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Predicting Perceived Situation Awareness of Low Altitude Aircraft in Terminal Airspace Using Probe Questions

Thomas Z. Strybel, Kim-Phuong L. Vu, John P. Dwyer , Jerome Kraft, Thuan K. Ngo, Vanessa Chambers, and Fredrick P. Garcia
Center for the Study of Advanced Aeronautic Technologies
Department of Psychology, California State University, Long Beach
1250 N. Bellflower Blvd. Long Beach, CA 90840, USA
{tstrybel@csulb.edu; kvu8@csulb.edu; jdwyer@csulb.edu; itzjerome@hotmail.com; tngo4@csulb.edu; vchambers@csulb.edu; fpgarcia@gmail.com}

Abstract. The purpose of the present study was to evaluate the effectiveness of subjective and objective probe questions in predicting situation awareness as measured by the Situation Awareness Rating Technique (SART). The data for this evaluation were taken from a previous investigation in which instrument-rated pilots flew automated ILS approaches into the Dallas-Fort Worth (DFW) Airport while monitoring the status of patrol vehicles proximal to their approach path. At three points during a simulation run, pilots were administered a questionnaire containing seven questions designed to probe situation awareness. At the end of the run, SART was administered. We found that certain probe questions can predict SART scores. However, the usefulness of these probes requires that the questions be designed in conjunction with scenario development to ensure that operationally critical variables are being probed, and that sufficient variability in the responses allow assessments of relations with sufficient statistical power.

Keywords: situation awareness; aviation; simulation

1 Introduction

Situation awareness (SA) has been extensively studied in aviation and human factors because it is generally agreed that high levels of situation awareness are critical for safe and efficient operations in the national airspace system. Air Traffic Controllers (ATC) refer to SA as “having the picture,” and pilots call it “staying ahead of the aircraft” [1], [2]. Because of the importance of SA in aviation operations, there has been strong interest in developing reliable and valid measures of SA. However, a single valid metric of SA is currently unavailable, despite decades of research in this area. The difficulties in achieving valid, reliable, and generalizable measures lie in the ambiguities surrounding the definition of SA and the complex relationship between SA and other factors known to affect task performance such as workload.

SA has been viewed as either the cognitive processes involved in achieving high awareness of one’s surroundings or the information that determines the state of the operator’s awareness. Most definitions of SA, in the latter view, assume that good SA requires information about past, present, and future events [3], [4]. The measurement of SA is also difficult because the relationship between SA and performance is not simple. For example, Durso et al. noted that measures of SA may not always predict operator performance because “. . . the situation might be very simple, or the operator may get lucky” (p 721) [4].” Nevertheless, the absence of situation awareness has been shown to contribute to operational errors. For example, in a review of major carrier accidents over a four year period, 88% of the errors can be traced back to low SA [3]. In other reviews, 69% of ATC-reported incidents involved failure of gathering appropriate information needed for good SA [5]. Moreover, the severity of ATC operational errors is related to controller awareness of the error: Lower awareness results in more severe errors [6], [7], [8].

The importance of developing valid SA metrics will be increased in future years, as we move to more automated air traffic management environments. Automation may change the traditional roles of operators in the airspace, and the effect of these changes on SA need to be determined. Preliminary research on the effects of automation on SA has identified several potential problems. First, automation might take the operator out of the loop and add more demands for vigilance monitoring. However, human performance on vigilance tasks is poor. Second, by taking the operator out of the loop, operators may not be able to easily regain SA during system failures or emergencies because they were not fully aware of system status prior to the failure [9]. Third, SA will be impacted by the reliability of the automated tools and the tendency for operators to become overly involved with the automation tool itself [10], [11]. For example, datalink has been shown to improve the overall efficiency of communications by reducing the number of communications failures. However, datalink, by reducing or eliminating party line chatter, can also reduce pilot SA of ATC current workload level [12].

1.1 Situation Awareness Measures

Over 20 years of research has been conducted on SA, and numerous measurement techniques have been developed for the construct. Recent reviews of SA measurement techniques list between 9 and 17 different tests and measures [2], [13]. Although the specific measures vary, these metrics can be roughly classified as probe techniques, subjective ratings, or performance measures.

The use of probe techniques involves submitting queries to the operator during a simulation run. These queries are designed to gather information that is assumed to be relevant to SA (e.g., asking a pilot to estimate the distance a nearby patrol vehicle from his/her aircraft, or "ownship"). The most widely researched and utilized probing SA technique is Endsley's freeze-probe technique, SAGAT, in which the simulation is stopped in the middle of a simulation run and operators are asked questions about the simulation environment [1], [3]. For air traffic management applications, the queries usually relate to the location and characteristics of aircraft in a sector (for controller SA) or in the vicinity of an aircraft (for pilot SA). According to Endsley, the questions queried should be created from a prior Goal Based Task Analysis Technique which identifies SA information requirements and classifies them according to which dimension of SA they are tapping (perception, integration, or projection into the future). SAGAT has been criticized because scenario freezes may disrupt performance. The task of air traffic management is dynamic, and freezinf may prevent interactions of elements within the system to unfold realistically. Endsley found no significant differences in ATC performance between simulation runs in which the scenario was frozen and those in which the scenario was not frozen [1]. However, because controller performance in simulated and real environments is generally very high, a lack of significance effect of scenario freezes could be the result of inadequate statistical power. Therefore, the question of whether scenario freezes disrupt performance has not been adequately tested. In nuclear power plant operations, SA has been shown to drop during periods of workload transition (i.e., from normal to high conditions [14]). Scenario freezes may create similar costs in workload transitions in different contexts even if no performance change is observed.

Other probe techniques query the operator while the simulation is still running; the scenario is never frozen. SPAM asks questions of controllers or pilots via his/her landline [8]. The questions are developed by subject-matter experts, so they are relevant to the operator's task and more compatible with how controllers represent traffic information during the scenario. Durso suggests that part of SA involves knowing where to obtain information, instead of holding the information in memory. With SPAM, SA is measured as the number of correct responses, and response time is used as a secondary indicator of workload.

Rating methods require that either operators provide self-ratings of SA, or subject-matter experts rate an operator's SA. The most widely used measure of SA that makes use of self-reported rating scales is SART [15]. SART is a multidimensional scaling technique that consists of a series of questions that have bipolar responses. The number of dimensions varies between different SART forms. The simplest version, 3D-SART, a simplification of the 10 dimension version, assesses three dimensions of SA: demands on attentional resources (complexity, variability, and instability of the situation), supply of attentional resources (division of attention, arousal, concentration, and spare mental capacity) and understanding (information quantity, and information quality). A combined SART scoring technique is often used as an estimate of overall SA: SART-Combined = Mean Understanding Rating – (Mean Demand Rating – Mean Supply Rating).

The lack of task specific questions in SART is both an advantage and disadvantage. Because SART questions are not task specific, it can be administered to both pilots and ATC. On the other hand, the lack of specificity means that SART does not provide much diagnostic information regarding the causes of poor SA. Nevertheless, SART is the most widely used rating method of SA measurement, most likely because it is easy to administer and score. Moreover, SART measures the operator's perception of his/her SA, which may or may not be related to performance or actual awareness.

Performance measures assess SA in terms of system variables. Such measures are objective and non-intrusive. However, the assumption that system outcomes are based solely on operator SA is tenuous because the relationship between SA and system performance is complex. Presently, there is no performance measure that has been shown to be directly related to SA level and is independent of other performance factors, such as workload. In general, performance measures assess SA in scenarios and on tasks that have been carefully developed to probe the operator's SA. One technique for obtaining performance measures of SA is to introduce errors into the scenario and use speed of detection and accuracy of correction as SA metrics.

1.2 Present Study

The present study is a preliminary evaluation of the effectiveness of subjective and objective probe questions in predicting subjective SA as measured by SART. We used the final approach phase of flight because there are unique information demands required of pilots in this flight phase [16]. The data for this evaluation were taken from a previous investigation in which instrument-rated pilots flew automated ILS approaches into the Dallas-Fort Worth (DFW) Airport while monitoring the status of patrol vehicles proximal to their approach path [17]. These vehicles were characterized as multi-vehicle flights on patrol missions over DFW reservoirs. Furthermore, they were identified as either piloted patrol aircraft, or unpiloted patrol aircraft. The patrol vehicles flew ziz-zag courses parallel to, and ahead of, the participant's ownship aircraft (but at substantially slower speeds than ownship), and either leveled off, or climbed precipitously in the vicinity of the ownship course Final Approach Fix (FAF), as shown in Figure 1. Also, these patrol vehicles flew either to one side of the ownship course, or on both sides (i.e., 'straddling' the ownship course). These variables influenced SA by altering the extent to which pilots could predict patrol vehicle proximity to ownship. In this paper, we examined whether pilots' situation awareness, as captured by SART, could be predicted by different types of probe questions administered throughout the simulation runs.

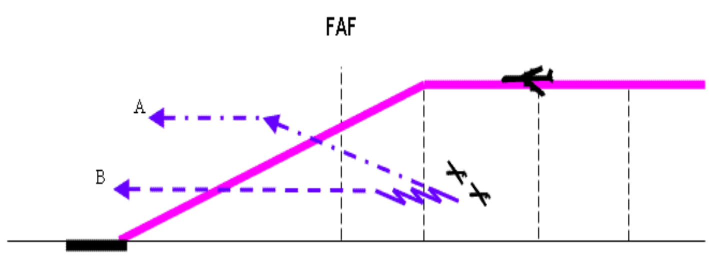

Fig. 1. Illustration of a patrol vehicle flight path relative to ownship's approach path. Dotted line A depicts a climbing patrol vehicle flight's maneuver at the FAF, and dotted line B represents the patrol vehicles in level flight past the FAF.

2 Method

2.1 Participants

Nine instrument-rated pilots (all males) served as participants in the simulation. The group averaged approximately 2,700 hours of flight experience. Participants were recruited through a local flight instruction school in Long Beach, California. Each participant was paid $160 for 8 hours of their participation.

2.2 Apparatus and Procedure

The simulation was conducted using the Multi-Aircraft Control System (MACS), Aeronautical Datalink and Radar Simulator (ADRS), and DagVoice suite of software developed by NASA Ames Research Center. MACS allows each individual computer station to be run in one of several modes: air traffic control, pilot, data analyzer, and simulation manager [18]. The MACS pilot interface used in the simulation consisted of a stripped-down, generic, modern commercial transport cockpit with a primary flight display, a navigation display, and a landing gear and flaps setting control. The pilot's navigation display also showed traffic in the vicinity of ownship, and provided traffic call signs and altitudes. ADRS was used as the radar simulator and communications hub between individual workstations (pilots, psuedopilots, ATC, and simulation manager). DagVoice, a flight simulation voice-over-Internet-protocol (FS-VoIP) software system, allowed multi-channel communication, emulating ATC radio communications [19].

The portion of the DFW terminal area directly involved in this experiment encompassed the low-altitude airspace surrounding the south arrival corridors to the 13 Right and 18 Right runways. The pilots were briefed on the block altitude airspace, and crossing corridor clearances that had been issued to the patrol vehicles. In each scenario, one participant flew an approach to Runway 18 Right and a second participant to Runway 13 Right. Pilots were informed of which approach they were to fly and given time to study the relevant approach plate prior to the start of the run. The entry of the two piloted aircraft in each trial was staggered by about 2 minutes to allow the controller time to manage both approaches, and for the experimenters to administer several questionnaires to the pilots during the runs. A confederate pseudopilot controlled other aircraft in the airspace except for the patrol vehicles, which were always automated. The role of the air traffic controller was played by a confederate, who was trained in basic ATC terminology, and communicated scripted clearances to the pilots. ATC also issued traffic advisories throughout the simulation run to increase party-line verbal communication.

Pilots were informed that automated ILS approaches would be used for all runs. As a consequence, pilots did not have to change aircraft flight parameter settings, but instead only monitored flight progress to ensure that the aircraft was on its intended course at the given altitude and speed. Participants were required to manually deploy flaps throughout each approach (from fully retracted to Flaps 40). For landing on 18 Right, each pilot ownship entered the scenario just outside of ICKEL (Waypoint 1) at 3000 ft MSL and 210 KTS. Pilots were instructed to contact Regional Approach Control immediately. An illustration of the task sequence is captured in Figure 2. At initial contact, the controller acknowledged the aircraft, gave instructions to maintain 3000 ft MSL, and passed traffic information regarding the patrol vehicles. At YOHAN (Waypoint 2), the controller issued pilots a speed reduction clearance to 170 KTS. Pilots read back the clearance to ATC, and monitored the aircraft to ensure speed capture. At LEGRE (Waypoint 3), pilots were issued another speed reduction clearance, this time to 150 KTS, cleared for landing on 18 Right, and instructed to contact the DFW tower at NETEE, the FAF for the ILS approach to 18 Right. Pilots again responded by reading back the clearance. They lowered the landing gear and went to Flaps 40 at NETEE. Pilots then performed a short Landing Checklist (verifying that gear was extended and that final flaps had been set). A similar procedure was used for landing on 13 Right.

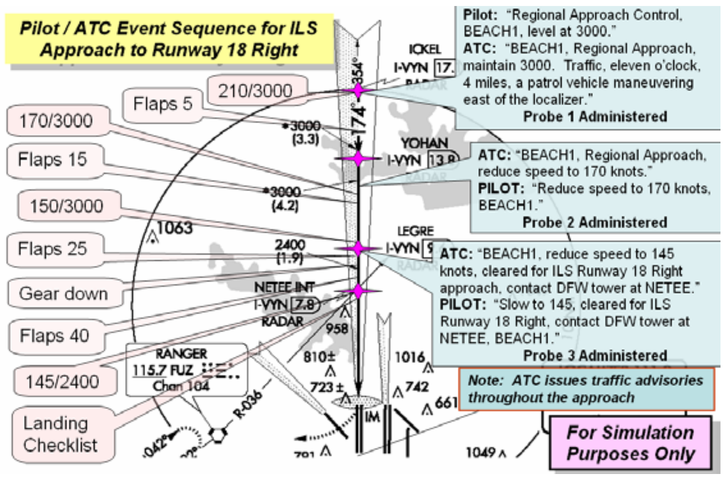

Fig. 2. Depiction of pilot activities, and pilot/air traffic controller communications for the ILS approach to Runway 18 Right at DFW.

2.3 Situation Awareness Measures

Pilot situation awareness was measured during, and at the end of, each simulation run. During a simulation run, pilots were administered a questionnaire containing seven questions designed to probe situation awareness. One question probed awareness of surrounding traffic (e.g., "How many aircraft were to the left/right of ownship when you were at Waypoint X?"). One question probed awareness of ownship status (i.e., "What was your speed at Waypoint X?"). Four questions probed awareness of the patrol vehicles in the vicinity: "How far was the patrol vehicle from ownship at Waypoint X"; "What was the patrol vehicles clock position relative to ownship at Waypoint X?"; "What was the patrol vehicle's speed at Waypoint X?"; and "What was the patrol vehicle's altitude at Waypoint X?". These six questions assessed pilots' awareness of objective information in the simulated airspace, meaning that the accuracy of the responses could be determined. The final question asked pilots to rate their perceived threat of possible encroachment of the patrol vehicle in relation to ownship using a 10-point scale, with 1 representing no threat and 10 representing extreme threat. This seven-item questionnaire was administered at three points along the approach in each simulation run (as shown in Figure 2): After pilots read back ATC clearances at initial contact (Waypoint 1), after Waypoint 2, and after the FAF (Waypoint 3). At the end of each run, the Situational Awareness Rating Technique (3D-SART) was administered.

3 Results

Table 1 presents summary statistics for SART-combined and component scores. SART combined scores range from 1 to 14, with 14 denoting high SA. Component scores range from 1 to 7, with 7 denoting high SA. From Table 1, situation awareness was moderate at best, and in some conditions was quite low. Previously, SART-combined and understanding were shown to be affected by the interaction of patrol vehicle type and maneuver [17]. In the present paper, we evaluated whether individual SA probe questions would predict subsequent SART scores administered at the end of each simulation run. The effectiveness of situation awareness probes, administered during a simulation run, was analyzed by regressing SART post run scores against responses to the probe questions that were administered at three waypoints during the simulation run. Three separate regression analyses were performed. The first set of analyses examined the accuracy of pilot responses to objective questions (e.g., deviation of pilot estimate of patrol vehicle distance from actual distance) against SART scores to determine if these objective measures of situation awareness, averaged across the three administrations of the probes, predicted SART. The second set of analyses examined pilot estimates of probed variables (e.g., pilot estimate of patrol vehicle distance regardless of accuracy), predicted SART scores. The last set of analyses evaluated the degree to which the pilot responses to probe questions at each waypoint predicted SART scores.

Table 1. SART Score Summary

	Mean	Standard Deviation	High	Low
Combined	5.22	1.54	8.92	0.50
Understanding	4.44	1.07	6.33	2.00
Demand	4.16	1.13	6.67	2.00
Supply	4.96	0.86	6.50	3.25

For the three of six objective probe questions, the variability in the correct answers between simulation runs was quite small. For example, patrol vehicle relative position to ownship was either 11 or 1 o'clock in every scenario, and very few errors were made by the participants. Performance on the three remaining objective questions was measured as root-mean-square error in patrol vehicle distance from ownship, root-mean-square error in number of aircraft in the left/right quadrant and root-mean-square error in ownship speed. These variables were used to predict SART combined and component scores. However, none of these models were significant.

For the second analyses, SART-combined and SART component scores were regressed against the following pilot estimates: estimated number of aircraft in the left/right quadrant, estimated distance of patrol vehicle from ownship, estimated ownship airspeed, and perceived threat of patrol vehicle encroachment (rightmost columns in Table 2). The regression equations predicting SART scores from pilot estimates were significant for the SART-combined and two of its components: SART-understanding and SART-demand. For SART-combined, a significant regression model was obtained [$F(4,66)=2.70; p=.04$, adjusted $r^2 = .09$]. The regression model had two significant coefficients: estimated distance [$t(66) = -2.58$; $p = .006$] and threat rating [$t(66)=-1.992$; $p=.05$]. Estimated distance was shown to be the stronger effect ($\beta = -.368$) compared with threat rating ($\beta = -.251$). Larger distance estimates and higher threat ratings were associated with lower SART combined scores.

A similar model was obtained for SART-understanding [$F(4,66) = 4.91$; $p = .002$; adjusted $r^2 = .18$]. As in the previous model, estimated distance [$t(66) =-2.78$; p=

.004] and threat ratings [t(66) = 2.043; p = .045] coefficients were significant. For SART-understanding, however, the distance coefficient was negative, while the threat rating coefficient was positive. That is, lower distance estimations and higher threat ratings were associated with higher SART-understanding scores. A significant regression equation was also obtained for SART-demand scores [F(4,68) = 8.76; p < .001; adjusted r^2 =.31]. Here, threat rating and estimated speed coefficients were significant [t(68) = 4.14; p <.001 and t(68) = -3.50; p = .001, respectively]. Higher threat ratings were associated with higher SART-demand scores, but higher speed estimates were associated with lower SART-demand scores. The regression model for predicting SART-supply was nonsignificant.

The significant relationships in the aforementioned models for probe question responses and SART scores used probe responses that were averaged across the three administrations (one at each Waypoint) during the simulation run. To determine if those relationships were a by product of a specific waypoint, we regressed probe responses at each waypoint against SART. As shown in Table 2, changes over the waypoints for each estimate were consistent with actual airspace parameters. Threat ratings also increased from the initial waypoint to the final waypoint, consistent with the experimental manipulation. Significance was obtained for only the SART-understanding [F(12,45) = 4.046; p<.001] and SART-demand components [F(12,45) = 6.39; p<.001]. SART-understanding was predicted by threat rating at waypoint 3 [t(45)=3.41; p<.001]. SART-demand was predicted by threat rating at waypoint 3 [t(45)=6.04; p<.001] and estimated speed at waypoint 2 [t(45)=-2.46; p=.018].

Table 2. Actual (Act) and Pilot Estimates (Est) of the Flight Parameters That Were Probed, and Threat Ratings, at Each Waypoint. Standard deviations are provided in parentheses.

Estimate	Waypoint 1		Waypoint 2		Waypoint 3		Average	
	Act	Est	Act	Est	Act	Est	Act	Est
Distance (nm)	6.0	5.1 (2.0)	4.8	4.5 (1.9)	4.0	3.2 (1.7)	4.9	4.3 (1.7)
Number Aircraft	3.1	2.5 (1.7)	4.7	3.6 (1.9)	3.2	4.1 (2.6)	3.7	3.4 (1.6)
Speed (kts)	210	210.1 (9.3)	210	200.4 (17.6)	135	144.3 (13.0)	185	184.4 (9.6)
Threat Rating		2.7 (1.9)		2.5 (2.1)		3.6 (2.6)		3.0 (1.9)

4. Discussion

From this preliminary investigation of using probe questions to predict subjective SA for pilots flying an ILS approach to DFW, some findings emerged that could potentially contribute to future designs of SA probes. In the first analysis we showed that accuracy of estimated airspace parameters did not predict any SART measure of SA. Although this suggests that SART measures only perceived SA, it is more likely that the small range of potential responses to these probes may have limited any ability to detect the relationships between accuracy measures and SART. Obviously, the development of probe questions should be done in the context of scenario development to ensure that potential probes are operationally relevant and the responses to them have sufficient variability for adequate statistical testing.

Pilot estimates of airspace parameters did significantly predict SART scores in the second analysis. Two variables that accounted for most of the variance by the regression models were estimated distance of patrol vehicle from ownship and rating of perceived threat of encroachment. The dominance of distance estimation and threat ratings was probably created by the demands of the scenario. Pilots were briefed on the characteristics of patrol vehicles flying near an approach flight path at the beginning of the experiment. Consequently, pilots paid particular attention to these vehicles. The significant regression coefficients that were obtained for estimated distance as a predictor of SART-combined and SART-demand were found only when distance estimates were averaged across all waypoints: Individual distance estimates at each waypoint did not significantly predict SART. However, the distance of patrol vehicle changed continuously throughout the scenario as the pilot overtook the slow-moving patrol vehicle and this may have limited the effectiveness of the individual distance estimates at each waypoint in predicting SART.

On the other hand, threat ratings and estimated ownship speed were predictive at specific waypoints. The effectiveness of these predictors may have been due to the scenario design. Estimated speed predicted SA only at the second waypoint, where a speed change had just been issued by ATC. Threat ratings at waypoint 3 (the FAF) significantly predicted SA because the separation between ownship and patrol vehicle was smallest here, and pilots were subsequently most concerned about the patrol vehicle.

In conclusion, these preliminary analyses showed that probe questions administered during a simulation can predict SART scores administered after a simulation run. However, the usefulness of these probes requires that the questions be designed in conjunction with scenario development to ensure that operationally critical variables are being probed, and that sufficient variability in the responses allow assessments of relations with sufficient statistical power. Finally, it should be noted that pilots were concerned about interruptions introduced by the probes during the simulation run, despite the fact that they were essentially monitoring an automated approach into DFW as opposed to actively flying the approach. Effective probes must be administered in a way that does not interfere with the operator's task.

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