Evaluating SAVER: Measuring Shared and Team Situation Awareness of Emergency Decision Makers

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ABSTRACT

Large scale emergencies are usually responded to by a team of emergency managers or a number of sub teams for safety and efficiency. Team coordination has attracted considerable research interest, especially from the cognitive, human factors, and ergonomic aspects because shared situation awareness (SSA) and team situation awareness (TSA) of team members are critical for optimal decision making. This paper describes the development of an information system (SAVER) based on SSA and TSA oriented systems design. Validation and evaluation of the implemented design show that decision performance is improved by the SAVER system.

Keywords

Situation Awareness, shared situation awareness, team situation awareness, emergency, decision making.

INTRODUCTION

Large-scale urban emergencies such as tsunamis or volcanic eruptions are usually managed by several teams, e.g. police, healthcare, emergency managers, etc. The level of coordination within and between teams is so complex that if a single link fails it can risk the safety of the whole operation, for example, the mass evacuation of a city. Therefore, the coordination between teams is often supported by computer-based systems which can make available, process, and interpret huge amounts of information in a short space of time. A system design based on the shared situation awareness (SSA) of individuals and team situation awareness (TSA) can in principle improve the decision support performance of such systems.

In this paper we describe the design, development, and evaluation of a system we have dubbed Situation Aware Vigilant Emergency Reasoner (SAVER) based on SSA and TSA design principles. The paper first discusses SSA and TSA and their various definitions before presenting the SAVER design and implementation. It then details the experiments devised to evaluate SAVER and explains the results prior to drawing conclusions and making suggestions for further work.

SITUATION AWARENESS AND EMERGENCY DECISION MAKING

The first step in any type of decision making is understanding the situation so that its requirements can be fulfilled to achieve the decision makers' goals. Situation assessment done by an individual decision maker for naturalistic decision making is called situation awareness (SA) (Endsley, 1995).

Early work due to Adams et al (1995), Durso and Gronlund (1999), Smith and Hancock (1995) and Endsley (1995) has produced a range of definitions of SA and because there is no universally accepted meaning (Stanton et al., 2005) it is important to describe the way this particular study is using the concept. SA is often defined operationally in terms of the goals and decisions for a specific task (Endsley, 2000) so that a formal and broadly accepted definition of SA that has been found applicable across different domains describes SA as:

"The perception of the elements in the environment within a volume of time and space, the comprehension and the projection of their status in near future" (Endsley, 1988).

This definition reveals three levels of SA (Endsley, 2000):

Perception is level 1 of SA. It means understanding the importance of information about any situation. For example in the context of a tsunami, the earthquake magnitude, source location, depth and direction near an earthquake epicentre are related attributes.

Comprehension is level 2 of SA. It indicates how people combine, interpret, store, and retrieve information. Comprehension also covers the integration of multiple pieces of information and the determination of their relevance to a person's goals. For example, combining the SA level 1 attributes are described in the above example will indicate if the event is under water or near a coastline and, if so, whether its intensity will trigger a tsunami and its likely impact.

*Projectio*n is level 3 of SA. It is the ability to forecast new situations from previous and current ones. This ability allows for timely decision making that predicts future situations and counters risk. For example, wave height predictions and anticipated times of tsunami arrival on specified coast locations etc. can help to initiate controlled evacuations.

SITUATION AWARENESS IN COLLABORATIVE SYSTEMS

In larger events, several organizations may be involved in emergency response and management and these may be co-located or spread over multiple locations. Additionally, managers may have different cultural backgrounds, environment, educational, experience, and goals depending on their roles. Therefore, generating a common and accurate understanding of a situation that minimises error is a considerable challenge. Coordination is a key factor, especially as some participants may have expertise that needs to be accessed to handle various aspects of the emergency. In this regard, coordination has two aspects: coordination of people and organizations, and coordination of information and communications. The process of information coordination and decision support should ensure that managers have the information necessary for decision making bearing in mind that event data are frequently evolving and often uncertain and incomplete. The support system should also present data and information in readily usable formats.

Moreover, in emergency situations most decision making and associated actions involve teams composed of individuals from the same or multiple organizations, depending on the type and scale of the emergency. A team is defined as "*two or more people dealing with multiple information resources, who work to accomplish some shared goal*" (Salas, 2005). Due to the major requirement of team work in current disaster management organizations (Fiore et al., 2003), the concept of team situation awareness is currently receiving increased attention (Salmon et al., 2009; Stanton, 2010) from both the human factors and disaster management communities.

Shared Situation Awareness (SSA)

Shared Situation Awareness (SSA) refers to the SA requirements of individual team members that they hold in common (Endsley and Jones, 2001). In an earlier paper, Endsley and Jones (1997) defined SSA as: "*the degree to which team members have the same SA on shared SA requirements*". Endsley and Robertson (2000) also suggest that successful team performance requires that team members have a good SA for their individual circumstances and also the same SA for those elements that are shared.

Bolstad and Endsley (2000) propose that the development of SSA involves the following four factors:

1. Team SA Requirements – the degree to which the team members know which information needs to be shared.

2. Team SA Devices – the devices available for sharing this information.

3. Team SA Mechanisms – the degree to which team members possess mechanisms, such as similar training or combined training and exercises that help to build shared mental models.

4. Team SA Processes – the degree to which, team members engage in effective processes for sharing SA.

Superficially, the shared concept of SSA would seem to explain how individual SA scales to the team level. However, there is an additional dimension of interaction and awareness at the group level which we have to consider. To describe this interface we need to invoke the concept of team situation awareness.

Team Situation Awareness (TSA)

Team Situation Awareness (TSA) is much more complex than individual SA or SSA. Salas et al. (1995) argued that there is a lot more to TSA than just combining team members' SA. Also, due to other issues such as cognitive, social, and team interaction factors, research into the construct is challenging, scarce, and difficult the outcomes are sometimes confusing reflecting different backgrounds and approaches. TSA is multi-faceted comprising individual team member's SA, shared SA between team members, and also the combined SA requirements of the whole team. TSA is mostly understood as a shared understanding of the same situation (e.g. Nofi, (2000). Salas et al., (1995) suggest that TSA comprises two important, but badly understood processes, namely individual SA and team processes, and depends on communication at the various levels of SA. For example, perception of elements at level 1 SA is effected by communication of mission objectives, individual tasks and roles, team capability, and team performance factors. Similarly, the comprehension at level 2 SA is impacted by the interpretations made by other team members, so it is evident that sharing individuals' SA leads to the development or modification of other's SA. And the mental schema limitations of an individual can be offset by information exchange and communications (Salas et al., 1995).

Salas et al., (1995) consequently defined TSA as "*the shared understanding of a situation among team members at one point in time*" and concluded that

"*team SA occurs as a consequence of an interaction of an individual's pre-existing relevant knowledge and expectations; the information available from the environment; and cognitive processing skills that include attention allocation, perception, data extraction, comprehension and projection".*

Moreover, the most widely used model of SA provided by Endsley (1995) defines TSA as:

"*the degree to which every team member possesses the situation awareness required for his or her responsibilities*" (Endsley, 1995).

And it is argued if any one of the team members has poor SA, it can lead to a significant failure of the entire team (Endsley, 1995). However, this definition of TSA undervalues the team factor and concentrates on an individual's SA required for their responsibilities, rather than explaining team level SA.

A preferred approach due to Shu and Fruta (2005) conceives TSA as a partly distributed and partly shared understanding of a situation among team members. According to these workers in team situation awareness:

"Two or more individuals share the common environment, up to the moment understanding of a situation of the environment, and other person's interaction with the cooperative task."

This definition postulates that TSA has two basic elements, individual situation awareness and a differentiated form of shared situation awareness that the authors call mutual awareness (MA). Mutual Awareness (MA) refers to the awareness that individuals have of each other's activities, beliefs and intentions. For example, if team members want to recognize a situation cooperatively then, in addition to their own SA of the situation, each individual needs to recognize how the others sees the situation, and how these others sees the individual's SA (Javed et al., 2011). If any one of these three elements is missing then TSA is incomplete.

In addition, underpinning mutual awareness is the belief that team members are willing to cooperate in coordinated decision-making leading to task execution. The linking of situation awareness and cooperative action is a valuable aspect of Shu and Furata's definition that recommends its application to this work.

SITUATION AWARENESS ORIENTED INFORMATION SYSTEM DESIGN

There are two major belief systems in human factors work related to the design of systems; the technology-centered approach, and the user-centered approach (Endsley et al., 2003). Traditionally, systems have been designed from a technology-centered perspective but the user-centered design (UCD) is arguably a better approach to producing effective systems. Following the UCD approach, SA-oriented system design focuses on the development of information systems that support and improve users' SA so that they can make good decisions.

Supporting a user's SA is different in different domains (Endsley et al., 2003) and it can be achieved by describing the users' dynamic information needs in that particular domain as completely as possible. In the domain of emergency decision making, however, the literature suggests that the identified needs are invariably confined to the current physical tasks or procedures enacted by decision makers thereby ignoring the broader goals and leading to an incomplete knowledge of the decision-making requirements.

Information Presentation

Apart from the information needs of decision makers, SA requirements also focus on how information is integrated and presented to inform each decision (Endsley et al., 2003). The extent, the accuracy, the relevance to needs, and the manner of presentation of information are all critical influences on the generation of SA in the time-critical, dynamic, and complex scenarios that characterize emergencies.

However, most of the previous studies related to supporting emergency response operations have focused on identifying the low-level information required for carrying out tasks. There is a very little work that deals with the presentation of information to enhance the SA of the individuals or teams.

Situation Awareness Oriented Design Principles

Endsley et al., (2003) proposed 50 design principles for systems that aim to enhance SA and, more recently (Bolstad et al., 2006), she has prioritized eight of them as critical for good situation awareness. Briefly (see the Bolstad et al. paper for details) the eight main principles are as follows:

1. Organizing information around Goals: Displays and interfaces should present the information needed to support the decision making to achieve a particular goal.
2. Present level 2 SA information directly: Support comprehension by displaying information that is processed and integrated in SA terms. Reduce the need for users to process information.
3. Provide assistance for level 3 SA: Support decision making with systems that are capable of projecting future events and states of the current situation.
4. Support global SA: Design displays that deliver the big picture (e.g. an overall map visible at all times) and minimise attention narrowing.
5. Support trade-offs between goal-driven and data-driven processing: A balance between goal-driven and data-driven system design is required so that both can complement each other.
6. Keep the user focused on important attributes: This makes it easier for a user to bring their accumulated experience to bear on a situation and to amplify their awareness (Kaplan and Simon, 1990).
7. Take advantage of parallel processing: Parallel systems can save time by processing multiple information streams and validation checks concurrently.
8. Use information filtering carefully: Filter information to reduce overload but impose appropriate criteria to avoid removal of key material.

It is worth reiterating, however, that these principles are directed to improving individual situation awareness and they do not address SSA or TSA requirements directly.

SHARED AND TEAM SITUATION AWARENESS ORIENTED SYSTEM DESIGN

To extend the above principles to SSA and TSA, we have to go back to Endsley's seminal book on *Designing for Situation Awareness* (Endsley et al., 2003). From this source, we can deduce the following principles for shared and team situation awareness systems design:

- Build a common picture to support team operations showing the overall goals.
- Provide flexibility to support shared SA across tasks and team members.
- Support communication of comprehensions and projections across teams.
- Standardize information flows and formats.
- Supply information in explicit form so that team members share the same comprehension of a situation.
- Proactively share information to save time.
- Share team members' SA on request (pull) instead of broadcasting (push)
- Avoid information overload in shared displays.

We have used these principles to design and develop a prototype of a mass evacuation support system dubbed Situation Aware Vigilant Emergency Reasoner (SAVER) (Javed and Norris, 2011). SAVER employs proactive information sharing about the team's data requirements, goals, and tasks so as to enhance SA in all of its forms. The objective is to improve decision making and the execution of those tasks appropriate to mass evacuation. The remainder of this paper describes the research to validate the concepts and evaluate the situation awareness of individuals and teams with the SAVER prototype.

SITUATION AWARE VIGILANT EMERGENCY REASONER (SAVER)

SAVER is intended to draw together information from relevant sources to present it to emergency decision managers. The system is designed on the basis of the SA, SSA and TSA oriented design principles discussed in the previous sections. Apart from supporting SA, shared SA, and team SA for decision making, SAVER also provides recommendations for action reinforced by reasoned explanations. The manager can then evaluate the recommendations. This process provides confidence that key scenario factors have been identified and appropriate solutions considered. The human decision maker can override the system recommendations if he/she feels that SAVER has not addressed all of the relevant issues, although the more likely outcome is that the manager will find that the memory, pattern matching, and goal-orientated features of the system will fill the gaps in user knowledge and enhance situation awareness.

SAVER's operation employs the three-stage model of situation awareness (Endsley, 1995) outlined above. By providing the information about critical situation cues for the goals or tasks of the user at level 1, SAVER facilitates comprehension (level 2) of a situation in the form of projections and recommendations (level 3) to achieve user goals. An example is predicting the information required by various users according to their roles and various tasks during different phases of an emergency. Similarly, data received from sensors (e.g. earthquake or tsunami wave sensors) are directed to user(s) who need(s) them in a useable form and accompanying them with recommendations on their significance, e.g. whether the accumulated information indicates the generation of a tsunami or not. Moreover, providing and updating predictions about how situations might evolve gives managers foresight into which areas will require evacuation first, the special evacuation needs (e.g. schools, hospitals) of designated areas, and what type of resources will be required for evacuation.

Information about the SA requirements for various roles of emergency managers was gathered using a technique called Goal Directed Information Analysis (Prasanna, 2009). By structuring the SA ontologically within its architecture, SAVER generates logical rules and restrictions that can be used to derive inferences from assertions (Javed et al., 2011). To save managers' time and improve the shared and team SA, SAVER proactively shares the appropriate and required information appropriate to a particular team member amongst all team members.

SITUATION AWARENESS MEASUREMENT

Designing systems that support users in intensively complex situations is a significant challenge (Kirlik and Strauss, 2006) and clearly assessing the success of such designs depends upon the measurement of controlling factors or criteria. But how do we measure SA, which depends strongly on environment and task (Salas et al., 1995)?

Techniques for measuring SA fall into two basic categories; firstly, direct measurement, i.e. objective real-time investigations or subjective questionnaires assessing observed SA, and secondly, indirect measurement that infers SA based on a user's functional state, behaviour, or performance. Our approach to assessing individual shared, and team SA focuses on both direct and indirect approaches but we are reporting the results of objective measurements in this paper.

In using objective measures, an individual's perception (level 1 SA), comprehension (level 2 SA) and projection (level 3 SA) of a situation are compared with the simulated reality. Data can be collected in three ways (Saner et al., 2009); in real time as a task is being completed, during an interruption in task activity (freeze), or in a post-test after a task is completed. The best example of this approach is Situation Awareness Global Assessment Technique or SAGAT (Endsley, 2000). SAGAT can be used to measure SA on all three levels (Endsley, 1995). This type of measurement directly taps into the operator's perceptions rather than inferring them from the behaviours that may be influenced by other factors (Endsley, 2000).

We have built our SA measurement methodology on SAGAT by modifying it according to the requirements of shared and team SA measurement, which endeavours to capture both the cognitive and environmental determinants of SA. In principle, our computer-based system should enhance all forms of SA by reducing the cognitive workload associated with tasks such as short- and long-term memory retrieval thus allowing the user to concentrate on comprehension and projection.

Our measurement framework for shared and team SA is based on a team cognition model for mutual belief (Nonose et al., 2010). This model, which was initially proposed by Kanno et al., (2003), is composed of three layers of mental components that represent the structure of mutual belief in teams. The first layer represents an individual's cognition, the second layer represents beliefs in a partner's cognition, and the third layer represents a belief in a partner's belief (Nonose et al., 2010).

Though the model was reliable in their experiments, Nonose et al., (2010) used a subjective approach by asking users questions about how they felt about their own SA or team members SA. Because a user's belief about their SA may differ from their actual SA, we have adopted an objective approach by observing the direct performance of users to see what they know about themselves and about their team members.

Experiments

Experiments to measure the various forms of SA were carried out using the SAGAT methodology as described above and with teams of two persons. The tests were performed with and without SAVER to compare its effect. A web-based application for questionnaires was used to gather responses. A total of 58 questions was asked during four different freeze points. A stress factor was introduced by showing a timer with every question. The duration of a response was also measured since time is an important factor during emergency decision making. To reduce learning bias, experiments were done in two parts on two different days with more than a week apart. Out of a total of eight groups, four were asked to perform the experiment with SAVER first and then without

SAVER, and the other four groups were asked to perform experiments first without and then with SAVER. The results within these two groups were cross-checked and no significant difference between their performances was found (P-Value = 0.520) confirming that the performance of group members was not affected by the previous experiment session.

Scenario

A tsunami simulation scenario was used during the experiments and team members were asked to complete a situation report. First, SAVER provided information to individuals about an earthquake according to the SA oriented design and three levels of SA. The session was then frozen and a web-based application automatically opened with a question for the participant. A timer appeared along with the question to encourage a rapid response. Once, the participant had answered all of the questions at that freeze point, the scenario resumed and proceeded to the next point. Participants were asked directly about the situation, e.g. the location of the earthquake source, and answers were shared with team members once the question and answer session ended. At the next freeze questions were asked about the future evolution of the situation and about team members' understanding of it.

Before each question session SAVER provided participants with the information needed to perform the tasks demanded by their assumed roles required at that specific phase of the emergency (see Figure 1). Participants were allowed to use web sources and communication with the partner if required.

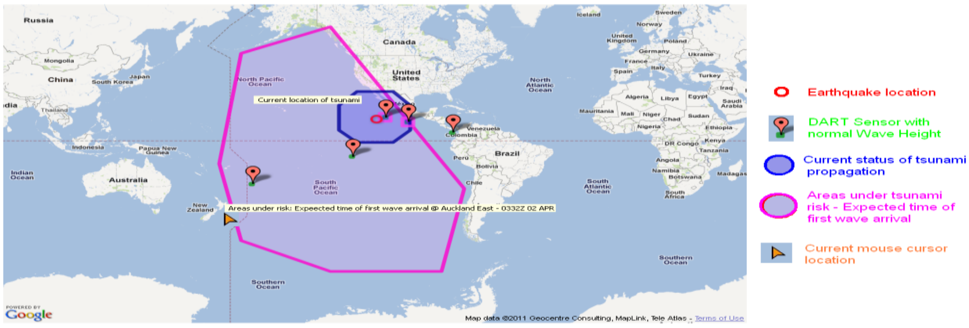


Figure 1. Screenshot of SAVER showing current tsunami location and its expected arrival time at coasts

When participants were not using SAVER, they were provided with a website similar to the United States Geological Survey **(**USGS) providing the earthquake and Deep-Ocean Assessment and Reporting Tsunami (DART) information available on the National Oceanic and Atmospheric Administration (NOAA) website. They had to process the information needed to complete their situation reports. When not using SAVER, the participants were also allowed to use the Internet and communicate with their partner. During both type of experiments participants were asked the same questions but with changed scenario data.

All the participants (n=16) were real emergency managers with 2 (novice) to 8 (experienced) years of practical experience and all of them had participated in either a real event or in a national exercise. All participants were asked questions about their perception, comprehension, and projection. In addition, they were asked about their information and SA requirements that were common to them and their team member to measure shared SA. Similarly, they were also asked about their team member's perception and projection for team SA.

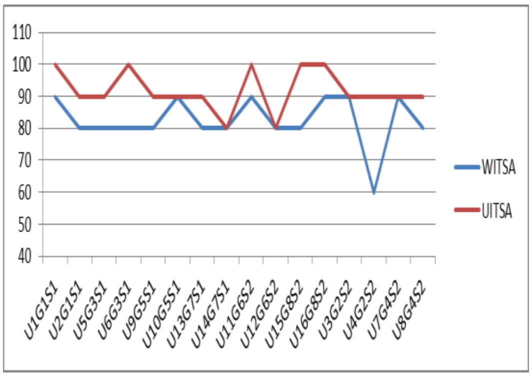
RESULTS AND DISCUSSION

At a freeze point, questions were asked about each of the three SA levels. The total number of correct answers (as a percentage) was then calculated as a measure of SA. The same approach was adopted to calculate equivalent measures for SSA and TSA. Individuals were coded according to their own unique identifier U1, U2…), their team's identifier (G1, G2…), and whether he / she performed the experiment with SAVER first or not. For example, user 1 in group 1 using SAVER in the second session is coded as U1G1S2. Figures 2a-2c show the results of the impact of SAVER on individual SA, SSA and TSA and Figures 3a-3c show the results on the group values of these awareness measures. In these graphs, the red lines correspond to experiments using SAVER (UI[SA, SSA, TSA]) and the blue lines indicate experiments without SAVER (WI[SA, SSA, TSA]).

Figure 2a shows the results of measuring individual SA with and without SAVER. The results show that individuals who have used SAVER performed very well compared with those who did not. Moreover, an independent sample t-test was conducted and a significant difference was found in the score with using SAVER (M=82.6, SD=8.4) and the score for without using SAVER (M=73.0, SD=10.5); T-Value = -2.84, P-Value = 0.008.

(a: SA)

(b: SSA)



(c: TSA)

Figure. 2. Comparison of individual SA measurement results with (UISA, UISSA, UITSA – red line) and without (WISA, WISSA, WITSA – blue line) using SAVER

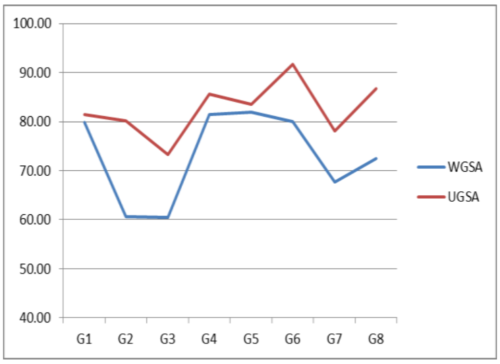
Figure 2b shows the results of measuring shared SA with and without SAVER. They reveal that there is an improved performance by those using SAVER during the experiment. An independent sample t-test shows that a significant difference is found in the scores for participants using SAVER (M=78.6, SD=9.0) and those not using SAVER (M=62.1, D=18.0); T-Value = -3.27, P-Value = 0.004.

Figure 2c shows the results for measuring team SA with and without using SAVER. The result of using SAVER is considerably better than the results for not using SAVER. The independent sample t-test shows a significant difference in the scores for participants using SAVER (M=91.9, SD=6.6) and the score for not using SAVER (M=82.5, SD=7.8); T-Value = -3.70, P-Value = 0.001.

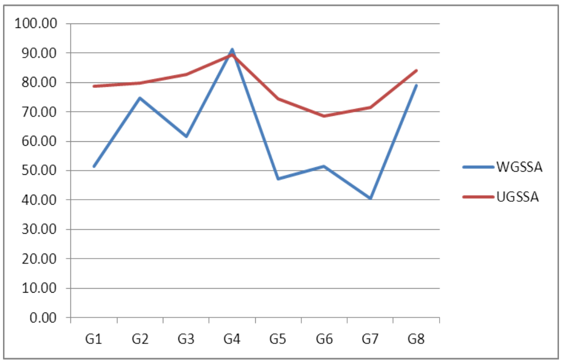
The results for groups were obtained by summation of group members' scores together and it is found that all measurements for SA, shared SA, and team SA are statistically significant, see Figures 3a – 3c.

Figure 3a shows the results for measuring team SA with and without using SAVER. An independent sample t-test for group SA shows that there is a significant difference in the score for using SAVER (M=82.6, D=5.6) and score for not using SAVER (M=73.1, SD=9.1); T-Value= -2.51, P-Value = 0.029.

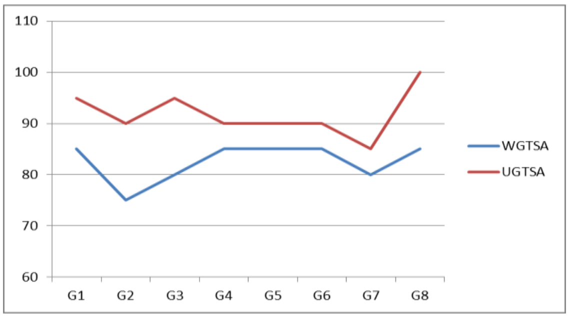
Figure 3b shows the result of shared SA measurement for groups. There is a huge improvement in the score of a group that used SAVER during the experiments. From the independent sample t–tests there is a significant difference in the score for using SAVER (M=78.6, D=6.9) and score for not using SAVER (M=62.1, SD=17.8); T-Value = -2.45, P-Value = 0.037.



(a: SA)



(b: SSA)



(c: TSA)

Figure. 3. Comparison of Group SA measurement results with (UGSA, UGSSA, UGTSA – red line) and without (WGSA, WGSSA, WGTSA – blue line) using SAVER

Figure 3c shows the result of shared SA measurement for groups. There was a huge improvement in the score of a group that used SAVER during the experiments. By using the independent sample t–tests it is shown that there is a significant difference in the score for using SAVER (M=78.6, D=6.9) and the score for not using SAVER (M=62.1, SD=17.8); T-Value = -2.45, P-Value = 0.037.

The results above show that individual SA, shared SA, and team SA were all improved by using SAVER during the experiments. It appears that the SAVER's SA-oriented design improved SA by providing individuals with information in a format that helped them to improve their attention and also remember details by supporting their short term memory with relevant information processing. Similarly, by sharing the information about team members, SAVER allowed them to know about their team members' understanding of situational cues and their beliefs, which enhanced team situation awareness. Moreover, team SA was also improved because the demand on team members' cognitive resources was lower when SAVER was doing most of the processing for them and also when they were considering its recommendations and suggestions for answering the questions. This last observation was supported by using other questions in the survey in which users were asked to rank the sources that they used every time they answered complex questions that needed some processing. Most of the users who were not using SAVER, ranked communication with their partner as their first priority and previous experience as second whereas most of the individuals who used SAVER preferred SAVER's suggestions over their experience. This result could be attributed to the fact that the experiment was a simulation not a real.

SAVER shared information about team members' SA requirements that helped team members to assess the common SA requirements correctly, and ultimately the shared SA of individuals who used SAVER was much higher than those who did not use it. This suggests that a system with such features can be very useful for real events.

A current limitation of this prototype study may be that the simulated scenario was too easy or too predictable. We intend to conduct further experiments with more complex scenarios to test this suggestion.

CONCLUSION

This paper has described the design and evaluation of a decision support system (SAVER) for emergency managers using a mass evacuation scenario arising from a tsunami simulation as a test case. The paper identified situation awareness design principles and discussed the development of an evaluation process to test if SAVER could improve the individual, shared, and team situation awareness of users. The results, although obtained with simple scenarios, strongly suggest that the system design and architecture do indeed enhance the situation awareness of team members and by extension the quality of the decisions they make when dealing with emergencies.

Further systems design and evaluation with more complex scenarios seem likely to confirm this suggestion and lead to a very fruitful line of research that could have a significant impact on the design of collaborative emergency management systems.

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