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Scan patterns on overland navigation in varying route difficulty: is total-flight-hours (TFH) a good measure of expertise?

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Helicopter overland navigation is a cognitively complex task that requires continuous monitoring of system and environment parameters and many hours of training to master. This study investigated the effect of expertise on pilots' gaze measurements, navigation accuracy, and subjective assessment of their navigation accuracy in overland navigation on easy and difficult routes. Twelve military officers who ranged in flight experience, as measured by total flight hours (TFH) completed a simulated overland task. They first completed map study of a route comprised of easy and difficult route sections, and then had to 'fly' this simulated route in a fixed-base helicopter simulator. They also completed pre-task estimations and post-task assessments of how hard it would be to navigate to each waypoint in the route. Their scan pattern was tracked via two eye tracking systems. The tracking systems captured both the participant's out-the-window (OTW) and topographical map scan data. TFH was not associated with navigation accuracy and RMS (root mean square) error for either legs. For the easy routes, experts spent less time scanning out the window (ρ=-.61), had shorter OTW dwell (ρ=-.66), For the difficult routes, experts appeared to slow down their scan by spending as much time scanning out the window as novices, while also having fewer MAP fixations (ρ=-.65) and shorter OTW dwell (ρ=-.69). However, TFH was not significantly correlated with more accurate estimates of route difficulty. This study found that TFH did not predict navigation accuracy or subjective assessment but was correlated with some gaze parameters. It may be that TFH is too crude measure to use as a measure of expertise for task specific activities (e.g., overland navigation).

INTRODUCTION

A common goal in training is to train novices to behave and think like experts so that novices can more quickly attain satisfactory levels of performance and decision making skills (Klein, 2008). The goal of this study is to identify measures of the differences in overland navigation to enable identification of experts and novices and improve training. In aviation, performance generally is assessed by level of flight control, typically defined by RMS error of flight trajectory, accuracy of flight decisions, and depth of understanding of the issues surrounding the decision. Expert pilots, defined by total-flight-hours (TFH) or FAA ratings, consistently perform these tasks better than less experienced pilots (Bellenkes et al. 1997; Kennedy et al. 2010; Morrow et al. 2009; Taylor et al. 2005). Helicopter overland navigation is a particularly challenging aviation task for trainees and instructors as it entails additional cognitively demanding tasks above and beyond flight control. For example, a common flight performance measure, RMS error of flight trajectory, does not predict expertise levels in helicopter overland navigation (Sullivan et al. 2011) as it does in other aviation tasks. This is because helicopter pilots are trained to adapt their between-waypoints navigation solution based on current observation. For example, pilots may elect to deviate from a straight-line connection between waypoints to take advantage of a guiding feature that was not readily apparent in pre-flight planning. (Sullivan et al. 2011). Thus, in training helicopter pilots, a different measure of expertise beyond RMS error is needed.

Another limitation of using RMS error as a measure of flight expertise is that it does not provide information regarding experts' underlying cognitive strategies while flying or how these strategies may change with accrued experience. Currently, little is known about the learning process underlying improvements in flight control and navigation. For example, do experts simply demonstrate more precise control or do they do things in a qualitatively different way, by perhaps sampling different sources of information (Bellenkes et al. 1997; Kaneda et al. 1994)? In order to better explain *why* pilots' performance differ by expertise level and to find cues for assessing their cognitive states, we suggest observing human behaviors (e.g., where they look) which influence their performance (e.g., how they navigate). Even for one of the most common causes of mishaps, the breakdown in cockpit scan, developing a good scan strategy has not been given high priority during training and no standardized scan training has been systematically constructed yet (Bellenkes and Ford, 2002).

Among several candidate psychophysiological measures for human cognitive states in real time, eye movements are relatively easy to collect in real operational environments, and recent eye-tracking technology provides non-intrusive devices to collect ocular data (Di Nocera et al. 2007). Using eye scan behavior to detect expertise differences has been successfully utilized in several domains (e.g., Marshall 2007; Shapiro and Raymond, 1989). Regarding expertise in the aviation domain, scanning differences between novice and experts occur, in which experts utilize a more efficient and effective scan pattern with a greater frequency of fixations, shorter dwell times, and a greater number of fixations on salient stimuli (Kaneda et al. 1994). On pilot decision making, experts had longer dwell times to relevant cues when a failure was present and generally made better decisions in terms of speed and accuracy (Schriver et al. 2008).

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Importantly, experts' scanning patterns are correlated with better performance as measured by reduced flight path error on all axes and faster reaction times (Bellenkes et al. 1997; Huemer et al. 2005). Thus, by knowing expert pilots' scan patterns for different aviation tasks and decisions, training novice pilots can be improved by (1) teaching them how to scan the environment more effectively, and (2) detecting experts' underlying cognitive strategies based on their scan pattern; these strategies can then be taught to novices.

The previously mentioned studies did not investigate expertise and visual scan differences in helicopter overland navigation tasks, which are considered to be more cognitively demanding and continuously complex than fixed wing aircraft operating tasks. Recently, Sullivan et al. (2011) demonstrated that when pilots were on track during an overland navigation task, flight expertise predicted gaze parameters and scan management skills but did not predict flight performance measures, such as RMS error. However, it is unknown whether this pattern of results also occurs when pilots are faced with more difficult navigation routes in which they are more likely to be off track. We thus focused on improving our understanding of cognitive processing associated with helicopter overland navigation by analyzing gaze measurements, navigation accuracy, route difficulties, and expertise level of pilots.

We made the following hypotheses for helicopter overland navigation tasks regarding route difficulty and expertise represented by TFH: 1) TFH is positively associated with navigation accuracy on both the easy and difficult route sections, but not associated with RMS error. 2) TFH is strongly associated with an efficient scan pattern for the both the easy and difficult route section.

METHODS

Participants

There were 12 male military personnel, aged 29 to 40 years who participated in the study. The minimum skill requirement for the study was completion of at least one overland navigation class. Among the 12 participants, three participants were helicopter flight instructors and two participants had other navigation-related instructing experience. Expertise was defined by the total flight hours (TFH), in which higher TFH values indicate increased expertise of the pilot. TFH varied from 0 to 3,100 hrs (avg = 1,488 hrs, std = 1,104 hrs) and overland-flight-hours varied from 0 to 2,500 hrs (avg = 612 hrs, std = 853 hrs). No special neurological, visual acuity, or spatial ability tests were performed. The study was approved by the Naval Postgraduate School (NPS) Institutional Review Board. Participants were recruited from e-mail advertisement through NPS e-mail account holders. All the participants were given written informed consent to participate, with the right to withdraw at any time.

Equipment

The basic elements of the apparatus included the flight simulator X-Plane 8.6, a 46" wide screen to present OTW view, a 40" wide display for the map and instrument display, two stereo cameras and associated faceLAB 4.6 software for collecting eye data, and cockpit-style seat with sided mounted joystick. Data from X-Plane 8.6 and faceLAB were sent to an Image Generator (IG), which provided an OTW and a map view combining an OpenSceneGraph terrain model of Twentynine Palms, CA. The helicopter was designed to be on an automated terrain-following mode at fixed 150' above ground level (AGL) flying at 60 knots. However, the pilot was able to control the heading of the aircraft using the lateral control of the joystick. The joystick pitch control (up/down) was programmed to change the up/down view of the OTW, not the actual pitch angle of the aircraft. The map display presented a 1:50,000 topographical land map typically used for flight planning and execution. The map was fixed in position about the pair-wise mean of the waypoints, whereas the orientation of the map was synchronized to the aircraft's heading to maintain a track-up orientation. The bottom portion of the screen contained instruments to support navigation task: the left-most instrument display was a compass typical of legacy Navy H-60 (SH/HH-60F/H) displays. To the right of the compass display were typical barometric and radar altimeters. The rightmost portion of the instrument cluster contained a digital-style elapsed time clock.

Navigation task

The navigation task was to fly over 12 waypoints (indicated as black circles on Figure 1) after studying the area utilizing Falcon View flight planning software, a system widely employed by diverse communities within DoD. The first waypoint (wp) is located slightly south of the map so it is not shown in the figure. Each waypoint pair has a "doghouse" that indicates (from top to bottom): the next wp number, the recommended heading to reach that waypoint from the previous one, the distance between waypoints, and the amount of time it takes to traverse the distance assuming a speed of about 60 knots. The task was created so that some legs would be more challenging than others. The difficulty of each leg was assessed by a subject matter expert (SME) when designing the whole route. The SME determined that the legs from wp 2 – 4 were easy, whereas the legs between wp 5 – 7 were difficult. We refer to wp 2 – 4 as the easy route section and wp 5 – 7 as the difficult route section. The Results section focuses on these two route sections; notable points from other waypoints data are described in Discussion for an organized reporting.

Navigation Performance Measure

The accuracy of navigation performance was assessed separately for the easy route section and the difficult route section. Navigation accuracy was quantified as a 2 if the pilot was on-track for both legs of the section (e.g., on-track for wp 2-3 and wp 3-4 in wp 2-4), 1 if the pilot was on track for only 1 leg (e.g., on-track only for wp 5-6 in wp 5-7), and a 0 if they were off-track for both legs. Being on track was determined based on whether or not the participant was closely located (threshold was .5 km) to designated wps and by participant's debrief. Navigation accuracy is a parameterized variation of the conventional RMS error. Navigation accuracy allows acceptable deviation which captures "good-enough" or "satisfying" characteristics of tracking tasks (Kaneda et al. 1994) whereas RMS error penalizes any errors deviated from wps.

Demographic survey

This survey had questions regarding participants' age, gender, branch of military service, total flight hours, overland navigation hours, days since last flight, instructor experience, and years of aviation experience.

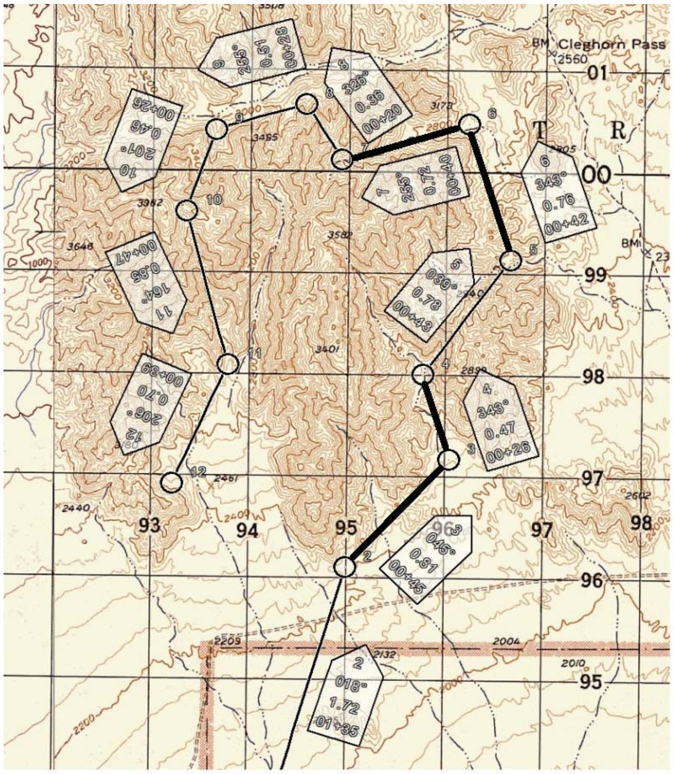

Figure 1 Flight route showing 2nd to 12th waypoints with corresponding dog houses: wp2-4 and wp5-7 are shown in thick lines (Sullivan et al. 2011).

Procedure

After a brief introduction, participants were asked to read and sign an informed consent form. They then completed a demographic survey. The next step was a calibration of faceLAB stereo cameras to verify that the visual scan data was usable (error less than 3 degrees) before participants started the navigation tasks. Participants were asked to sit in the simulator chair, where eye-tracking cameras had been mounted in between the chair and the simulator screen. Once the calibration was done, the simulated flight environment was explained to the participants (e.g., altitude and speed maintained by Autopilot, forward/backward movement of the flight stick controls the view of the helicopter, the digital map stay oriented automatically, etc.) and then they flew a practice route. The practice run took about seven to eight minutes, giving participants enough time to get familiar with the simulated environment and the simulator itself.

Following the calibration phase and equipment familiarization navigation route exercise, participants were briefed on the main navigation route (Cleghorn West, Figure 1) for up to 20 minutes. After the brief, participants completed the pre-task questionnaire and then were directed back to the flight simulator and evaluators re-verified calibration. Participants then flew the main route (6 min long) while evaluators collected eye-scan data and flight information. If a participant went too far off course, the experimenter would verbally intervene, giving them a course to guide the participant back to a waypoint. Participants then completed the post-task questionnaire and were debriefed. Total experiment time varied from one hour to 1.5 hour.

Statistical Analyses

We used Spearman's rank correlation to see if TFH is associated with flight performance and/or visual scan characteristics. For a regression analysis on the easy route section between TFH and gaze parameters, we refer the reader to Sullivan et al. (2011).

The main outcome measures for the flight and navigation performance were 1) RMS error of the flight trajectory and 2) navigation accuracy, i.e., whether pilots were on-track (within .5 km from the wps) or off-track (deviated more than .5 km). The RMS error was defined as

$$\text{RMS error}_{k,k+1} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i^a - x_i^o\right)^2},$$

where for n data points between waypoints k and k+1 x_i^a is the actual flight position and x_i^o is the corresponding reference trajectory point for the ith point.

The main outcome measures for visual scan patterns were 1) median of dwell duration, 2) OTW scan time, 3) number of OTW-MAP view changes, and 4) number of fixation points per unit time. Dwell duration (or the duration of fixations) is calculated as a period between consecutive saccades (Morrow et al. 2009). Because the navigation tasks had two different views (OTW and MAP), the variables, OTW and MAP scan time ratio and number of OTW-MAP view changes, were included to account for how many features pilots scanned per view. Data from faceLAB, X-plane and IG were combined into a text file and all data were processed in MATLAB R2010a. The main outcomes from the survey data were self reported level of navigation difficulty.

RESULTS

We used a significance level α=0.05 for testing hypotheses. Spearman's rank correlation is denoted by ρ and the corresponding p-value is shown as p. As would be expected, TFH was correlated with overland flight hours, days since last flight, and days since last overland flight ($|\rho|$'s >.6 and p's <.05), but not with any other demographic variables, such as age or branch of service. Route difficulty affected actual flight and navigation performance. As expected, and as can be seen in Table 1, RMS error increased and navigation accuracy decreased from the easy route section to the difficult route section ($t(11) = 5.171$, $p<.001$ and $t(11) = 3.924$, $p<.01$) respectively. Ten pilots were on course for the easy route whereas only three pilots were on course for the difficult route. These results confirmed the SME's evaluation. Table I shows mean and standard deviation of each dependent measure on the easy route section and the difficult route section respectively. Dwell parameters in the helicopter navigation tasks were in the range of results previously reported (Velichkovsky et al., 2000). Also, the distribution of dwell duration was skewed to the left. We therefore used the median dwell duration in statistical analyses rather than using mean dwell duration.

None of the gaze parameters were significantly different between the two route sections, possibly due to wide range of variability in all gaze parameters, with the most variability occurring with median Map dwell duration. Of note, the number of fixations per OTW view was more than that of the MAP view in both routes (easy route: $t(11)=3.067$, $p<.01$ and difficult route: $t(11)=3.586$, $p<.005$) and OTW scanning time was more than 50% for both routes. This result indicates that regardless of route difficulty, pilots tend to spend more time looking and fixating OTW relative to the MAP view.

Table I Mean, median and standard deviation (std) of dependent variables

	Leg 1 (easy, wp2-4)			Leg 2 (difficult, wp5-7)		
	mean	median	std	mean	median	std
Navigation Perf. (max =2.0)	.92	1.0	0.19	0.62	0.5	0.22
RMS error (ft)	11.5	9.05	7.8	30.6	30.5	14.2
Median dwell duration (msec)	229.1	215.8	47.3	212.8	208.6	34.1
Median OTW dwell duration (msec)	226.5	227.1	38.7	213.9	207.6	43.1
Median MAP dwell duration (msec)	297.5	224.8	159.0	257.5	230.1	91.4
Num. of OTW fixations per view	4.1	3.0	2.6	3.3	2.4	1.8
Num. of MAP fixations per view	1.74	1.79	.65	1.78	1.55	.61
OTW scanning time (%)	61	60	12	56	56	9
Num. of OTW-MAP view changes per second	1.35	1.34	.63	1.30	1.20	.56

Navigation accuracy was correlated with two gaze parameters and RMS error on the easy route (Median dwell, $\rho=-.45$, $p<.1$; median OTW dwell , $\rho=-.52$, $p<.05$; RMS error, $\rho=-.52$, $p<.05$): pilots who were on-track showed less median dwell on the easy route. In contrast, no significant correlation was found in difficult route with any gaze parameters or RMS error. Navigation accuracy was correlated with RMS error and OTW dwell duration in easy route ($\rho=-.52$, $p<.05$; $\rho=-.52$, $p<.05$;) whereas none with in difficult route. As would be expected, most gaze parameters were correlated with each other on both the easy and difficult routes; for example, OTW dwell and OTW-MAP view changes were correlated negatively in both legs ($\rho=-.66$, $p<.05$ and $\rho=-.69$, $p<.001$ respectively).

HYPOTHESIS 1: Spearman's correlation analysis partly supported our hypothesis regarding the relationship among TFH, navigation accuracy, and RMS error. TFH was not a significant predictor of either navigation accuracy or RMS error for both easy and difficult route sections. The lack of association between TFH and RMS error is consistent with our previous work (Sullivan et al. 2011).

HYPOTHESIS 2: Spearman's correlation analysis supported our hypothesis on the association between TFH and gaze parameters. TFH was associated with several scan parameters on both the easy and difficult route sections. TFH predicted median dwell, median OTW dwell, Number of fixations per OTW, and Number of OTW-MAP view changes in both easy and difficult route sections. These results indicate that pilots with more TFH showed a more efficient scan pattern characterized by shorter overall dwell, shorter median OTW dwell, less number of fixations per OTW and more number of OTW-MAP view changes. TFH × gaze parameter interactions also were found. TFH was negatively associated with OTW scan duration for the easy route ($\rho=-.61$, $p<.05$), whereas no differences in OTW scan duration were found for the difficult route section. On the other hand, TFH was negatively associated with number of fixations per view and number of fixations per MAP view only on difficult route section ($\rho=-.61$, $p<.05$ and $\rho=-.65$, $p<.05$). The interactions suggest that more experienced pilots make subtle changes to their scan pattern when route difficulty increases, where they spend more time scanning out the window and look less often at the map. In contrast, less experienced pilots do not change their scan pattern when navigation difficulty changes.

DISCUSSION

Our hypotheses were only partially supported. Regarding Hypothesis 1, TFH was not a significant predictor of either navigation accuracy or RMS error for both easy and difficult route sections. For hypothesis 2, TFH was associated with a subtle change in scan pattern between the easy routes and difficult routes. For the easy routes, experts spent less time scanning out the window, yet had as many fixations as less expert pilots. For the difficult routes, experts appeared to slow down their scan by spending as much time scanning out the window as the novices, while also having fewer overall fixations and MAP fixations.

There are a few possible explanations for the lack of a relationship between TFH and navigation performance and gaze parameters. First, TFH may be too crude a measure of expertise for task specific activities. Even instructor-experienced pilots, which could be a measure of pilot expertise, did not predict gaze and navigation performance on both legs. A better measure of overland navigation expertise may be total overland hours, particularly in this cohort of military pilots, some of whom have most of their flight hours over water. However, overland flight hours did not predict gaze parameters better than TFH. Alternatively, it could be that the difficult routes were very challenging even for the experienced pilots. Evidence supporting this view is that mean level of navigation accuracy for the difficult route was quite low, .62 out of a maximum score of 2.0. Additionally, during the difficult route, more experienced pilots showed a scan pattern that was more representative of a novice scan pattern: longer scan time out the window and fewer fixations. Finally, even the more experienced pilots underestimated how challenging the difficult route would be, suggesting that they were unprepared when confronted with that part of the navigation route. Other surprising results were that gaze parameters only partially predicted navigation accuracy and changes in route difficulty. Pilots with better navigation accuracy in the easy route had lower median OTW dwell times. As shown in Table I, no significant change was shown in OTW scanning time between easy and difficult route sections. However, increased variability in OTW scanning time during the difficult route could have masked any significant relationship between OTW dwell time and navigation accuracy for this route.

As an exploratory analyses, participants were grouped into two groups according to their navigation accuracy (on-track vs. off-track) in both route sections. The purpose of the grouping was to see if on-track participants can be characterized differently from off-track participants in terms of gaze parameters. Table II shows dependent measures comparison between these two groups. The descriptive statistics suggest differences between the two groups, but we did not conduct statistical analyses due to the small sample size. Three participants were in the on-track group and two participants were in the off-track group. The rest of the participants showed combination of on- or off-track navigation accuracy, thus they are not included in this exploratory analysis.

Table II Mean, median and standard deviation (std) of dependent variables for participants who were on-track or off-track for both easy and difficult route sections

	On-track participants			Off-track participants		
	mean	median	std	mean	median	std
TFH (hrs)	1780	1600	454	575	575	813
OFH (hrs)	867	850	575	50	50	70
RMS error (ft)	16.4	14.2	.5	29.7	29.7	7.0
Median dwell duration (msec)	215.9	196.7	36.6	250.9	250.9	8.35
Median OTW dwell duration (msec)	228.6	214.6	46.3	245.1	245.1	7.06
Median MAP dwell duration (msec)	220.3	213.3	52.1	286.2	286.2	15.01
Num. of OTW fixations per view	3.7	4.3	1.4	2.2	2.2	0.07
Num. of MAP fixations per view	1.5	1.6	0.2	1.7	1.7	0.54
OTW scanning time (%)	63	62	8.1	55	55	15
Num. of OTW-MAP view changes per second	1.3	1.4	0.2	1.25	1.25	.09

We can conclude TFH predicted gaze parameters but, in this cohort of military pilots, it was too crude to use as a measure of expertise for task specific activities. As future work, task specific measures of expertise should be studied. We should be able to characterize/predict who will perform task well based on eye gaze pattern, vs. those who have scan breakdown. This research is particularly important towards preventing CFIT (Controlled Flight Into Terrain) and mid-air collisions while conducting low level VFR operations. Scan strategy also differ by task; therefore a “portfolio” of successful scan strategies by aviation task could be developed.

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