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DOI: 10.1177/1071181312561030

The online version of this article can be found at:
http://pro.sagepub.com/content/56/1/46
Eye Tracking-Based Target Designation in Simulated Close Range Air Combat

Stephen D. O’Connell¹, Martin Castor¹, Jerry Pousette², Martin Krantz³
¹ Swedish Defence Research Agency (FOI), Stockholm, Sweden
² Milso AB, Stockholm, Sweden
³ Smart Eye AB, Gothenburg, Sweden

The ability to lock on targets as quickly and easily as possible while maintaining speed and a tactically advantageous position is crucial to success in air combat. The capability of remote eye tracking systems has recently improved significantly and has opened up new possible applications. A modern eye-tracker was integrated in an advanced flight simulator environment and an experiment was conducted. The independent variable was target designation mode that was varied between: Heads-Up Display (HUD), Helmet Mounted Display (HMD) and a solution based on eye tracking. Eleven participants flew in the experiment and mean times to designate targets indicate significant advantages for the eye tracking based solution.

INTRODUCTION

In air combat it is very important to “get the first shot” in order to take the initiative from the enemy, while still maintaining a tactically advantageous position and high speed of the own aircraft, as this increases survivability. This is an old adage in air combat, which still is valid. The consequence of low speed and lost initiative is very evident in Within Visual Range (WVR) scenarios, i.e., the classical “dog-fight”, where visual contact with the enemy is important. Although medium range missiles today are the preferred weapon for air-to-air engagements, which are planned to be played out in a Beyond Visual Range (BVR) scenario, an engagement can for several reasons, e.g., Rules of Engagement concerning the visual identification of targets or the appearance of previously undetected targets, develop into a situation where short range missiles are preferable. Modern short ranges missiles such as the IRIS-T or AIM9X can be launched in off-boresight angles that earlier were impossible to launch from, and thus the space of launch possibilities have recently increased significantly.

However, target designation still needs to be performed through some interaction between the pilot and the weapon and sensor systems. Helmet Mounted Displays (HMDs) or Helmet Mounted Trackers (HMTs) have for decades shown promises of tactical advantages (e.g., Adam, 1994; Olson, Arbak, & Jauer, 1991). HMD systems are now becoming operational in modern fighter aircraft (e.g. systems such as JHMCS, Cobra, and HMDS) and have been operational in helicopters (e.g. the IHADSS system) for at least two decades. See Franck et al. (2009) for an overview of current and future helmet mounted displays.

An HMD provides a display that allows the pilot to continue having relevant information concerning the own and enemy aircraft, superimposed on the normal visual scene, while looking in any possible angle. Hence, compared to when the pilot is constrained to a situation where tactical information only is available on the Heads-Up Display (HUD) and on the head-down displays, an HMD provides several benefits. However, an HMD system also comes with a cost as the weight of the display system adds to the total weight on the pilot’s head, and even relatively small weight additions become a factor during high-G maneuvers. Total life-cycle costs for HMDs also make alternative solutions worth investigation. Havig et al. (2009) describe a number of reasons to why HMDs have had problems to attain the widespread use that the systems could potentially achieve.

Recent advances in eye tracking technology, specifically the performance of remote eye trackers, resulted in a set of research questions related to how eye tracking could be utilized to even further enhance pilot’s target designation, possibly without some of the drawbacks of HMDs. With remote eye tracking there is no longer a need for additional equipment on the pilot’s helmet, which is an important feature in the high-G situation of WVR engagements.

In order to study these research questions, a state-of-the-art eye tracking system was integrated in a fighter aircraft simulator, and an experiment was conducted. A presentation concept called QATEP (Quick Access Target Eye Pointer) was developed, with its key features implemented. The QATEP concept comprises several other components apart from target designation, such as attention cueing for visual target detection, but in the experiment reported here only the differences in target designation performance using eye tracking, HUD and HMD-like systems are presented.

METHOD

Objective

The objective of the reported experiment was to investigate the differences in target designation times for three experimental conditions, i.e. target designation via HUD, HMD and QATEP.

Task

The task in each trial consisted of directing and releasing the seekers of 12 generic infrared (IR) guided missiles on target aircraft in a free-flight WVR tactical scenario, with missile performance similar to that of AIM-9X. A fighter
aircraft equipped with 12 missiles is currently unrealistic, but chosen during the experiment in order to provide many launch situations and collect a larger dataset. The participant was flying freely in a generic fighter aircraft model through a target area where 12 computer-generated target aircraft were flying in pre-defined patterns between altitudes of 3000 to 30000 feet. The given task was to visually scan the environment around the aircraft for these targets, and when a target was found, direct the IR seeker as quickly as possible to the target. When the IR seeker audio tone sounded to indicate detection, the participant pressed a button to attempt to release the seeker on that target. If the release was successful, the missile was to be subsequently fired. The IR seeker missile could be released on targets at up to 90° off-boresight and a missile subsequently fired at the same target.

Procedure

Each participant was given written instructions before the trials. The participant was instructed to perform the task as quickly as possible, but with maintained efficiency. The instruction stressed to not wait and observe the outcome of a fired missile, but to move on and find another target. In the event that no targets could be observed, the participant could glance at their tactical map display, where all targets were shown, in order to avoid leaving the target area. Each trial lasted for a maximum of 5 minutes, or until all 12 missiles had been fired.

Before the experimental trials, each participant was briefed about the concept of eye tracking and its role in this experiment. After reading the instructions, the eye tracking system was calibrated for the participant. Three test trials were given, one for each target designation mode, in which the participant could get familiarized with the scenario and task, as well as understand the mode. The tracking quality was also verified during these trials. After the experimental trials, a questionnaire was completed by the participant. The total time per participant was approximately 2 hours.

Participants

Eleven subjects participated in the experiment; 6 active or former pilots in the Swedish Air Force, and 5 engineers or combat air controllers with combat flight simulator experience. The mean of flight hours for the pilots was 2271 (1045 h to 4525 h), i.e. experienced to very experienced pilots. All participants were male and ages ranged from 30 to 60 (mean = 40.6). Participation was voluntary and no compensation was given.

Hardware setup

Participants were seated in a pilot station (see figure 1) of the combat flight simulator at the Swedish Air Force Combat Simulation Center (FLSC). The FLSC consists of eight pilot stations of which one was used for the reported experiment. The visual Field of View for the pilot station used is approximately ±100° horizontally, and ranges from +80° to -40° vertically. The domes where the “out of the window view” was projected consisted of 6 projection surfaces with a high-reflection coating, each illuminated by a 1400x1050 pixel resolution projector. The dome had a diameter of 6 meters, with the pilot station in the center. Given blend zones with partial projector image overlap, the pixel size was approximately 3.2x3.2 arcmin. Software for image generation and distributed rendering was provided by Presagis Vega Prime. Software and hardware for blending and geometric correction of each image channel was provided by Mersive.

Figure 1. The remote camera eye tracking system.

Gaze and head tracking was provided through a remote 8-camera infrared eye tracking system, Smart Eye Pro. The eye tracking in Smart Eye Pro is provided by detecting corneal reflections from four IR illuminators in the participants’ eyes. Furthermore the pupil is tracked as well as the head pose in 6 degrees of freedom. The measured data is fused and create a three dimensional gaze vector, automatically compensating for the pilot’s head movements. The cameras were mounted around the participant, approximately 30 degrees apart (see figure 1), alternately placed below and above the participants’ head. Using this setup, acceptable tracking quality could be achieved in almost the full dome, excluding only the outermost 20 degrees at the dome edges. Tracking quality measurements of various camera setups are presented in detail in O’Connell et al. (2011). In the setup evaluated here, tracking accuracy was between 1 degree, in central areas, and 3 degrees, towards the dome edges. The cameras, lights and mounts covered a negligible part of the visual field.

Variables

The experiment evaluated three different target designation modes for directing the IR seeker, i.e., the independent variable was target designation mode, varied between HUD, HMD and QATEP modes.

In HUD mode, the IR seeker was slaved to the center of the aircraft’s HUD, i.e., the nose direction of the aircraft. To direct the IR seeker to a target, the aircraft had to be maneuvered so that the sight presented in the HUD directly overlayed the target.

In HMD mode, the IR seeker was slaved to a simplified HMD, represented by just a green square presented on the dome surface in the direction of the participant’s head. Thus,
cues and symbology common in HMDs such as target locator lines, closure rates and target slant ranges were absent. To direct the IR seeker to a target, the participant’s head had to be turned so that the green square directly overlayed the target.

In QATEP mode, the IR seeker was slaved to the participant’s gaze direction. To direct the IR seeker to a target, the participant had to be looking directly at the target.

The primary recorded measure, i.e., the dependent variable, was the time elapsed between the instant that the participant visually detected a target in the environment, and the instant that the participant pressed the seeker release button (following the sounding of the seeker’s audio tone). This time will be referred to as response time in the following sections. Hence, response time will reflect the time taken to move the seeker to the target, and the subsequent attempt to release it.

In addition, the target positions in the environment were recorded when they were detected. In the HMD mode, the head direction was also recorded.

**Experimental design**

The participant’s initial aircraft starting heading was varied between north, south, west or east for each condition. The starting altitude was 9000 feet in each case. In each case, the target area was directly in front of the aircraft when trials were initialized.

Each participant flew with all three target designation modes in a repeated measures within-subjects design. Each mode was used in two separate trials, each trial running for 5 minutes. In total 656 valid recordings of response time were made. During each trial, 9.9 observations of response time were made on average (656 / (3 modes x 2 trials x 11 participants)).

The trials were blocked in groups of three, one for each mode. Two such blocks were completed per participant, hence two trials per condition or six trials in total. The blocks were constructed using a partial Latin squares design, and distribution of blocks between participants was counterbalanced through random permutations. The initial heading of the aircraft was evenly distributed between the modes.

**RESULTS**

**Learning effects**

Analysis of the data showed no significant effect of trial on response time (F(1,10)=0.04, ns), thus showing that there was no general performance improvement in the second trial run of each target designation mode. This observation indicates that the measures applied in order to minimize training effects due to task and scenario familiarization were successful.

**Response time**

The results were analyzed using analysis of variance (ANOVA), using a repeated measures design with subject as a random variable and a fixed model for all other independent variables. When analyzing for effects, we applied a logarithmic transformation to the response time in order to remove the strong positive skew of the response time data, which otherwise would have produced a violation of the analytic assumption of lack of skew and homogeneity of variance.

All response times over 10 seconds, 18% of the data in total, were excluded from the statistical analysis since such long times were almost exclusively caused by the absence of a seeker tone, even though the participant managed to point the seeker at the target. The absence of a tone could be caused by the target being too distant for detection by the seeker, or the target being positioned in such a way that the signature was too faint for detection, or both. These exclusions from the analysis did not change the pattern of statistically significant results, but will improve the accuracy of the data since missile seeker performance was out of the scope of the experiment.

The analysis showed a significant effect of target designation mode on response time (F(2,20)=24.4, p<0.001), shown in figure 2. Post-hoc Scheffé comparisons revealed that the QATEP mode was significantly faster (0.81 s, 22%, on average) than the HMD mode (F(2,30)=10.8, p<0.001). The HMD mode was also found to be significantly faster (0.89 s, 19%, on average) than the HUD mode. The response times for the QATEP mode were 1.70 s (37%) shorter than the HUD mode on average.
An in-depth analysis of the number of response times per second interval observed within each mode is shown in the diagram in figure 3. As can be seen in the diagram, the QATEP mode tends to peak in the first bin with response times below 1 s, where it produced the largest number (55) of responses, followed by HMD mode (18) and HUD mode (3) throughout all trials. HMD mode tends to peak in the interval 1-2 s, while HUD mode tends to peak in the interval 3-4 s. This difference in the distribution of responses in the first bin was found to be significant when analyzing $\chi^2$ contingency tables ($\chi^2(2)=29.1$, $p<0.001$).

**Gaze and head direction**

An analysis of the target position in the environment at the time of attempted seeker release for the HMD and QATEP modes is shown in figure 4. Thus, the head was pointing in this direction in the HMD mode, or the gaze was pointing in this direction in QATEP mode. Only two recordings of head pitch over 40º was made (both around 41º) in HMD mode, while 38 recordings were made above that threshold in QATEP mode. In QATEP mode, recordings were made up to 60º pitch angle.

**Questionnaire Data**

In the post-trial questionnaire participants responded to questions using a five-point Likert scale. Participants were first asked to rate the perceived neck strain (see figure 5(a)) for each mode (1=no strain, 5=painful). Wilcoxon Signed Rank tests on the ranks of ratings showed that the HMD mode was rated significantly more straining than the HUD mode (Wilcoxon statistic=0.0, $p<0.05$) and the QATEP mode (Wilcoxon statistic=21.0, $p<0.05$). There was no significant difference between the HUD mode and the QATEP mode (Wilcoxon statistic=0.0, ns).

Participants were also asked to rate their perceived efficiency (see figure 5(b)) in each mode (1=very inefficient, 5=very efficient). Wilcoxon Signed Rank tests on the ranks of ratings showed that the QATEP mode was perceived more efficient than the HUD mode (Wilcoxon statistic=6.0, $p<0.05$), as was the HMD mode (Wilcoxon statistic=3.0, $p<0.05$). Although the median rating for QATEP mode was higher than the HMD mode, this difference was not found to be significant (Wilcoxon statistic=8.5, ns).

**DISCUSSION**

The analysis of head and gaze direction, shown in figure 4, reveals a clear threshold in the pitch axis at 40º, above which there were almost no recordings of HMD target pointing direction. Although this coincides well with the upper range of comfortable neck extension, or upward pitch motion, which is approximately 30º (Woodson et al., 1992; Openshaw & Taylor, 2006) it is far from the absolute maximum of approximately 70º (Windle, 1980). Therefore this threshold could in part be attributed to a limitation in the head tracking range of the present camera setup of the Smart Eye Pro tracking system. Nevertheless, gaze tracking cannot be achieved without the tracker system detecting the head model, so the difference in maximum pitch angle between the head and gaze vectors gives a conservative indication of the added target designation range, 20º, given by the QATEP mode on the vertical axis. It is conservative, since the maximum recorded gaze pitch angles are just on the upper limit of the tracking system’s vertical range of gaze tracking.

Due to these limitations in the operational range of the tracking system, and the fact that no head motion recordings were made in QATEP mode, prevents any further quantitative studies on the range of head or gaze motion from the experimental data. In addition, we used a dome environment with a limited Field-of-View, and the experimental task was not specifically demanding participants to look at extreme angles.

The experiment was performed without any G-force simulation, and without an actual HMD. Thus, participants were not subjected to any forces related to the additional head-supported weight and a displacement of the center-of-mass (CM) imposed by a physical HMD in actual flight, which are critical biodynamic issues in the design of HMD systems (Meltzer et al., 2009). These issues can lead to neck strain and an increased risk of neck injury (e.g. Perry & Buhrman, 1997; Coakwell et al., 2004; Melzer et al., 2009). Axial (left-right) head rotation beyond ±35º and neck extension (upward motion) beyond 30º can be considered high-risk in high-G situations (Coakwell et al., 2004). Given these biodynamic
issues, the HMD target locations recorded in this experiment, as shown in figure 4, would not likely be realistically possible in an actual combat scenario, but rather restricted to approximately ±30° horizontal rotation and 30° in upward vertical rotation in normal circumstances, and even more restricted, approximately ±15° horizontal rotation, in high-G situations.

The human eye can rotate approximately ±45° to a visible target (Stahl, 1999) without head motion. Thus, a target designation system based on human gaze could potentially operate within this range even with no head motion, or up to ±75° including the normal HMD motion limits mentioned above. However, due to the absence of display weight and displaced CM, the actual head motion range would not be as restricted by the limitation of these biodynamic issues. Thus, in theory, the full operational range of a gaze-based target designation system would be the same as what is visible to a pilot flying without an HMD.

This experiment has shown that target designation in a WVR air combat scenario is significantly faster in QATEP mode, where the pilot’s gaze is used as a targeting vector, than using the HUD or HMD. The implications of the analysis presented in Figure 3 also indicate promises from eye tracking, beyond the shorter mean response times presented in Figure 2. In WVR air combat the time window of a launch opportunity is often as short as two seconds (personal communication with experienced pilots) and any system that provides target designation possibilities within this window is more likely to provide the pilot with an advantage. The number of target designations made below one second after visual detection was over three times larger in QATEP mode than in HMD mode, while almost no such quick designations were made in HUD mode.

**FUTURE RESEARCH**

These results provide an initial indication that gaze-based target designation in WVR air combat scenarios can be very fast and efficient, while being potentially less straining for the neck due to both reduced amplitude of required head motion and the fact that no equipment is mounted on the helmet. Camera placement is always problematic in the constrained environment of a fighter cockpit, but the miniaturization of cameras is very rapidly progressing. Miniature, very light-weight, cameras can probably also be integrated inside the visor of the helmet and remove the need for least some of the cameras in the cockpit.

Further studies should address issues regarding safety, including how to select individual targets in close formations, and how target designation can be confirmed.

It is important to note that as the QATEP concept used in this experiment does not contain a visual display, several of the features of a HMD are lost. Some of these features can probably be provided by other sensory modalities such as 3D-audio and tactile displays, and this could be an area for further research. Further studies of the QATEP implementation can also study other features of eye tracking systems, for example attention cueing for visual eye contact. Applications of remote eye tracking of the kind studied here also are transferable to a number of other domains where visual detection of objects is important.

**ACKNOWLEDGEMENTS**

This research has been conducted within the framework of the National Avionics Research Program, funded by the Swedish Governmental Agency for Innovation Systems (VINNOVA). The project has been a joint effort between the Swedish Defence Research Agency (FOI), Smart Eye AB and Milso AB.

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