Evaluation of Process Tracing Technique to Assess Pilot Situation Awareness in Air Combat Missions

Ketut Sulistyawati, Yoon Ping Chui, Yeow Min Tham, and Yeow Koon Wee

Centre for Human Factors and Ergonomics
School of Mechanical and Aerospace Engineering
Nanyang Technological University
50 Nanyang Avenue, Singapore 639798
sulis@pmail.ntu.edu.sg, mypchui@ntu.edu.sg,
thamym@singnet.com.sg, weey0001@ntu.edu.sg

Abstract. This paper evaluates a process tracing technique developed to assess pilot Situation Awareness (SA) in air combat missions. Using the tool, the assessment of pilot SA and translation of pilot behavior to an observer assessment form is done through observation and analysis by Subject Matter Experts. The tool is found to impose minimal interruption to the task performance, which is desired from an assessment tool that is to be applied in a highly dynamic environment such as air combat. It is also found to be advantageous in providing comprehensive and detailed information of the dynamic changes in pilot SA and the situation assessment process, as well as the quality of SA acquired. Some problems with the tool are identified and modifications to minimize them are proposed.

Keywords: situation awareness, aviation, air combat, method, process tracing.

1 Introduction

Developing and maintaining a good Situation Awareness (SA) is highly critical in the aviation domain. Problems with SA have been identified to be a major causal factor in both military and commercial aviation mishaps [1]. SA is defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [2]. Specifically for air combat environment, US Air Force operationally defined SA as "a pilot's continuous perception of self and aircraft in relation to the dynamic environment of flight, threats, and mission and the ability to forecast and then execute tasks based on that perception" [3]. In air combat, the ability to obtain a higher SA would determine winning and losing in the battle. Enhancement of SA is therefore of high interest. Various interventions, such as personnel selection, system design, and training, are done as attempts to result in higher pilot SA. A valid assessment of pilot SA is thus needed to evaluate the effectiveness of these interventions.

D. Harris (Ed.): Engin. Psychol. and Cog. Ergonomics, HCII 2007, LNAI 4562, pp. 824–833, 2007.

Prior to the deployment of any assessment tool, an understanding of the pilot's task in air combat mission is necessary. This provides several implications on the requirements that need to be fulfilled by the SA assessment tool, namely:

1. Practical, with minimum level of intrusion to task performance. The air combat environment is highly dynamic. The fighter pilots need to obtain and process vast amount of information to develop and maintain the awareness of many complex and dynamic events that occur simultaneously in flight. Using an assessment tool that potentially interfere with this process, such as stopping (freezing) the simulations several times during task performance, may alter the task nature.
2. Capture the dynamic changes of SA. The faster the environment changes, the faster one's SA has to be updated. Developing and maintaining a pilot's SA is synonymous with being involved in a three-dimensional spatial relationship that is further complicated by the fourth dimension of time compression. A pilot may have perfect SA at one time and completely losing it at another time if he does not update his SA at the same pace as the system's dynamic. Therefore, capturing the changes in pilot SA would provide useful information regarding his ability to develop, maintain, and recover from lost of SA.
3. Assess the achievement of different stages of pilot SA. Air combat situation assessment involves the loop of "*search - detect – perceive – interpret - project*". The pilot needs to scan and search for contacts and information from various sources of information, such as radar, visual lookout, tactical data link displays, and voice communication with ground and airborne controller and friendly aircrafts. This information is then analyzed to obtain further information of enemy status in relation to own or friendly aircraft in terms of relative status (e.g., relative speed, distance, closure rate, and threat level) and predict enemy's intentions and actions, which may affect the pilot's decision of actions. Capturing the stages of SA achieved by the pilot can determine the quality of his situational assessment.

To date, Situation Awareness Global Assessment Technique (SAGAT) [4] is a method that is most commonly used to assess SA. The pilot SA can be assessed objectively by querying their perception, comprehension, and projection of future status, and then checking the responses with the actual situation. This allows an assessment of the stages of SA achieved by the pilot. The method requires the mission to be frozen and displays blanked out at randomly selected times. The collection of SA data at several points makes it possible to capture the changes in SA from moment to moment. However, although the method has received many validation studies [5, 6], there are some concerns in applying this method in air combat scenarios. As the method requires freezing of missions, it cannot be applied in real life situations. Even in simulated missions, the freezing can be intrusive to pilot performance and may change the nature of the task, thus violating the first requirement.

Another commonly used method is Situation Awareness Rating Technique (SART) [7]. SART is a subjective measure of SA; it requires the participants to rate the level of their SA using a Likert-type scales. The method includes three dimensions which are believed to be related to SA, i.e., attentional demand, attentional supply, and understanding of the situation. SART is advantageous as it is relatively lower in cost and easier to administer and implement. However, the rating may be potentially confounded by workload and perceived performance rather than based on SA alone [8]. The participants may not exactly know their own awareness level, i.e., it is possible that they are not aware that they have low SA. SART rating was found to be more related to operator's confidence level of his/her SA [9]. The method itself is basically non-intrusive. However, if the ratings are to be collected several times to capture the changes in SA within one mission, a certain level of interruption to the mission cannot be avoided. Finally, it is not possible to determine the levels of SA achieved using this method.

Tham [10] developed a method to assess pilot SA specifically in air combat environment. The method is based on process tracing technique by Subject Matter Experts. It seems to be non-intrusive and able to capture the dynamic changes of pilot SA as well as the stages of SA acquired, thus fulfilling the requirements described previously. This paper aims to review this method in a greater detail to reveal its potential application in air combat missions. Several recommendations are proposed to further improve the method.

2 Process Tracing Technique to Assess Pilot SA

The tool developed by Tham is based on process tracing technique [11], which is to be completed by Subject Matter Experts (SMEs) using an observer assessment form. The participants are asked to think aloud during the mission. The process tracing can be performed concurrently during task performance, or retrospectively using a playback of the recorded scenarios. The technique tracks and monitors the SA and SA processes of the pilot, rather than measuring it quantitatively. The completed observer assessment form would indicate the progress of the different SA processes and SA achievement associated with each and every enemy aircraft, as well as that of ground threats and friendly force.

The method was applied in an experiment that aimed to examine the differences in pilot SA in performing air combat missions with and without the use of Joint Tactical Information Distribution System (JTIDS). The air combat environment was simulated using a PC-based game called Jane's USAF. The air combat scenarios were made up of multiple enemy fighter aircraft, bombers and helicopters at different ranges and headings, Surface to Air Missiles (SAMs) and Anti-Aircraft Artilleries (AAAs), as well as friendly aircrafts. Eight experienced fighter pilots (with minimum of 900 total flying hours, of which no less than 600 hours were on fighter aircraft) participated in the experiment. The assessment of pilot SA was performed by a SME, who was a fighter pilot with 1200 flying hours, 1000 hours of which were on fighter aircraft. The recorded missions were reviewed during debriefing to get the participants to further elaborate on the decisions made and maneuvers executed, as well as to fill in information gaps due to non-verbalization by the participants. The SME completed the observer assessment form through numerous reviews of the recorded simulations and explanations obtained during debriefing. Figure 1 shows an example of a completed observation sheet.

		Enemy Aircraft					
Knowledge of Enemy Aircraft	Ranges (nm)*	# 1	#2	#3	#4	#5	#6
	40-35						
	35-30						
	30-25	A: 01					
	25-20	A: 234	B: 01234	B:0123	B: 01	B: 01	
	20-15	Shot (tail)		C: 0123	C: 012	C: 012	
	15-10		Shot	C:2		C: 3	
	10-5						C: 012 Shot
	5-0						
Combat Performance	No Action						
	Kill Enemy	A: Yes	B: Yes				C: Yes
	Evade Enemy			B: Yes C: Yes	B: Yes C: Yes	B: Yes C: Yes	
	Killed by Enemy						
	Damaged by Enemy		B: Yes	B: Yes		C: Yes	
	Spike Awareness		B: Yes	B: Yes		C: Yes	
Awareness of Enemy SAM/AAA		A: Unaware of AAA, flew over it while after shooting down Mig-29 and during locking up and verifying friendly B: Unaware of SAM, flew over it while shooting down Mig-29 C: Turned back flew over SAM again					
Awareness of Friendly Aircraft		A: Lock up friendly helicopter and verified status					
Self-Awareness	Deviation (track/altitude)	No unintentional deviation					
	Positional Awareness	No problem					
	A/C Control	No problem					
Situation Description		Sit A: Single Mig-29, radar lock beaming no real threat, shot tail on, flew over AAA, Mig-29 shot down, end Sit B: First Mig-29 hot, lock up and looked at Mig-23 then came back to Mig-29 to shoot, after shot, saw Mig-21 and also Su-35 and another Mig-23, shot by mig-29 reacted to RWR and broke left cold to defend, gave up radar picture, absorbed one shot though chaff/flare end Sit C: Turned back towards east, saw Mig-23, then Mi-24, Mig-21 and Su-35, realised Mi-24 nearest at only 6.7nm shot Mi-24 and saw another 5 aircraft: Mig-21, Mig-29, Su-35, Su-27 and Mig-23all at 25-30nm, then shot at Su-35, spiked by Su-35, broke left towards north to defend seeing only spikes on RWR end					

Fig. 1. Example of a completed observation sheet

The pilot knowledge of the enemy aircraft is noted with ranges, because the distance separation between aircrafts is one of the most important factors that influence all tactical decisions, game plans and maneuvers in air combat. The level of threat posed by an enemy aircraft is usually determined by its aircraft type and weapons, particularly its radar capability and weapon effective ranges. Knowledge of critical ranges is extremely important to successfully avoid detection and weapon employment by the enemy. Ranges, together with aircraft aspect (i.e., relative heading), determine the full picture of the threat level. For instance, an enemy at 20 nautical miles (nm) coming straight would be more threatening than one beaming (going across) at 15 nm. The monitoring of ranges also parallels the scrutiny of the temporal dimension. The elapse of ranges are reflective of the time elapse, except that in air combat the effects of elapsed time can be accentuated or attenuated by the effects of relative heading.

The SME, as far as possible, defines different critical situations based on the breaks in the chain of events or occasions. For every distinct events taking place during the mission, the observer has to provide an account and relevant comments on the development of the situation. This would make the assessment more meaningful, as the development of the processes of situations and the subsequent attainment of SA can be better understood in the context of the situation(s).

The SME analyzes the behavior and verbalized thoughts of the pilots to infer quality of SA achieved. The following annotation scheme is used to note the stage of pilot's knowledge of the enemy aircraft:

- Stage 0: when an enemy aircraft first appears on radar
- Stage 1: accurate identification of existence of the enemy aircraft
- Stage 2: accurate perception of the enemy aircraft, e.g., type, range, bearing, and altitude
- Stage 3: accurate interpretation of the enemy information, e.g., threat level, if there is an opportunity of getting into offensive position
- Stage 4: accurate prediction of the next status: e.g., enemy's reaction, projection of relative position.

For combat performance, the events associated with each bandit comprise "*no action*", "*evade enemy*", "*kill enemy*", "*killed by enemy*", "*damaged by enemy*" and "*spike awareness*" (the awareness of being engaged by the enemy aircraft). These events represent all the possible options available to the pilot when dealing with bandits. The accomplishment of these combat performance events would be recorded and was annotated by "yes" and "no" for each and every situation encountered during the mission. Therefore, the assessment of the participant's combat performance is specific to the respective situation but not to that of the overall mission. Self awareness is assessed in terms of occurrence of navigational deviation and loss of awareness of own position (lost or off-track through unintentional means, whereas deliberate deviation for engagement with enemy does not constitute loss of own awareness), occurrence of loss of control of own aircraft (i.e., flying the aircraft in out-of-acceptable speed/heading/altitude that may be construed as dangerous), and occurrence of loss of awareness of wingman's position.

For instance, in Figure 1, *situation B* (the gray-shaded part), can be read as follows. For enemy aircraft #2, the knowledge of the pilot in the range of 25-20 nm was noted by "B: 01234". This indicates that situation B began with the enemy aircraft #2 appearing on the pilot's radar display in that range and that *Stage 1* through *Stage 4* knowledge level was achieved. The vertical down-pointing arrow indicates the progress of the situation with the #2 bandit closing in until it got shot in the range bracket of 15-10nm. In the process as marked by the diagonal arrow pointing to the right, bandits #3, #4 and #5 also appeared on the radar and *Stage 3* achieved on #3 while only *Stage 1* achieved on #4 and #5. From the *Combat Performance* rows, the form indicates that #2 was destroyed but the participant also suffered damages though he was aware of the incoming missile from his positive *spike awareness*. The participant was also unaware of the SAM in situation B as indicated in the form.

3 Evaluation of the Process Tracing Technique

3.1 Advantages

An evaluation of the process tracing technique, with its associated observer assessment form in the representation format as shown, reveals its advantages as follows:

- The technique imposes minimal interruption to the task performance of the pilots. Although they were asked to think aloud during the mission, they were told to do so not at the expense of their performance. Indeed, pilots have been doing so since training days, and think aloud has become a habit. In instances when the participants did not verbalize their thoughts and actions, such information can be obtained during the debriefing by playing back the recorded mission.
- The completed form can provide an understanding of the dynamic changes of pilot's awareness and task prioritization. For instance, from the completed observation forms of the experiment [10], the following information regarding the situation assessment of fighter pilots can be obtained. When the participants encountered multiple enemy aircrafts at ranges *20nm* and beyond, *Stage 3* knowledge for all bandits can be achieved while up to *Stage 4* was obtained for the nearest bandit. The moment one to two bandits closed in within the participant's own weapon's range (around 20nm), more attention was allocated to these bandits. *Stage 3* was still maintained for the nearest and next nearest bandit but the knowledge level of the rest of the bandits had dropped to *Stage 2* or even *Stage 1*. If there were more than one bandit closing in to less than 10nm, information level of the other bandits was dropped to *Stage 2* or *Stage 1*. When one or more bandits were acquired and found to be inside *5nm*, the participant could only concentrate on one at a time to obtain a lock-on for shots. These were so-called "pop-out" bandits that had not been detected previously and had suddenly appeared and acquired by the pilot on the radarscope or JTIDS in close proximity. At such close ranges, the participant did not process information beyond *Stage 1* but only attempted to achieve lock-on and get the bandit within missile envelope (i.e., dynamic launch zone of missile or DLZ) and shoot as fast as possible. This was carried out without information processing to check for actual bearing, range and aspect angle, as they were not deemed as critical at that moment. Only after the nearest or highest-threat bandit was dealt with, he would then acquire information on others through radar search or JTIDS. The compression of time and space determined that once the enemy was within the killing zone, there was no need to "*spare extra brain bytes*" to process such information but to just get the bandit within weapon envelope and shoot.
- The technique was found to be able to reveal the differences in pilot SA when flying with and without the use of JTIDS. The differences identified were mainly

associated with *quality* (the level of completeness of the situation depiction). For instance, in a situation where there were multiple (more than two) bandits closing in from beyond 20nm, the pilots flying with JTIDS were noted to be able to achieve at least *Stage 3* and up to *Stage 4* knowledge, while they were only able to achieve up to *Stage 3* when flying without JTIDS.

3.2 Limitations

Despite of these advantages, several drawbacks of the tool were identified. First, although there was a noticeable difference in the speed of information processing and rate of SA development from initial detection (*Stage 1*) to interpretation (S*tage 3*) of bandits between operations with and without JTIDS, it was not clearly shown in the observation form. This suggests that the use of range (nm) as a reference to note down the SA progression is not sensitive enough. Second, to be valid, the judgment of SA level achieved by the pilots can only be done by SMEs who are highly experienced and have high exposure to the missions. However, this is unavoidable for a tool that is targeted to provide a specific and detailed assessment of SA. The dependency on the SME can perhaps be reduced with the use of a list of observable events and behaviors pertinent to good SA processes, such that trained observers can also perform the assessment. The achievement or non-achievement of these events can be used to indicate the level of SA attained, as well as the stages of situation assessment reached. Finally, it is difficult to quantify the overall pilot SA using this tool, which is sometimes required as an input for statistical analysis. As a result, comparing the SA level across pilots, missions, or system designs using this tool is not as straightforward as using other methods such as SAGAT and SART. Nevertheless, the method offers a deeper understanding of the processes involved in SA acquisition and maintenance, revealing the 'hows' rather than the 'whats' of SA.

3.3 Proposed Modification

Several modifications were proposed to mitigate the identified problems and to enhance the tool. An observation sheet with the proposed modifications is illustrated in Figure 2. The major modification is an inclusion of time dimension to the tool to improve the sensitivity in recording the progress in SA development. This time element also allows for easier interpretation of the data, informing what situation the pilot is facing from moment to moment, how many enemies he is exposed to at the same time frame, indicating his workload level and providing explanations to his achievement of SA. In addition, using this timeline format allows for an easier comparison of the SA progression across pilots or missions. Figure 3 used three lines to illustrate the different progressions in SA and action of the pilots. Line 1 shows that contact with the enemy is done within a shorter period of time compared to Line 2 and 3. A faster successful engagement would imply a more effective development of SA and weapon engagement by the pilot. Another situation where a pilot has a slow detection and interpretation of the enemy aircraft, which leads him to have a difficulty in gaining a point of advantage over the enemy and such that he has to evade for survival, can be translated in a similar shape to Line 3.

	Ranges (nm)	Time elapsed →				
		00:00	00:05	00:10	00:15	00:20
Enemy Aircraft	40-35	A: 0↓		B: 0↙ C: 0↓	B:1234	B: No Action
	35-30					
	30-25		A:1			
	25-20		A: 234		C:1	C: Damaged by C: Killed by
	20-15			A: Engage	C: Evade	
	15-10			A: Kill		
	10-5					
	5-0					
Spike Awareness			A: Yes		C: Yes	
SAM / AAA			SAM: Damaged by			
Friendly Aircraft						Loss awareness of wingman
Deviation (track)		On track	On track	Deviate	Deviate	Deviate
Deviation (altitude)		On track	On track	On track	Deviate	Deviate
Remarks			Unaware of SAM missile		Aware that enemy B is not a threat, no action is necessary	

Fig. 2. A simple illustration to the proposed modification

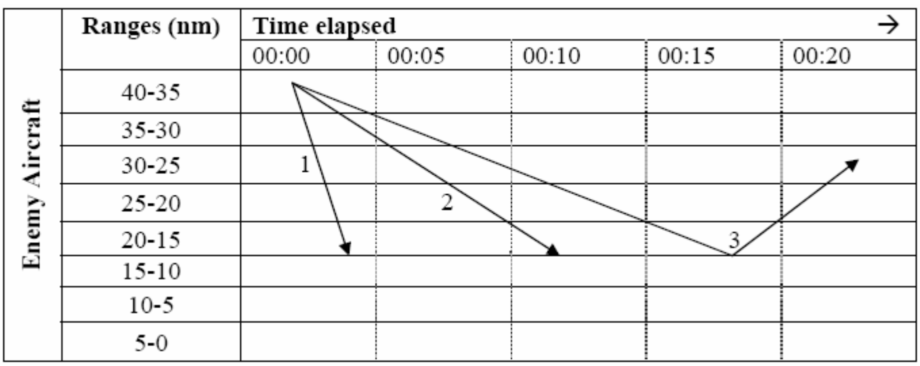

Fig. 3. Illustration of different progression in SA and action

Some modifications to the notation are also proposed, i.e., using alphabets to represent the enemy aircrafts instead of situations, and incorporating the actions taken to deal with the enemy within the time frame instead of on separate rows. Another additional feature proposed is to note the direction of enemy approaching. As mentioned previously, a combination of ranges and relative heading can indicate the threat level of the enemy aircraft. For instance, Figure 2 indicates that enemies B and

C are approaching at the same ranges, but B is beaming while C is coming straight. Thus, the pilot who understands that B has lower threat would decide to engage C first and perhaps ignore B if time and resources do no permit a successful engagement with B. As all of these are shown in the observation sheet, we can understand that "no action" taken on enemy B does not mean that the pilot had a low SA on B, but that he had a good picture of the overall situation and an effective management of resources.

4 Conclusion

Air combat environment is highly dynamic. A tool to assess pilot SA that does not alter this dynamic nature is desired. In this study, a measurement tool based on process tracing technique was evaluated. The tool was found to be powerful to elicit the situation assessment strategies and processes, produce comprehensive and detailed information on pilot SA, and trace the dynamic changes in SA from moment to moment. Based on this information, further investigation can be done to find out the source of SA decrement and the behavior that can help to recover loss of SA. The tool is thus viewed to have a good potential to be applied in air combat missions. However, some problems with the method were also noted, and modifications to minimize these problems were proposed. However, further studies to evaluate and validate this modified tool are required.

References

1. Endsley, M.R.: Situation awareness in aviation systems. In: Garland, D.J, Wise, J.A., Hopkin, V.D. (eds.) Handbook of Aviation Human Factors, pp. 257–276. Lawrence Erlbaum Associates, Mahwah (1999)
2. Endsley, M.R.: Toward a theory of situation awareness in dynamic systems. Human Factors 37, 32–64 (1995)
3. Carreta, T.R., Perry, J.D.C., Ree, M.J.: Prediction of Situational Awareness in F-15 Pilots. The. International Journal of Aviation Psychology 6, 21–41 (1996)
4. Endsley, M.R.: Situation awareness global assessment technique (SAGAT). In: Proceedings of the IEEE National Aerospace Electronic Conference, vol. 3, pp. 789–795 (1988)
5. Endsley, M.R.: Predictive utility of an objective measure of situation awareness. In: Proceedings of the Human Factors Society 34th Annual Meeting. Orlando Florida, pp. 41–45 (1990)
6. Endsley, M.R.: Direct measurement of situation awareness: Validity and use of SAGAT. In: Endsley, M.R., Garland, D.J (eds.) Situation Awareness Analysis and Measurement, pp. 147–173. Lawrence Erlbaum Associates, New Jersey (2000)
7. Taylor, R.M.: Situational awareness rating technique (SART): the development of a tool for aircrew systems design. In: Situational Awareness in Aerospace Operation (AGARD-CP-478). NATO-AGARD, Neuilly Sur Seine, France (1990)
8. Jones, D.G.: Subjective measures of situation awareness. In: Endsley, M.R., Garland, D.J (eds.) Situation Awareness Analysis and Measurement, pp. 113–128. Lawrence Erlbaum Associates, New Jersey (2000)

9. Endsley, M.R., Selcon, S.J., Hardiman, T.D., Croft, D.G.: A comparative analysis of SAGAT and SART for evaluations of situation awareness. In: Proceedings of the 42nd Annual Meeting of the Human Factors and Ergonomics Society. HFES, Chicago IL, pp. 82–86 (1998)
10. Tham, Y.M.: A study on the assessment of situational awareness of pilots operating with and without tactical data link systems in simulated air combat. Unpublished Final Year Report. School of Mechanical and Production Engineering, Nanyang Technological University, Singapore (2003)
11. Hollnagel, E., Pederson, O., Rasmussen, J.: Notes on Human Performance Analysis. Riso National Laboratory, Electronic Department, Roskilde Denmark (1981)