-invasive nature of its collection, pupillometry has seen widespread use in psychological and physiological research (Aura et al., 2021; Kahneman & Beatty, 1966; Vogels et al., 2018; for review see Eckstein et al., 2017). Thus, eye tracking promises to be an important tool in the operator state monitoring toolkit. Consequently, the U.S. Army Aeromedical Research Laboratory (USAARL) has acquired and deployed several infra-red, video-based, eye tracking systems from different commercial vendors to support several research efforts.

Advances in digital video sensor technology have allowed higher resolution infrared images of the eyes to be collected from increasingly smaller camera systems. Advances in computer vision and feature recognition algorithms allow modern infra-red video-based eye trackers to make precise, detailed recordings of the eye's behavior in near real-time, and under an expanding variety of conditions outside of the strict constraints of the laboratory setting. The current literature describes several algorithms for assessing alertness, fatigue, familiarity, loci of attention, line of sight, regions of interest, and cognitive workload from modern eye tracking data sets. To track the eyes effectively, the eye tracking system must maintain a clear view of the eye, and a stable image of the pupil. Eye-related operator state monitoring metrics, including gaze patterns, eye movements, and pupillometry, are impossible to obtain without effective tracking of the pupil. Thus, the research activity described in this report was interested in analyses specific to the proportion of time where pupil tracking data were lost or spurious over the course of a choreographed sequence of fixations about the cockpit followed by a short, low-level, flight through a simulated urban environment.

The biggest challenge to effective eye tracking using video-based systems in an aircraft cockpit, particularly the U.S. Army Black Hawk Multi-Role Medium Lift Helicopter (UH-60M), is maintaining a clear view of both eyes and a stable image of each pupil. Each of the systems evaluated here represents a different approach to that fundamental problem. Head-mounted systems typically direct one, or more, cameras to each eye, individually. This simplifies the challenge of detecting the pupil in a complex image. The eye tracking systems that rely on a single camera, or multiple cameras, mounted remotely, distant from the eyes, utilize computer vision and feature recognition algorithms to identify and target both pupils amongst a far more complex scene captured within the images collected.

The first, and most common approach, is to mount a single camera directly in front of the participant and use a wide-angle lens and advanced tracking algorithms to compensate for a restricted view of the eyes. Systems using this configuration tend to have a smaller field of view and a more limited range of head positions over which effective tracking is possible. These systems are typically designed to work best with single-screen desktop experiments, and the vendors are often hesitant to promise capability beyond this restricted setting. In these settings, these systems offer superior gaze estimation accuracy and pupil tracking at a lower price-point than multi-camera array systems. The single remotely mounted camera system is further detailed in the left column of Table 1.

A second approach to track the head and eyes over a much wider range of head positions is to use multiple cameras, capturing the eyes from different angles via multiple synchronized camera feeds. Using this configuration, the camera capturing the image with the best view can be used, or a composite image generated from all of the cameras simultaneously. Such systems tend to be more complex, more difficult to operate, and an order of magnitude more expensive, but promise the same superior accuracy of the single camera systems over a much wider field of view. The multiple remotely mounted camera array system used in this study employs this strategy. This eye tracking system is detailed is the middle column of Table 1.

A third approach that is gaining traction in the operational use of eye tracking involves head-mounted systems. A typical head-mounted eye tracking camera system directs a small camera, mounted on a helmet or eyeglasses frames, to each eye, and uses a separate forward-facing camera to register gaze position to the environment. This camera system is detailed in the right column of Table 1. These systems are susceptible to motion artifacts and typically do not reach the levels of accuracy achieved by the dash-mounted systems, but what they lose in accuracy, they gain in reliability, and most suffer no limitations due to changes in head position. Thus, these head-mounted systems see widespread use in studies where the participant must remain mobile, or when a remotely mounted camera's view of the eye may be obscured.

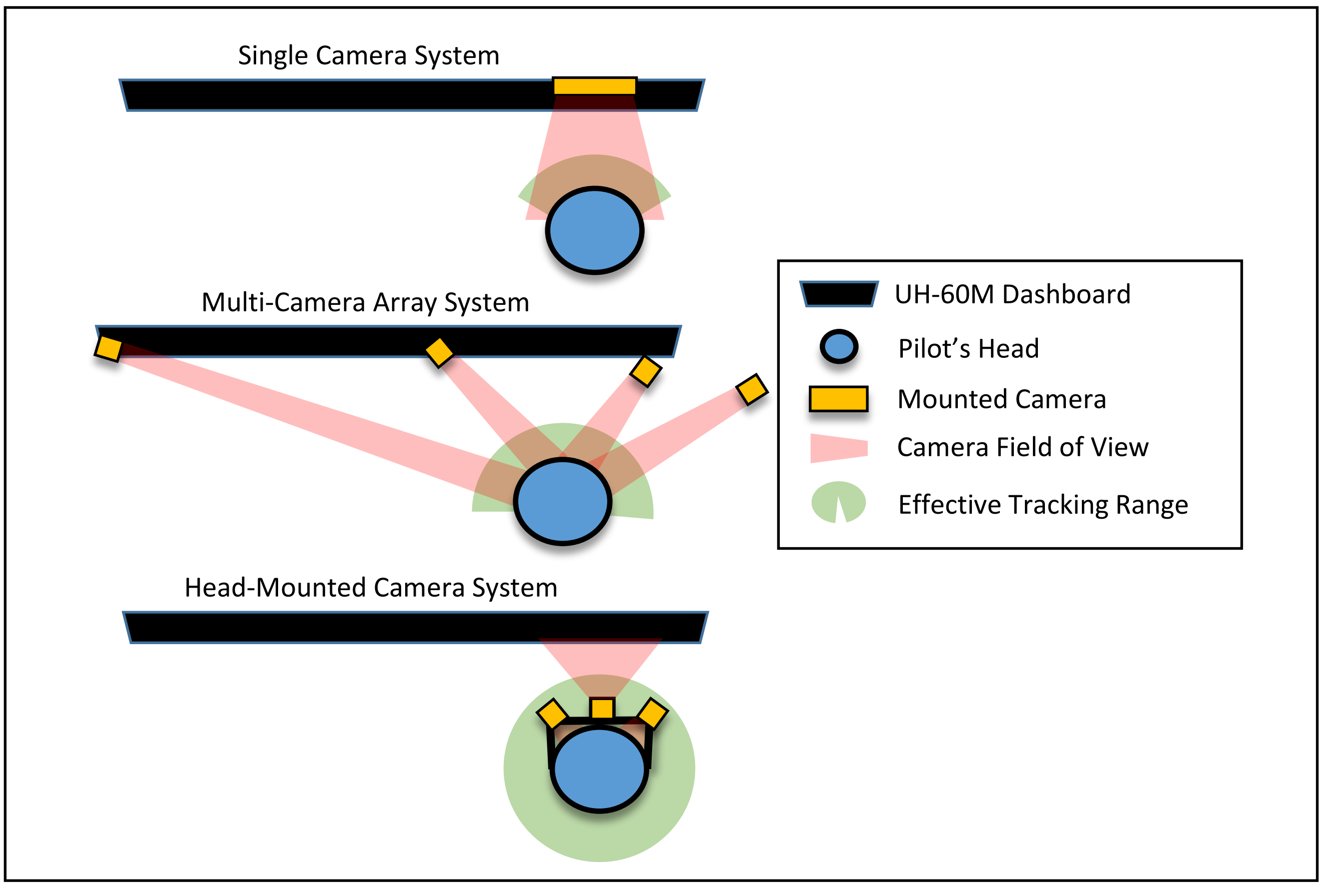

Figure 1. Diagram of the mounting configuration for each one of the eye tracking modalities tested.

As USAARL researchers move forward with incorporating eye tracking into additional projects, we are seeking the ground-truth regarding which modality of eye tracking is most effective (e.g., minimal data loss) within the specific mounting and lighting constraints of the UH-60M Black Hawk cockpit. Thus, we sought to directly compare the three, widely used eye tracking systems, each representing one of three common design modalities, using a simple and repeatable procedure. The objective of this activity is to determine which eye tracking system is best suited for capturing eye data within USAARL's UH-60M simulators (e.g., results in minimal data loss within our simulator setups).

Materials

Eye Tracking Systems Overview

Table 1 below provides an overview of the eye tracking systems used in this research activity to represent each eye tracking modality tested.

Table 1. Descriptions of the Eye Tracking Modalities Assessed

Eye Tracking Modality	**Single Camera System**	**Multi-Camera Array System**	**Head-Mounted Camera System**
Cameras	1 camera facing the pilot from a single location	4 cameras facing the pilot from different angles	3 cameras mounted on a single frame; 1 on each eye, 1 looking forward to capture scene view
Advantages	Simple setup, simplified analysis, nothing on the head	Simplified analysis, nothing on the head, flexible mounting locations	Simple setup, mobile, direct view of both eyes
Disadvantages	Limited effective mounting locations, restricted view of the eyes	Complex setup, expensive	Mounted on the head, may obstruct visual field

UH-60M Black Hawk Helicopter Flight Simulator

The Cockpit Academics Procedural Tool-Enhanced Visual Capable System (CAPT-E-VCS).

The Cockpit Academics Procedural Tool-Enhanced Visual Capable System (CAPT-E-VCS) flight simulator consists of a Black Hawk medium-lift model helicopter cockpit (UH-60M) and academic simulator (SGB Enterprises, California, USA) in front of which three projectors blend the out-of-the-window view onto a 12-foot, 270-degree field of view projection dome (Q4 Services, Inc., Florida, USA). The projectors use state-of-the-art X-IG image generation software (CATi Training Systems, Alabama, USA). All flights were conducted in clear weather, through a model of San Francisco, California.


Figure 2. UH-60M instrument panel.

Methods

Each system was installed to conform to the manufacturers recommendations to the greatest extent possible.

Data was collected from all three systems independently, within a single session, using the preferred software suite provided by each manufacturer. Importantly, the same members of the research team collected all the data in the same roles to further minimize the introduction of differences due to subtle changes to the methods of application and eye tracking calibration. The cameras and illuminators for the systems not being actively tested were powered-down to avoid infrared interference and unforeseen software interactions. The order of systems tested for each pilot was sequentially shifted using a Latin square, such that all three were collected at each position in the testing order. Specific variables collected and how they are stored and labeled varied between systems because of manufactured differences and propriety software. Consequently, evaluations were limited to aspects of the data common to all the systems tested with respect to their ability to resolve the pupil and/or provide an estimated pupil diameter.

Participants

Five male pilots, ranging in age from 25 to 46 years and currently rated by the U.S. Army to fly the UH-60M Black Hawk, served as the evaluators for this research activity. This study compared cameras from three different vendors, each utilizing a different configuration and arrangement of cameras to effectively locate and track the eyes. Descriptions of each of the eye tracking systems that were evaluated are listed below and summarized in Table 1.

Procedure

Pilots were seated in the right seat of the CAPT-E-VCS simulator, in a comfortable posture and flight-ready position, for the entirety of the recording session. The pilots were not wearing helmets, headphones, or other devices on their heads while the procedure was conducted to avoid interference with facial recognition algorithms needed to isolate and track the eyes. This remained the same throughout the duration of the evaluation. All three systems were tested in the order prescribed, back-to-back, as efficiently as possible. None of the pilots expressed any need for breaks or interruptions in the procedure, and all completed their testing sessions without leaving or adjusting the position of the seat.

Calibration.

Each system required its own calibration procedure, which were done per the vendor's recommended method.

The single camera eye tracking system required pilots to fixate a single dot as it moved from the center of the screen to each of the corners of the display. This required the mounting of a removable computer screen within the cockpit, placed at eye-level, directly in front of the pilots. The monitor was placed in front of the pilot just before calibration, and then removed once the calibration procedure was completed. This procedure took less than 60 seconds to complete, and all pilots required only a single calibration to complete the process to the vendor's quality standards.

The multi-camera array system required pilots to briefly move their head in view of all four cameras, and then were asked to sequentially fixate 12 pre-selected points inside the cockpit to complete the calibration procedure. This procedure took roughly two minutes to complete. It did need to be repeated in the case of a single pilot, to meet the vendor's quality standards for recording.

The head-mounted system required the pilots to hold, fixate, and move a small target card presented in view of the forward looking "world camera" to calibrate. This procedure completed in under 60 seconds. Two of the five pilots needed to repeat this procedure once to effectively complete the process within the vendor's quality standards.

Tasks.

After successful calibration, the pilots performed the following steps once the system began recording. See Figure 3 for a diagrammatic breakdown of the evaluation procedure.

1) The pilot was asked to complete a choreographed sequence of 14 fixations, guided by the experimenter, such that each point was fixated for roughly 3 seconds, in the same prescribed order. The choreographed sequence of fixations took roughly 60 seconds to complete.
    a. The points were chosen by researchers with helicopter flight experience and were distributed about the cockpit over their entire field of view (~180 degrees).
2) The pilots were instructed to bring the aircraft to a 10-foot hover and taxi forward for 30 seconds.
3) Once that time elapsed, they were instructed to lift the aircraft to roughly 100 feet altitude and proceed along the prescribed route at 120 knots for exactly 9 minutes.
4) The pilots were then instructed to find a suitable landing site and set the aircraft back on the ground within 60 seconds.

Once the aircraft was on the ground, the recording software was stopped and the system was powered down. The next system in the queue was powered on, the aviator was calibrated to the new system, and the procedure repeated. The entire sequence took roughly 12 minutes per system, and the entire procedure lasted roughly 45 minutes per pilot tested.

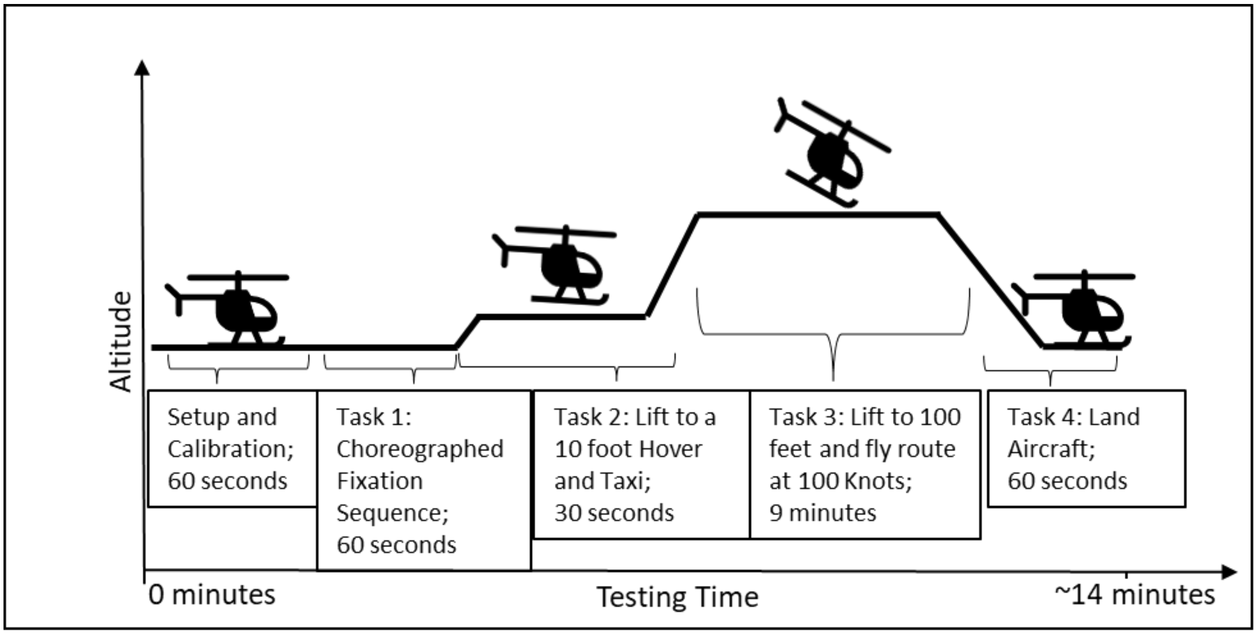

Figure 3. Outline of the testing procedure used for each eye tracking modality evaluated.

Exploratory data analysis.

Data were collected using the preferred proprietary software suites provided by each vendor. The variables containing the real-time estimates of the diameter of both the left and right pupil traces were then selected from the output data sheets generated by each system. The resulting traces were then down sampled to 60 Hertz (Hz), if necessary, to account for differences in the sample rates between the systems tested. Any data points marked by a system as missing pupil tracking, or data points with pupil diameter estimates occurring outside of two standard deviations from the mean for that recording were considered ineffective and marked as lost data.

Results

Data were aggregated across each testing session for each system. The frequencies of lost data were examined and are plotted below. Overall, all three systems were able to effectively target the eyes and provide reliable estimates of pupil diameter throughout the course of recording. Figures 4 and 5 show the percentage of data lost on the pupil diameter estimates of the left and right eye, accordingly, by each system, for each pilot. The single camera configuration resulted in the largest proportion of data lost, with roughly 20-30% of data points failing to track the pupils. The remotely mounted array and the head mounted system comparatively performed far better, only losing around 1-5% of data points collected over the course of the entire procedure. Between these two systems, however, the muti-camera array-based system consistently lost fewer data points across all pilots tested (.5-1.5%), albeit a difference that may be functionally trivial.

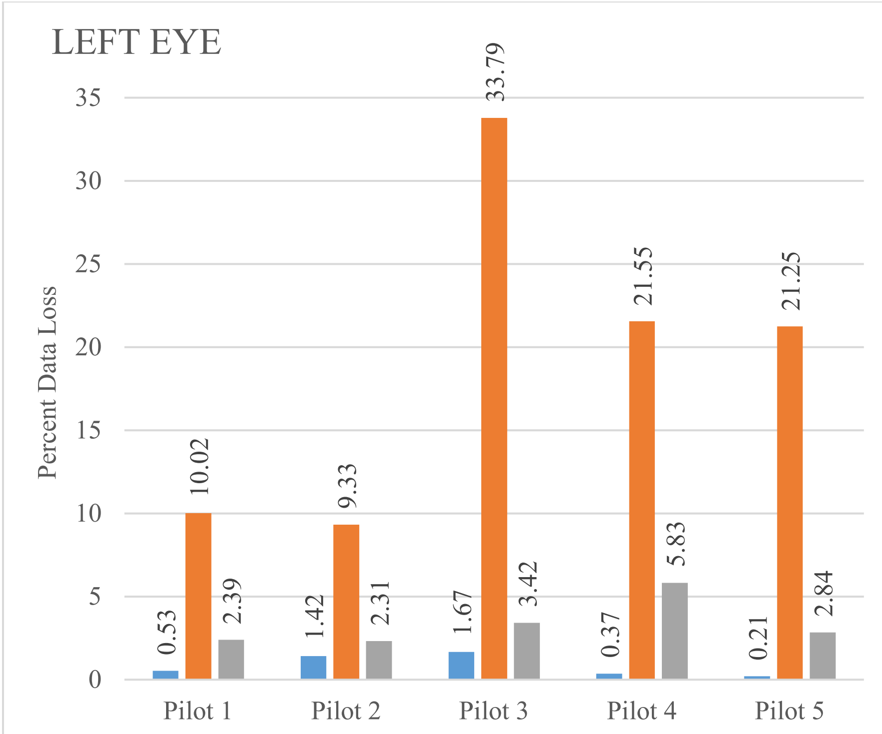

Figure 4. Percent of lost samples for the left pupil on the recording for each pilot and eye tracking system tested. From left to right: Blue - multiple remote camera array; Orange - single remote camera; Grey - head-mounted cameras.

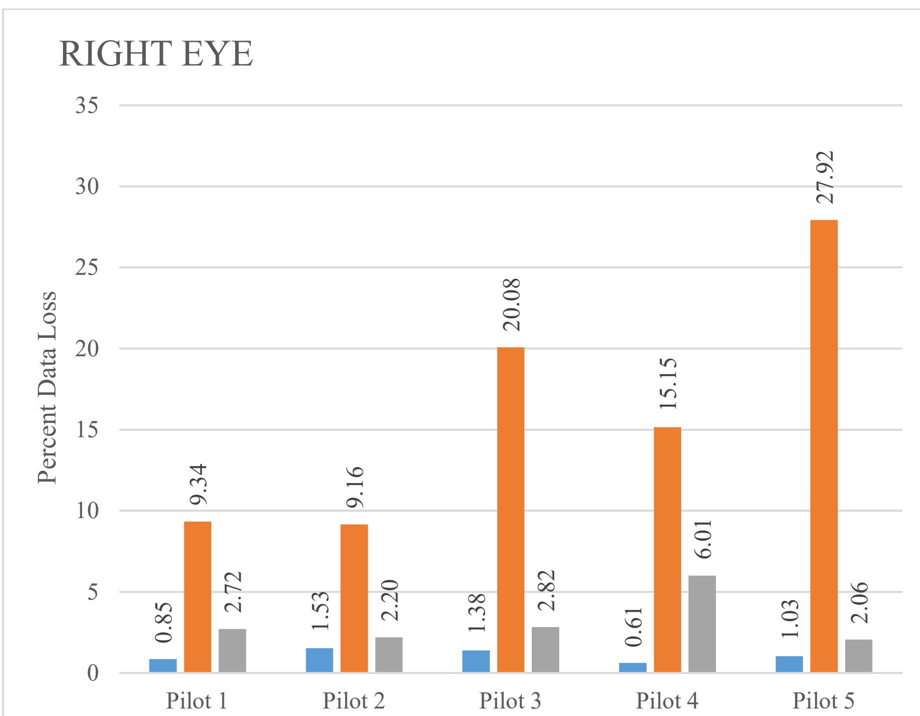

Figure 5. Percent of lost samples for the right pupil on the recording for each pilot and eye tracking system tested. From left to right: Blue - multiple remote camera array; Orange - single remote camera; Grey - head mounted cameras.

Discussion

The intent of this research activity was to evaluate the impact of eye camera system design on the ability of each system to effectively track the eyes when mounted in the UH-60M Black Hawk cockpit. Despite the inherent challenges posed by the unique mounting and lighting constraints of the UH-60M cockpit, all three modalities were effective in targeting and tracking the pupils of pilots engaged in routine flight tasks. Here we have provided an objective comparison on which systems may be best suited for inclusion in future operator state monitoring suites for research in these settings.

As shown in Figures 4 and 5, the head-mounted and multiple-camera arrays were able to better track pupils, leading to less data lost than the single-mounted camera system. This finding suggests both options (head-mounted and multiple-camera) are well suited to studies in the UH-60M simulators, and thus, selection can be tailored to the specific advantages of each mounted solution. In situations where the view of the face may be obstructed, head-mounted eye tracking solutions are designed well to work around these limitations, albeit at the expense of more challenging analyses when matching gaze patterns to specific static targets in the scene (such as symbology on a panel display). Multi-camera array systems are more sensitive to obstruction, but provided effort is applied to mounting location and matching the camera layout to static features in the environment, can deliver highly reliable data on par with, if not better than, head-mounted solutions. Further, given that the cameras are fixed in position relative to static elements in the scene, it is much easier to match gaze position to specific targets in the scene. However, there still remain significant challenges to demonstrating the effectiveness of infrared video-based eye tracking in the operational environment of the UH-60M helicopter. For instance, future efforts should be directed at evaluating how well these systems tolerate a moving platform, and how well they can track in setting closer to the operational environment.

Limitations

Both remotely mounted camera systems rely on facial recognition algorithms, which could be biased against underrepresented populations (Leslie, 2020). This study did not account for the diversity of the U.S. Army population, and thus, it remains unclear whether these systems will perform equally well for all pilots. The remotely mounted systems may also be susceptible to platform motion. The CAPT-E-VCS is a fixed platform simulator, and as such, the performance of the systems tested may be different when deployed on a simulation platform that moves or vibrates.

Conclusions

While the camera systems performed well enough to support their effective use in future studies, we saw the least data loss with the head-mounted and multi-camera array configurations. We recommend selecting between these two modalities, based upon the specific trade-offs of each, to support future research efforts in UH-60M simulators. Further testing should be conducted to see how these systems tolerate platform motion, instruments on the head (e.g., helmets, headphones, physiological monitoring equipment), and a more diverse selection of facial structures and features.

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Appendix A. Acronyms and Abbreviations

CAPT-E-VCS	Cockpit Academics Procedural Tool--Enhanced Visual Capable System
Hz	Hertz
USAARL	U.S. Army Aeromedical Research Laboratory

U.S. Army Aeromedical Research Laboratory
Fort Rucker, Alabama

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