Situation Awareness, Communication, and Teamwork: Re-examining the Role of a Team Display in Wildland Firefighting Command and Control

by

Chunyun Ma

A thesis submitted to

the Faculty of Graduate and Postdoctoral Affairs

in partial fulfillment of the requirements for the degree of

Masters of Arts

in

Psychology

Carleton University

Ottawa, Canada

Your file Votre référence
ISBN: 978-0-494-87775-3

Our file Notre référence
ISBN: 978-0-494-87775-3

Abstract

This study tested whether a team-oriented display can enhance teamwork and situation awareness (SA) especially with communication breakdown. It built up on previous studies concerning team display in a forest firefighting command and control context (Brandigampola, 2011). Thirty two dyads of undergraduate students played a team with a micro-world simulation of forest firefighting command and control (C2), with and without a team display, and their performance and SA were measured. In general, the results support the hypothesis that the team display can significantly facilitate SA and performance and reduce the negative impact of communication breakdown. With the team display, significant improvement of SA was observed for one team member—Incident Commander—even with communication breakdown; but such benefits were less consistent for the other team member—Ground Chief. The fundamental question whether improved performance with the team display was due to improved SA is discussed along with practical implications to other C2 fields.

Acknowledgements

Upon completing this thesis, I have so many people in my mind to whom I feel indebted in more ways than I can now reconstruct or evaluate. First, I want to thank my supervisor Dr. Avi Parush for his patient guidance, enthusiastic encouragement and useful critiques and I am looking forward to pursuing my Ph.D. under his supervision. Whenever I look back, I'd always remember two moments which I think changed my life—the very morning when I was still in China and Dr. Parush informed me through email that I was accepted by Carleton University; the day when Dr. Parush offered me the opportunity to join his research project on patient safety as a research assistant through which I have gained invaluable research experience.

My sincere thanks also go to Dr. Craig Leth-Steensen for his guidance in experimental design and statistical analysis. I would like to thank Dr. Momtahan, Dr. Logan, and Dr. Sears for serving on my committee and providing constructive comments and suggestions. I would also like to thank Geneviève Dubé, Denis Ouellet, and David Emmanuel Hatier from Université Laval, and Dr. Rego Granlund in Sweden for their generous help and countless replies to my questions with the simulation used in my study.

Special thanks should be given to Etelle Bourassa, our graduate advisor, who is always helping me with every important detail throughout the whole process.

I would like to extend my thanks to Seneca Brandigampola, from whom I learned valuable experience and lessons and later applied them in running experiments. Thank you Sharmili Shanmugaratnam for spending hours helping me proofread my thesis. Thank you Clare Mckennirey for helping me with data input even when you were already busy with your final exams.

I want to thank all my dear friends in Canada and back in China, who have been always by my side through thick and thin. Finally, I feel deeply grateful to my family for their continuous support, financially— and more importantly, spiritually, whom I could not have done this without.

Table of contents

List of Figures

List of Tables

List of Appendices

Introduction

On July 6, 1994, thirty-six fires were already burning in the Grand Junction District, near Glenwood Springs, Colorado, and the District Dispatch received calls reporting fire progresses or new fires within its jurisdiction every few minutes. A fire at the South Canyon which had been reported to the District Dispatch three days ago was escalating. Initially covering a half acre, the spotter described the fire as 30 acres, on extremely steep terrain, and burning downhill in all directions. The District Dispatch had assigned various firefighting resources to this fire, including smoke jumpers, air tankers, lead planes, etc.

The fire weather forecast had issued a RED FLAG WARNING for the Grand Junction area earlier that morning. At 3:20 p.m. a dry cold front moved into the fire at South Canyon area. As winds and fire activity increased, the fire made several rapid runs with 100-foot flame lengths within the existing burn. At 4:00 p.m. the fire crossed bottom of the west drainage. It spread up the drainage on the west side. It soon spotted back across the drainage to the east side beneath the firefighters and moved onto steep slopes and into dense, highly flammable Gambel oak. Within seconds a wall of flame raced up the hill toward the firefighters on the west flank fireline. Failing to outrun the flames, 12 firefighters perished. Two helitack crew members also died when they tried to outrun the fire to the northwest.

The tragedy described above has been adapted from a lengthy report of the South Canyon fire (South Canyon Fire Accident Investigation Team, 1994). In the aftermath of this entrapment, investigators found that, despite the various multi-level factors involved, critical fire weather indicators of blow-up conditions were not recognized by fire mangers; nor did firefighters receive or request spot fire weather forecasts from the Grand Junction District Dispatch (South Canyon Fire Accident Investigation Team, 1994).

In the above case, teams of experts in the forest firefighting domain who were responsible for command and control (C2) tasks played a critical role during fire suppression. The effectiveness of their teamwork, however, is not always guaranteed. A great deal of work has been conducted either to understand the factors that contribute to or degrade effective teamwork (Salas, Dickinson, Converse, &Tannenbaum, 1992; Cannon-Bowers, Tannenbaum, Salas, &Volpe, 1995; Salas, Stagl, &Burke, 2004b) or to enhance teamwork through various means such as designing tools to support teamwork (Wellens, 1993; Wright & Kaber, 2005; Davenport, 1997). In view of the criticality of teamwork in extreme circumstances, and as a follow up study to examine the efficacy of team-oriented information displays, the present research had two purposes: first, to explore and replicate the relations between Team Situation Awareness (TSA) and teamwork in simulated extreme circumstances; and second, to empirically test the effectiveness of a team-oriented information display in supporting teamwork of command and control teams in the wildland firefighting domain through a simulation.

The choice of the wildland firefighting domain is because in an immensely forested country like Canada, with 453 out of 922 million ha[1] covered with forest (Pyne, Andrews, &Laven, 1996), wildland fires can pose significant threats to life and property, livestock, communities, local economies, natural resources, and the environment. For

---

[1] ha is a written abbreviation for hectare. A hectare is a measurement of an area of land which is equal to 10,000 square metres, or 2.471 acres.

example, about 9,100 forest fires occur annually in Canada. The mean annual national burned area is 2.5 million ha, and 85% of it is accounted for by lightning fires. About $300 million is spent annually across Canada in dealing with forest fires. Although Canada enjoys a relatively low rate of fatality in fighting wildland fire, the situation is not completely optimistic. In an annual report of the Canadian Interagency Forest Fire Centre, 33 firefighters were killed during fire suppression in the last two decades (Canadian Interagency Forest Fire Centre Inc., 2010). Given the high potential for causing failures that lead to catastrophic consequences, research efforts that aim to reduce loss and increase safety in this domain are warranted. In addition, C2 tasks in such circumstances are fairly typical: interacting with dynamic information from multiple sources and collectively making safety-critical decisions. Thus this context provides a very relevant test-bed when examining the role of TSA and team displays in extreme C2 circumstances. Research findings in this domain could then be extrapolated to similar domains such as air traffic control, nuclear power plant, and other similar circumstances.

Scope of This Research

This present research addressed some of the key characteristics of teamwork in extreme circumstances. These characteristics are typical in a family of organizations, such as nuclear power plant and air traffic control, which is often collectively referred to as High Reliability Organizations, or HROs (those that exist in hazardous environments where the consequences of errors are high, but the occurrence of error is extremely low, see Baker et al., 2006, for more detail). Because some of those characteristics can also be inferred from the case presented previously, the following analysis uses that case to illustrate these characteristics whenever applicable.

Command and control teams (C2 teams). According to Curts and Campbell (2006) C2 can be defined as the exercise of direction by a designated leadership over resources in the accomplishment of a mission. The principal functions of C2 concern planning, directing, coordinating, and controlling the employment of available resources (Lafond, Vachon, Rousseau, &Tremblay, 2010). Although not explicitly mentioned in the case above, a team consisting of people from the District Dispatch and fire managers out in the fire ground played a key role in this case by executing C2 functions. None of them were engaged in actual firefighting activity; instead they were responsible for receiving and responding to information and requests, as well as for directing firefighting resources optimally. Similarly, air traffic controllers work as a team (e.g., terminal controllers and en-route controllers) and direct aircraft on the ground and in the air; their responsibilities are to separate aircraft to prevent collisions, to organize and expedite the flow of traffic, and to provide information and other support for pilots (Federal Aviation Administration, 2010). Failing to meet such duty could lead to dire consequences (Gorman, Cooke, &Winner, 2006).

Coordination and communication. In a decision-rich context like the C2 team in this case, task accomplishment relied on each team member working collectively toward the same goal and monitoring each other's performance simultaneously. Consequently this entails a large amount of information exchange. Such needs are often intensified as the team operates in a geographically distributed manner due to lack of visual cues and restricted information flow. In forest firefighting, for example, fire managers need to opportunely report firefighting progress from the ground to the District Dispatch so that appropriate plans for resource distribution can be made in advance. Also, forecasts of fire weather and other critical information need to be relayed to firefighting mangers; otherwise grave consequence could result. In aviation, for example, 26 people died when two US Army Black Hawk helicopters were mistakenly shot down by two USAF F-15Cs performing routine sweep operations. Investigators pointed out later that the tragedy could have been avoided if the enroute controller had explicitly informed the other controller about the unusual presence of the two Black Hawks in the no-fly zone (NFZ; Gorman et al., 2006).

Team situation awareness. Situation awareness has sometimes been informally referred to as "knowing what is going on". In team settings, this is an implicit yet critical factor for all sorts of C2 tasks, which often involve decision making based on constantly changing information. Decisions by a C2 team member based on incomplete/inaccurate information could cost dearly. In the previous case, for example, fire managers failed to recognize the adverse weather condition (i.e., escalating wind condition) and following decisions (e.g., crew deployment) contributed to the catastrophe afterwards.

Technology as an organic component. Radios and telephones are ubiquitous in C2 teams such as the one in the previous case. In addition, to support decision making tasks, graphic displays of various sizes are also widely adopted in wildland firefighting and similar domains.

Figure 1 shows an example of how large group displays (LGDs) are being used in modern C2 centers, in this case at the Australian Defence Force Warfare Centre. In this example, in addition to having access to their own personal displays, the users have access to a range of shared displays including LGDs and a number of smaller displays used to provide ambient information and for activities such as video teleconferencing

(Goin, Vernik, &Wark, 2010). Figure 2 is a picture taken during a visit to the Ministry of Natural Resources forest firefighting control center in Sudbury (Canada; A. Parush, personal communication, August 11, 2011). It illustrates the typical working environment in wildland firefighting under which a C2 team operates.

The design and efficacy of large group displays have been systematically addressed in previous studies. Design principles were first proposed in a study that looked for means and devices to mitigate the potential detrimental impact of information loss by a TSA augmentative display in the cardiac operation room (OR) (Parush et al., 2011b). Such principles were then applied to a different, yet intrinsically similar field—forest firefighting—to further explore their generalizability, where a team-oriented information display has demonstrated benefits to TSA (Brandigampola, 2011). The proposed study here will continue with this line of research by adding information loss circumstances to the scenario, thereby testing if a team display can enhance teamwork in a forest firefighting C2 context by facilitating recovery from communication breakdown.

In the following sections, the scope of this research will be delineated in more detail. To start with, as teams have become an indispensible element in coping with challenges within HROs due to its unsurpassed advantages over individuals, the next section will discuss existing research on team, teamwork, and their implications to pertinent domains.

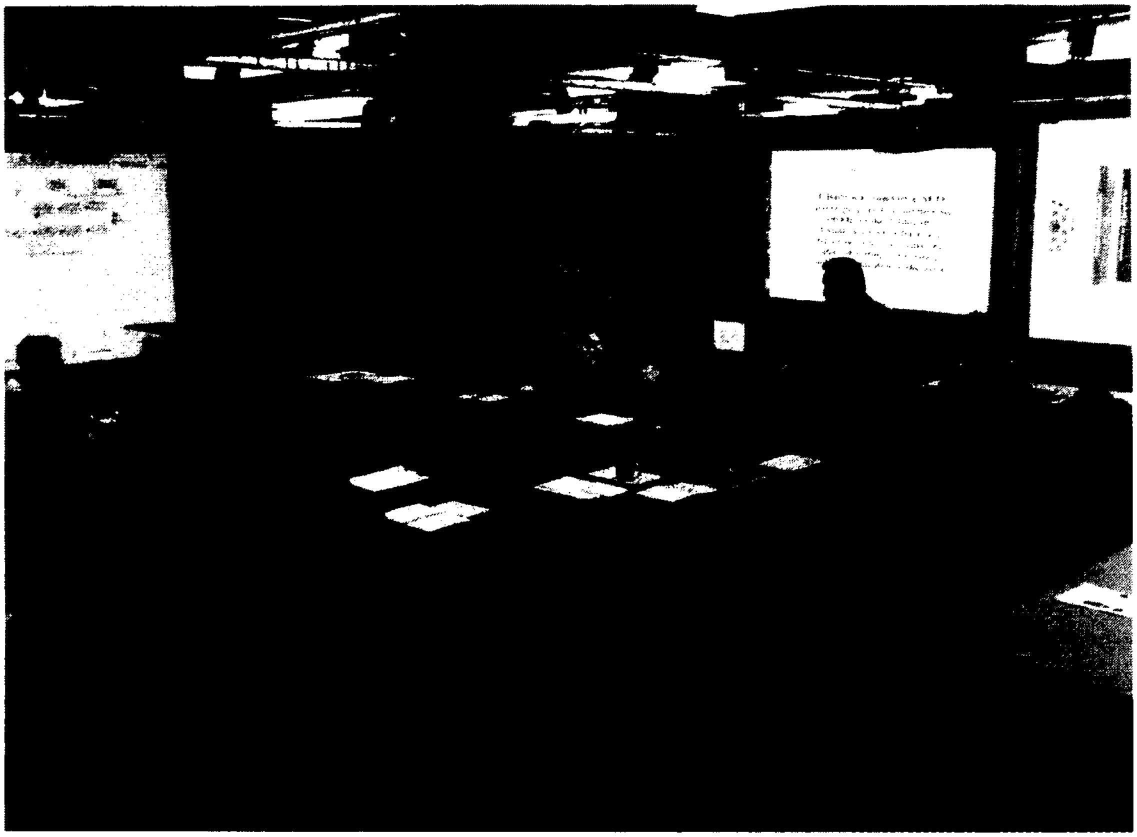


Figure 1. Large Group Displays being used at the Australian Defence Force Warfare Centre (Goin et al., 2010).

Figure 2. Command and Control center at the Ministry of Natural Resources forest firefighting control center in Sudbury, Canada (A. Parush, personal communication, August 11, 2011).

Teamwork in HRO C2

Definition and characteristics of C2 teams. Teams are prevalent in aviation, military, healthcare, nuclear power plants, manufacturing, and countless other domains where the task complexity exceeds the capacity of an individual. As the complexity of the workplace continues to grow, organizations increasingly depend on teams. As has been mentioned previously, teams and teamwork are especially significant in HROs where effective teamwork is critical to being safe (Wilson, Salas, Priest, &Andrews, 2007).

Salas and his colleagues (1992) have defined a team as "a distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/object/mission, who have each been assigned specific roles or functions to perform, and who have a limited life span of membership" (pp. 4). General agreement has been reached among many researchers (Dyer, 1984; Morgan, 1986; Salas et al., 1992; Paris, Salas, &Cannon-Bowers, 2000) as to variables that define a team (e.g., task interdependency, multiple sources of information, coordination among members, common and valued goals, specialized member roles and responsibilities, task-relevant knowledge, intensive communication, adaptive strategies to help respond to change).

Teams operating in highly complex and dynamic environments that are engaged in organizing and managing various resources are referred to as command-and-control teams—C2 teams (Salas, Burke, &Samman, 2001). Jones and Roelofsma (2000) described a C2 team as representing two or more individuals with specialized and interdependent roles who are necessarily brought together to perform complex, decision rich tasks in order to achieve goals that are central to those of the organization. Implicit in this definition are four dimensions that distinguish C2 teams from other types of teams (Jones & Roelofsma, 2000; Sundstrom, de Meuse, &Futrell, 1990): (a) the degree of task specialization, independence and autonomy of team members, or differentiation of members; (b) the degree to which the team activities are central to the goals of the organization as a whole, or organizational integration; (c) the degree to which team members actively engage in decision-making relevant to the accomplishment of the task; (d) the extent to which the team is necessary, as opposed to preferable, for carrying out the task. Therefore, C2 teams, such as military teams, firefighting units, medical emergency teams, and cockpit crews, are highly differentiated teams, generally highly integrated within the organizational structure, actively engage in decision-making, and are indispensable.

Team cognition and team effectiveness. Given its essentiality in industry, especially in HROs, there is more and more research on teams and teamwork, especially on what teams do, how they do it, why they do it, and how we can improve what they do. This section will briefly summarize those research efforts with the focus on team cognition and how it contributes to team effectiveness.

Team members need to possess certain knowledge that allows them to function effectively as a team. At a holistic level, i.e., when such knowledge has been processed or integrated in some way through team behaviors such as communication, coordination, or leadership, they could be referred to as *team cognition* (Cooke, Salas, Kiekel, &Bell, 2004). Cooke once defined team cognition as "[which] emerges from the interplay of the individual cognition of each team member and team process behaviors" (Cooke et al., 2004, p. 86; Cooke, Gorman, Duran, &Taylor, 2007, p. 155). This definition implies that team cognition is more than the sum of the cognition of the individual team members.

Team cognition has been investigated in the form of shared mental models (Cannon-Bowers, Salas, &Converse, 1993; Mathieu, Heffner, Goodwin, Cannon Bowers, &Salas, 2005), team situation awareness (Salas, Prince, Baker, &Shrestha, 1995; Salmon et al., 2008a), and together with others, all of which are generally viewed as contributing to team effectiveness (Mathieu, Heffner, Goodwin, Salas, &Cannon-Bowers, 2000; Salas & Fiore, 2004). Moreover, given the inability of these cognitive processes to be observed directly, communication on the team level is viewed as a central mechanism of information processing and is therefore used to study team cognition (Parush et al., 2011b; Foltz et al., 2008).

An accumulating body of evidence suggests shared mental models serve to facilitate coordinated team action (Blickensderfer, Cannon-Bowers, &Salas, 1998; Mathieu et al., 2000; Lim & Klein, 2006). This line of investigation is founded on the premise that team synchronicity can be achieved when team members develop clusters of shared and accurate instantiated knowledge structures (i.e., shared mental models, or SMM). Essentially, team members operating from a SMM have a common conceptual framework which enables them to perceive, interpret, and respond to dynamic environments in a synchronized, adaptive fashion (Salas, Stagl, &Burke, 2004a).

In contrast to mental models, situation awareness (SA), another cognitive process sometimes also referred to as "knowing what is going on", has a more dynamic nature. Considering the characteristics of C2 teams in a HRO context, which include dealing with constantly changing information, SA has been recognized as one of the critical constructs in team effectiveness (Salas et al., 1995). Actually, considerable research has documented the importance of SA for effective teamwork across a broad range of domains, from aviation (Vidulich, 2003) to emergency medical dispatch centers (Blandford & Wong, 2004) to military command and control (Gorman et al., 2006). In the following section, studies of this construct and its association with teamwork will be briefly outlined.

Situation Awareness (SA) in Team Settings

SA has been shown to be important in a variety of domains in which an up-to-date assessment of changing environment is often crucial in accomplishing tasks (Blandford & Wong, 2004; Klein, Calderwood, &Clinton-Cirocco, 1988; Roth, Multer, &Raslear, 2006; Stanton, Chambers, &Piggott, 2001). Examples include aircraft, air traffic control, tactical and strategic systems (e.g., forest fire suppression) to name a few. Problems with SA are consequently ubiquitous in these domains (Endsley, 1995b). In an investigation of causal factors underlying aircraft accidents involving major air carriers in the United States, 24 NTSB (National Transportation Safety Board) accident investigation reports from 1989 to 1992 were reviewed (Endsley, 1995a). It was found that the most prevalent causal factor (15 cases) was the aircrew's or controller's situation awareness. Likewise, Gibson (1997) reviewed incident reports gathered from the time period of November 1995 to March 1996 through the Aviation Safety Reporting System (ASRS). SA errors were identified in 205 out of 590 incidents as contributing factors (Gibson, 1997). In C2, Durso and colleagues (1998) studied 388 operational reports filed in 1993 and compared errors made by air traffic controllers who had SA with those who had lost it. The results showed that, among all these incidents, 62% of the controllers were 'unaware' that an operational incident was developing comparing to 38% were 'aware' of the situation but unable to rectify it in time. Further analysis revealed that a controller's unawareness of an impending error affects its severity and implicate different factors as the cause of that error.

Definition of SA. Although SA has been identified as critical, it is not well understood. Rousseau et al. (2004) suggested that a major problem with situation awareness is the lack of a common conceptualization. The definition based on Endsley's (1995b)three-level model has been adopted most widely in literature and was expressed in similar terms by other authors (e.g., Domínguez, 1994; Tenney & Pew, 2006):

> 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 (Endsley, 1995b, p. 36).

To better understand the concept of SA, it is also helpful to consider what is *not* SA:

State vs. process. Despite the fact that debates remain as to whether or not SA should be conceived as state or process (Durso & Sethumadhavan, 2008; Patrick & James, 2004), Endsley's definition explicitly perceives SA as a state. She further claims that SA is the resultant state of knowledge about the situation in the mind of the human operator which should be distinguished from the cognitive processes such as perception, comprehension, etc., which are responsible for achieving it by the human operator (Endsley, 2000; Stanton, 2001). The latter is often labelled as situation assessment. Generally, this distinction characterizes different research directions. While a better knowledge of SA requirements (SA as state) in particular domains has been achieved, it is less well understood how operators come to build up their situation awareness (SA as process) (Durso & Sethumadhavan, 2008).

Dynamic vs. static knowledge. Situation awareness consists of ever-changing information in the working environment. This contrasts with more static knowledge. Take bike riding for example, SA in this context would be being aware of passing pedestrians, vehicles, etc., rather than static knowledge such as traffic rules, although both types of knowledge are necessary for safety.

Distinct from decision making and performance. SA is closely linked to decision making as its main precursor (Endsley, 2000b) yet distinct from it. SA affects decision making partly through framing effects (Endsley, 1995b). As for performance, SA has not been directly linked to it although predictive relationship between them is often expected. Until now, mixed results still persist on this issue (Durso, 1998; Foltz et al., 2008; Salmon et al., 2008b). In a previous study (Brandigampola, 2011), dyads of participants took the roles of commander and operation officer and simulated as a firefighting team. Results showed that SA was not related to performance in the sense that the presence of a team display had significant impact in improving SA accuracy but not performance. Nevertheless, studies from both laboratory and field have shown that SA is closely related to performance (Sulistyawati, Chui, &Wickens, 2008; Durso, 1998; Farley, Hansman, Amonlirdviman, &Endsley, 2000). It is generally accepted that good SA can be viewed as a factor that will increase the probability of good performance but cannot necessarily guarantee it (Endsley, 1995b).

Separate from other cognitive factors that may influence it. The role of multiple cognitive processes and constructs in SA, including mental models, perception, attention, among others, has undergone extensive research efforts. While some models have been proposed (e.g., Endsley's three level model, 1995; Smith and Hancock's perceptual cycle model, 1995), for the most part, however, they all point out that SA is largely affected by a person's goals and expectations facilitated by mental models or schemata, which in turn influences where attention is directed, how information is perceived, and how it is interpreted.

Separate from other environmental factors that may influence it. Task and system factors that affect SA include system design, interface design, stress, workload, complexity, and automation. It is worth mentioning that workload and SA have been shown to be essentially independent constructs (Endsley, 1993; Durso, 1998; Wickens, 2008). In a meta-study through LISREL models (LInear Structural RELations, a statistical software package used in structural equation modeling), for example, subjective ratings of SA evidenced distinctive contribution when explaining the relationship between mental workload and performance (Nählinder, Berggren, &Svensson, 2004). Only under high levels of perceived workload will decrements in SA be expected. However, SA problems may also occur under low workload (due to vigilance problems). Thus, SA and workload may dissociate in various ways, depending on characteristics of the system design, tasks, and the individual operator (Endsley, 2000b).

In summary, SA could be viewed both as a process and a state that is separate from, but closely related to a number of internal and external factors. Together, they generate up-to-the-moment knowledge of the ever-changing environment which is then utilized as input for decision making and resultant performance by individuals. Since these individuals sometimes work concertedly as a team, the construct of SA has also been extended to the team level.

Definition of team situation awareness. At the team level, SA has been investigated in terms of team SA (TSA). It has been pointed out that TSA represents far more complexity than does simply combining the situation awareness of individual team members (Salas et al., 1995). Similarly, Endsley (1995b) commented that team SA involves unique activities, such as coordination and information sharing, although her three-level framework was criticized for underestimating the importance of communication when addressing SA in team settings (Gibson, 1997; Salmon et al., 2008b). In Salas's (1995) seminal work, he observed that TSA encompass at least individual SA and team processes (i.e., teamwork behaviors and cognitive processes) that facilitate team performance. He further defined TSA as "at least in part the shared understanding of a situation among team members at one point in time. This state of awareness is facilitated by team processes or behaviors that allow shared assessments to be developed and maintained." (Salas et al., 1995, p. 131)

Strictly speaking, there are slight differences between TSA and another closely related term—shared SA, though they are used interchangeably sometimes. Shared SA refers to the "degree to which team members possess the same SA on shared SA requirements" (Endsley, Jones, Schneider, &McNeese, 2001). Ideally, each team member shares a mutual understanding of what is happening on those SA elements that are in common. This concept is more relevant to teams that are located at the lower end of heterogeneity, i.e., teams in which members are often interchangeable and have much more overlap in their responsibilities. In contrast, team SA emphasizes "the degree to which every team member possesses the SA required for his or her responsibilities" (Endsley, 1995b). Implicit in this statement is the idea of heterogeneity and task interdependency. Therefore, this concept is more relevant to teams that consist of role-differentiated specialists. The success or failure of such a team depends on the success or failure of each of its team members. While both constructs are important aspects of SA in team settings, the latter (i.e., team SA) has greater relevance for a C2 team which is often characterized with specialized and interdependent roles. Therefore, this thesis will focus on team SA (TSA) when examining teamwork.

Research on TSA. Endsley's three level model, which was introduced previously in this thesis, has also been extended in order to describe SA on the team level with some success (Endsley et al., 2001); yet it also met some challenges and alternative theories have been proposed to fill the gap. Some researchers (Furuta & Shu, 2004; Shu & Furuta, 2005) contended that definitions of TSA in earlier models of TSA were mainly based on the perspective of observers. Instead, they argued that TSA should also be defined from the perspective of ''belief'' that team members possess in other members' SA in order to capture the dynamics of team cooperation. Still other researchers observed that predominant models of SA (e.g., Endsley's three-level model) were based on mentalistic assumptions focusing almost exclusively on individuals and therefore were inadequate for the study of teams in collaborative systems (Artman & Garbis, 1998; Salmon et al., 2008b; Stanton, 2010; Stanton et al., 2006). Consequently, they suggested that to study the control of dynamic systems, it is necessary to shift the unit of analysis from the individual to the whole cognitive system comprising a team of people as well as the artefacts that they use (DSA approach, see Stanton et al., 2006, for more detail).

Despite the different views on TSA, researchers generally agreed on the positive relation between TSA and team performance. In laboratory studies, for example, teams scoring better on queries assessing situation comprehension and projection were also performing at a higher level (Foltz et al., 2008), Similarly, belief based indexes for TSA (Nonose, Kanno, &Furuta, 2010) demonstrated unique contribution to team performance. Likewise, in field studies, Roth and colleagues (2006) used interview and field observations to examine the processes by which distributed teams develop and maintain team situation awareness in the context of railroad operations. The results evidenced that TSA contributed to the overall efficiency, safety, and resilience to error of railroad operations. Moreover, loss of SA in team settings could jeopardize safety and even lead to serious consequences. As in the Elaine Bromiley case (Harmer, 2005), surgical team leaders lost awareness of time passing and continued to intubate the patient even after several failed attempts. The patient died finally because of a prolonged period of hypoxia.

To summarize, importance of TSA to teamwork and safety has been well established. Many models of TSA exist, but most view the construct differently. This lack of a unifying theory poses challenges to issues such as measurement of TSA. However, such challenge should not hold back efforts to continually study this construct, provided good care is taken when dealing with related questions.

Measurement of SA/TSA. Because of the criticality of TSA in teamwork, its measurement is paramount for both system design and training. In a review of situation awareness measurement, Pew (2000)broke SA measurement methods down into four categories: direct system performance measures, direct experimental techniques, verbal protocols, and subjective measures. There has been no consensus about which method is most effective; rather, each method has its own merits and therefore is appropriate in certain contexts. For example, Vidulich (2000) reviewed current methods being used to measure situation awareness and tested their sensitivity for use in interface evaluations. In this meta-analysis, memory probes with a wide breadth including different aspects of the tasks received relatively high ratings and proved to be a sensitive metric for interface evaluation. With this method, queries or probes are asked concerning the state of the task or the environment. They are introduced either during ongoing task performance or, more often, by suspending the task or by freezing the simulation. One example of this method is SAGAT, or Situation Awareness Global Assessment Technique, which was formalized by Endsley (1988). Although issues are yet to be resolved of it (e.g., intrusiveness), this technique is by far the most commonly accepted one and has been repeatedly applied with success for examining SA across experimental treatment conditions (Wickens, 2008).

On the team level, research efforts have been called for specialized measurement of Team SA given its unique characteristics beyond adding up situation awareness of individual team members. While promising approaches (such as propositional networks, Stanton, 2004) have been invented in the last decade (Berggren & Johansson, 2010; Nonose et al., 2010; Patrick, James, Ahmed, &Halliday, 2006), more validation and field testing are required before they can be utilized. Currently most researchers still choose measurements that were initially developed for measuring individual SA and adapt them to team settings. For example, in a simulated air combat environment, SAGAT was employed to probe aspects in the responsibilities of oneself and other team members (Sulistyawati et al., 2008). Similarly, in evaluating TSA, a SAGAT-like questionnaire was presented every 2 minutes during the 10-minute trial and the subjects answered questions regarding their own cognitive states and beliefs on the other team members' SA, beliefs in the other team members' belief on their own SA (Nonose, 2010).

More than fifteen years ago, Salas (1995) discussed two critical measurements that should first be made for team SA: (a) individual SA; and (b) the team processes that team members use to build and exchange information and enhance team coordination (Salas et al., 1995). These two issues have received considerable attention over the years. Because TSA measurement is important to both system design and training, work in this area is continuing.

The central role of communication in building and maintaining TSA. Team communication has been defined as, "the process by which information is clearly and accurately exchanged between two or more team members in the prescribed manner and with proper terminology; the ability to clarify or acknowledge the receipt of information"(Cannon-Bowers et al., 1995, p. 345). Considering the intrinsic characteristic of teams (workload beyond what a single person could handle; requiring expertise in multiple domains; etc.), each member does not have the information necessary for developing and maintaining his/her own TSA all the time. Instead, team members have a certain degree of information interdependency. Such interdependency is especially typical in command and control (C2) environment. For example, in an emergency coordination center, the radio operator and the dispatcher are interdependent in the sense that the former needs what the latter is responsible for—the information on the location of the ambulances—while the dispatcher also needs an up-to-date report from the radio operator concerning the incident progress so that a timely adjustment of resources can be ensured. Moreover, specific failures in communication derail the process of building a shared understanding of the situation between team members, which leads to poor performance and errors (Stout, Cannon-Bowers, Salas, &Milanovich, 1999). Therefore, adequate (and accurate) information sharing via communication is critical to TSA and is essential to effective teamwork (Parush et al., 2011b). In the following section, I will briefly review detrimental effects of communication breakdown within HROs, especially the wildland firefighting domain, so that readers can appreciate the degrading impact that communication breakdowns can have on TSA and hence on team effectiveness.

Communication breakdown: degrader for TSA. The criticality of TSA for teamwork also implies that its degradation can lead to failure of teamwork or even serious consequences. Actually, many degraders for both individual SA and TSA have been recognized (e.g., fatigue, task overload, false ground mindset, poor communication, Nofi, 2000). Specifically, communication breakdown is one of the most common factors facing distributed C2 teams within HROs (Wilson et al., 2007). According to Wilson and colleagues, communication breakdowns are incidents in which there is a delay of or lack of the right information being transferred to the right person at the right time. They were associated with degraded team performance, increased error rates and adverse events. There have been many documented communication breakdowns that resulted in information loss and degraded information sharing within the OR team (Alvarez & Coiera, 2006; Lingard et al., 2004).

In the wildland firefighting domain specifically, a literature review conducted by Varone (1996) identified cases where firefighters have been killed or injured under circumstances where a radio communications failure was found to be a contributing factor. For example, in 1995, a wildland fire in Kuna, Idaho took the lives of two firefighters. The investigation team cited the lack of adequate communications as a significant factor in the deaths. The dead firefighters had been operating in the path of a rapidly moving fire. Their radio was not equipped to communicate with the Incident Commander (IC), and the IC as well as other officers on the scene were unable to warn them of the approaching peril. In 1991, Ross (Ross & Forest, 1990) wrote about the June 25, 1990, wildland fire in Tonto, Arizona, where a communications breakdown was cited as a major factor in the deaths of six firefighters. Fire crews from different agencies operated on their own frequencies and could not communicate with each other. In some cases, fire crews could not even communicate with their supervisors. The lack of coordination, and the fact that there was not a single frequency that all crews could communicate on, contributed to 11 firefighters being trapped in a canyon, 6 of whom died. More recently, Rohde (2002) pointed out deleterious effects that resulted from inability of IC and Operational Chief to communicate on fire suppression.

Although a factual foundation for the linkage of firefighter safety to effective fireground communications has been laid from cases cited above, little research has thus far examined this issue by looking for causal mechanism that underlies it. Previous research from other fields has established the negative effects of communication breakdown on situation awareness and performance, especially in time-critical settings such as C2 teams in HROs. For instance, Wilson and colleagues (2007) examined fratricide incidents on the battlefield and proposed a taxonomy which listed communication breakdown under teamwork breakdown which was linked to poor shared cognition. In aviation, Gibson (Gibson, Orasanu, Villeda, &Nygren, 1997; Gibson, 1997) sampled hundreds of ASRS (Aviation Safety Reporting System) incidents and found that loss of situational awareness (LSA) accounted for over one thirds of incident reports investigated; moreover, communication breakdown within crew members or between crew members and air traffic controllers occurred in almost half of these LSA events.

Given the likelihood of communication breakdown within a C2 team in HROs, researchers have been exploring alternative ways that enable information exchange, such as a situation display (Wellens, 1993). While information transmission can take place via both communication and shared situation displays (Endsley et al., 2001), a carefully designed situation display becomes critical for maintaining TSA during communication breakdown and thus enhancing safety. This study plans to draw lessons from research concerning display design with the hope that existing solutions could offer some insights on how to reduce the potential risks linked with communication breakdown within C2 teams set in wildland firefighting domain. In the next section, I will explain the rationale of designing a team-oriented information display to augment communication for C2 teams in a HRO context.

Team Display to Augment Communication and TSA

Ergonomics and human factors are concerned with the overall improvement of system effectiveness by two complementary processes: the design of environment (Parush et al., 2011a) and the selection and training of personnel. The two are complementary, as Roscoe (1980, p. 3) observed, since "the former serves to reduce the need for the latter; the latter completes the job left undone by the former". Given the scope of this study, it will focus on display design and its efficacy while acknowledging that both approaches are important for system optimization.

Within the scope of environment design, this study focused on designing a team-oriented information display, or team display. Douglas(2007) defined such displays as "computer information systems of various sizes, forms, and configurations which are designed to provide decision support and facilitate situation awareness" (Douglas, Aleva, &Havig, 2007, p. 4). Previous studies have already demonstrated beneficial effects of a shared situation display in supporting teamwork (Bolstad & Endsley, 2000; Davenport, 1997). When presented with up-to-the-moment interaction between teammates and shared workspace in a miniature view, for example, performance in a simulated pipeline construction task was significantly improved (Gutwin & Greenberg, 2004).

These studies, however, introduced new questions that were unanswered. Some of them only studied performance and did not address SA empirically, so that SA improvement/degradation was only inferred (Bolstad & Endsley, 2000). Other studies were carried out in ordinary working settings as opposed to life- and time-critical organizations, thus making their results difficult to generalize to the latter ones. Although it is arguable that such displays may have a larger impact when placed in HRO contexts like wildland firefighting, more empirical research is needed before one could jump to these conclusions. One such empirical study has been done by introducing a team display in a C2 team setting (Brandigampola, 2011). It revealed significant improvement of TSA by the team display. Surprisingly, this was not the case for performance; i.e., team performance did not significantly differ regardless of whether or not the team display was present. Such a result led to the suspicion that the improved SA due to the team display will only be beneficial to performance when conditions really deteriorate, e.g., communication breakdown that interrupts collaboration and coordination in the team. Motivated by this suspicion, this research introduced communication breakdown into a C2 team setting. Moreover, it examined whether a team display could reduce negative effects of communication breakdown on teamwork.

Team display in C2. In Command and control centers, shared situation displays of various sizes are more common (also see Figure 1and Figure 2) and have been generally seen as an indispensible tool to facilitate SA (Scott, Wan, Rico, Furusho, &Cummings, 2007). Extensive efforts have been spent on investigating the potential benefits of shared displays and design guidelines in a variety of domains (maritime: Dominguez, Long, Miller, &Wiggins, 2006; Jenkin, 2004; air force: Darling, 2004; Dudfield, Macklin, Fearnley, Simpson, &Hall, 2001; nuclear power plant: Roth et al., 1998; emergency responce: Resch, Schmidt, &Blaschke, 2007; urban firefighting: Jiang, Hong, Takayama, &Landay, 2004). It is generally agreed that such displays should support cognitive process of human operators, especially those that are working in time-critical, decision rich contexts, such as a C2 team (Roth et al., 1998). Common themes of these studies include reducing workload, improving SA, facilitating shared mental models, and improving decision-making. No conclusive results, however, have been generated concerning the usefulness of shared display in supporting awareness of commanders.

In firefighting and other fields in emergency management, team displays of various sizes have been utilized more and more (Toups, Kerne, Hamilton, &Shahzad, 2011; Bartels et al., 2010; Resch et al., 2007; Landgren, 2005), thanks to the advance of GIS (Geographic Information System) and sensor technology (i.e., availability of real-time satellite imagery). These displays are supposed to support communication and situation awareness especially in C2 contexts. For example, after 9/11, a report from McKinsey & Company (2002) pointed out the potential of replacing magnetic command boards with electronic boards equipped with wireless transmission equipment to better support communication and decision making. Another field study has supported that a large electronic display might help incident commanders to manage various issues including communication during urban firefighting (Jiang et al., 2004). More recently, a prototype application, called eMapBoard, was implemented with the goal of achieving situational awareness for an instantaneous assessment of environmental conditions in emergency management (Resch et al., 2007). In a study of incident management team (IMT) responsible for large scale wildfires, McLennan and colleagues (2006) suggested that a computer-based display that help maintain an up-to-date common operating picture of the fire situation, i.e., threats and resources, would be an extremely helpful tool for decision making.

Team display during communication breakdown. It is highly likely that situation displays and communication increase team effectiveness are by helping teams construct and maintain TSA. Therefore, a situation display that keeps updating team members would serve as a back-up during communication breakdown. Also, by alleviating its negative impact on TSA, time to recover SA after communication being restored would also be shortened.

Considering that the risk of a breakdown in teamwork is often amplified in dynamic environments like a C2 team, where the situation is changing at a fast pace and accurate and timely understanding is a key to making sound decisions, efforts to design a situation display that augments communication, and consequently TSA and performance, are warranted.

Designing a Team Display

The mere introduction of a team display into a C2 team does not guarantee that it will augment team performance or even be used by the team. Facilitating SA through augmenting communication with shared situation displays, regardless of the user or domain, will only be possible if the displays present the right information at the right time in an easily readable and understandable format (Douglas et al., 2007).

In order to determine what information would be beneficial on team displays, the present study will follow the same principles from previous studies (Parush et al., 2011b; Parush et al., 2009). That is to say, situation-related information that is critical for more than one team member will be identified and then displayed in an integrated, context-sensitive, dynamic, and continuous manner. While the previous studies used communication analysis, this study instead used hierarchical task analysis (HTA) to identify critical information that wildland firefighting C2 team members exchange in accomplishing their tasks (detailed in "Method"). Subsequently, the identified information was applied directly to the design of a team-oriented information display for a two-person C2 team in a wildland firefighting context.

Summary and Objectives

In summary, existing research on teamwork has demonstrated the criticality of TSA to C2 team effectiveness, especially in HRO environments such as forest firefighting C2. In addition, communication breakdown has degrading effects on TSA and hence on team performance, eventually detrimental to life and property. Moreover, evidence suggests that a carefully designed team display could support TSA and even improve team performance. However, conclusive results have yet to be generated showing benefits of such team displays to C2 teamwork in a HRO context.

This follow-up study built up on previous studies concerning team display in a forest firefighting C2 context (Brandigampola, 2011) and its design principles (Parush et al., 2011b). The objectives of this study was to test if a team display can enhance teamwork in a forest firefighting C2 context by improving team situation awareness and hence overall performance, and particularly by facilitating recovery from communication breakdown.

Research Questions and Hypotheses of this Study

Research questions:

- Can a team display facilitate TSA?
- Can a team display facilitate performance?
- Can a team display be beneficial in recovering from communication breakdown in terms of TSA?
- Can a team display be beneficial in recovering from communication breakdown in terms of performance?

Hypotheses:

- TSA will be significantly better when a team display is present compared to absent.
- Performance will be significantly better when a team display is present compared to absent.
- TSA recovery after a communication breakdown will be significantly better and faster when a team display is present.
- Performance recovery after a communication breakdown will be significantly faster and better when a team display is present.

Method

Participants

This research recruited 64 participants who were fluent in English. For the purpose of this study, pairs of participants were considered as units resulting in a sample size of 32 for analysis purposes. Each unit was also called "a team" in this study. 10 teams consisted of participants who were acquainted with each other, while the other 22 teams consisted of participants who had little or no interaction with each other prior to this study. Independent-samples t-test revealed no difference on performance between the aforementioned 10 vs. 22 teams ($ps > .1$). Participants' age ranged from 17 to 36 with a mean and a standard error of 20.33 and 3.08, respectively. Also, participants were almost evenly distributed in terms of sex, with 31 males and 33 females. All participants had either normal vision or corrected normal vision and normal color vision. Although self-report was used in this selection, what participants reported concerning color vision was also confirmed through experiments: all participants identified no problem perceiving all elements on both the team and individual displays. Participants received $10 per hour or 2% credit towards a psychology course as an incentive for their participation.

Task and Design

Experimental tasks. The task domain, which was forest fire fighting, was of secondary interest and had been chosen because it created a good dynamic task environment for the participants. The domain included forest fire/fires, houses, different kinds of vegetation and computer-simulated agents such as reconnaissance personnel and fire-fighting units. The task simulated the command and control context of managing a forest fire incident. Such command and control was typically based on a team consisting of several roles. For the purpose of this study, the team size was limited. Each team consisted of an Incident Commander (IC) and a Ground Chief (GC).

The IC was responsible for receiving fire alarms and weather reports sent from the emergency center. Since not all fire alarms were true, s/he had to dispatch a helicopter to the fire scene specified in the alarm message and verify it before making any orders to the GC. With a weather report, s/he could warn the GC about upcoming weather changes at a certain time as s/he saw appropriate. It was primarily the responsibility of the IC to set priority of fires when there were too many to fight at once. However, the IC also needed information input from the GC, such as the availability of workforces, their distance to a specific fire, and to what extent each burning fire had been under control.

The main task of the Ground Chief was to control firefighting and fire break units and coordinate them to put out fires. To accomplish this goal, s/he needs periodic information input from IC, including dispatch orders when new fires arose, fire priority, weather forecast, tactic suggestions, etc.

The task of the two team members was to save as many houses and forests as possible by controlling and suppressing simulated fires with available firefighting appliances, while houses always had the first priority. Therefore, participants must consider priorities of different properties in adopting a strategy for fighting the fires, whilst also considering current and forecast wind conditions, fire warnings and different fire spreading rates.

Study design. This study used a within-group, repeated measures design with two independent variables: display type and communication breakdown (also see Table 1).

1. Display type was a within-group variable with two conditions. In one condition, participants only had access to individual displays of their own. In the other condition, besides their own displays, participants also had access to a team display mounted on the wall in front of them (see appendix A).
2. Communication breakdown was the second within-group variable. In two out of the four experimental conditions communication breakdown was introduced by not letting the participants talk with each other. The "breakdown" was introduced twice during a given scenario, lasting one and two minutes respectively.

Table 1

Four different experiment conditions

	NO communication breakdown	**Communication breakdown**
Individual display only	Individual	Individual + Breakdown
Individual + team display	Team	Team + Breakdown

This experiment was designed to compare: (a) teams' performance, and (b) Situation Awareness (SA), using the 2×2 design (see Table 1). Every team completed all conditions with counterbalanced order. The four experimental scenarios were counterbalanced in terms of access to team display, communication breakdown and landscape orientation (see more detail in "Experiment scenarios"). The method of counterbalancing was a "Latin squared conditions by Latin squared stimuli (i.e., scenario)" (Neef, Trachtenberg, Loeb, &Sterner, 1991), which allowed for efficient samplings of the combination of orders and stimuli (also see appendix C).

Experimental scenarios. In this study, a total of seven experimental scenarios were developed, comprising three practice scenarios with different training emphases and four experimental scenarios. The first practice trial lasted 4 minutes; the second and the third lasted 5 minutes each. All experimental scenarios lasted 10 minutes each. The practice scenarios were designed to provide a chance for the participants to gain the appropriate knowledge and skill needed for the C^3Fire microworld simulation (see apparatus section later) and team collaboration. In addition, the experimental scenarios were designed to assess the participants' teamwork performance and SA under the four experimental conditions (details provided below).

Tasks in all scenarios were designed such that participants needed to strictly prioritize saving houses when completing a scenario. Participants were also informed of the fact that fires spread faster through pine forests than houses and normal vegetation and even faster than birch forests, and that the fires spread in accordance with the concurrent wind direction and strength. They were required to attend to multiple critical fires, random fire warnings, and frequent wind changes, whilst regularly monitoring and commanding the various firefighting appliances.

For the experimental scenarios, one scenario was constructed and then its map was flipped around to create four scenarios in total that were equivalent in landscape features, fire and wind behaviour, and difficulty, but not recognized as such by the participants (also see appendix B).

The design of displays. To design the team display, the author firstly identified all critical information that needed to be exchanged between IC and GC in fulfilling their tasks. This was accomplished by using an approach called hybrid Cognitive Task

Analysis (hCTA; Nehme, Scott, Cummings, &Furusho, 2006) which mainly consisted in hierarchical task analysis (HTA; Neville, 2006; Annett, 2003) and SA requirements analysis (Endsley, 2000a) (also see Appendix H). Information that had been identified was then integrated on the team display in a manner that, when communication broke down, it could provide needed information unavailable on individual displays. For example, on the team display, the simulator updated the geographical information system (GIS) around all simulated units so that each role could perceive fire progress surrounding units under both his/her and teammate's control.

Objects including houses, pine forests, birch forests, swamp, and normal vegetation were visible on both individual and team displays from the start of each experiment session. However, units under the control of each role were visible only on that role's individual display. For example, the IC could not see GC's firefighting or fire break units but helicopter on his/her display, unless GC's units were passed by IC's helicopter and vice versa. Similarly, on the individual displays, the simulator updated the GIS around the simulated units for the roles who were controlling these units. Figure 3-5 present the screen capture of three displays.

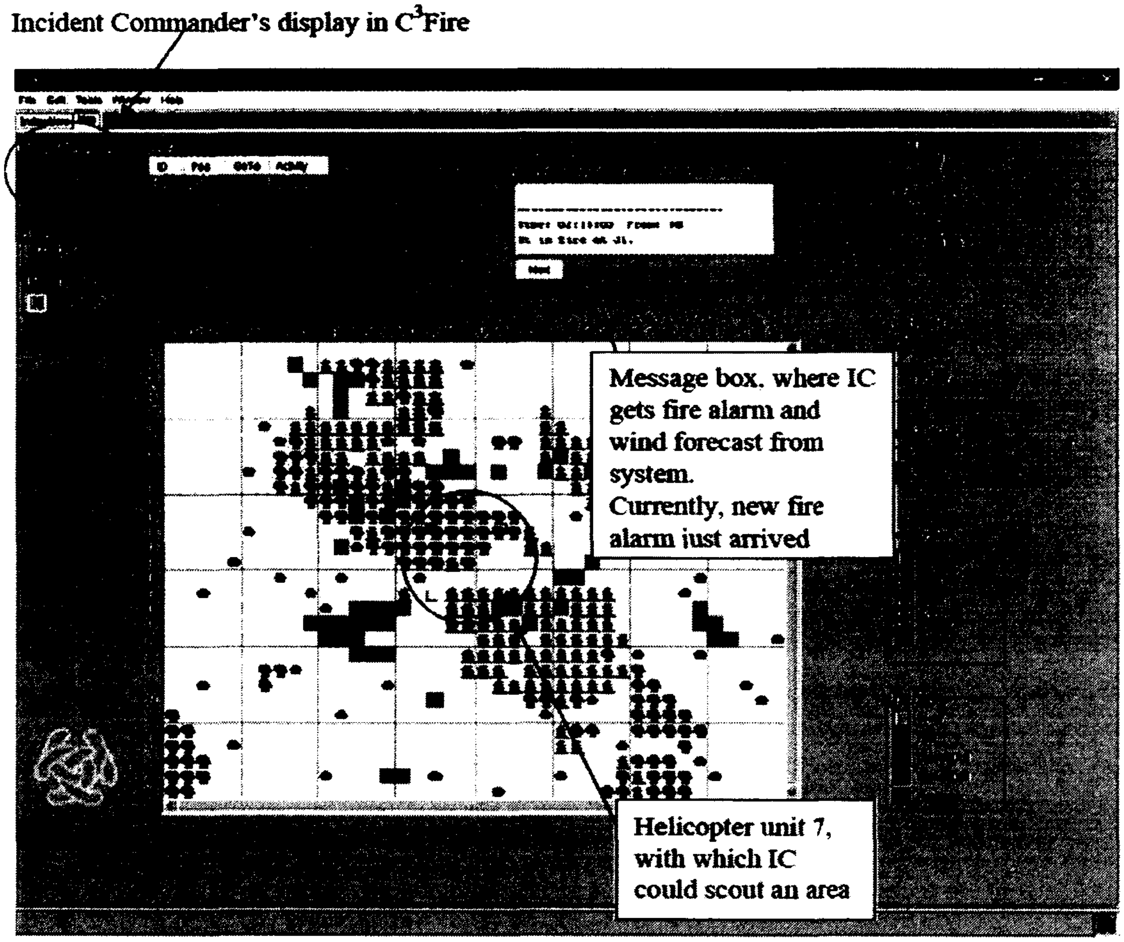


Figure 3. Screen capture of IC's display in C^3Fire.

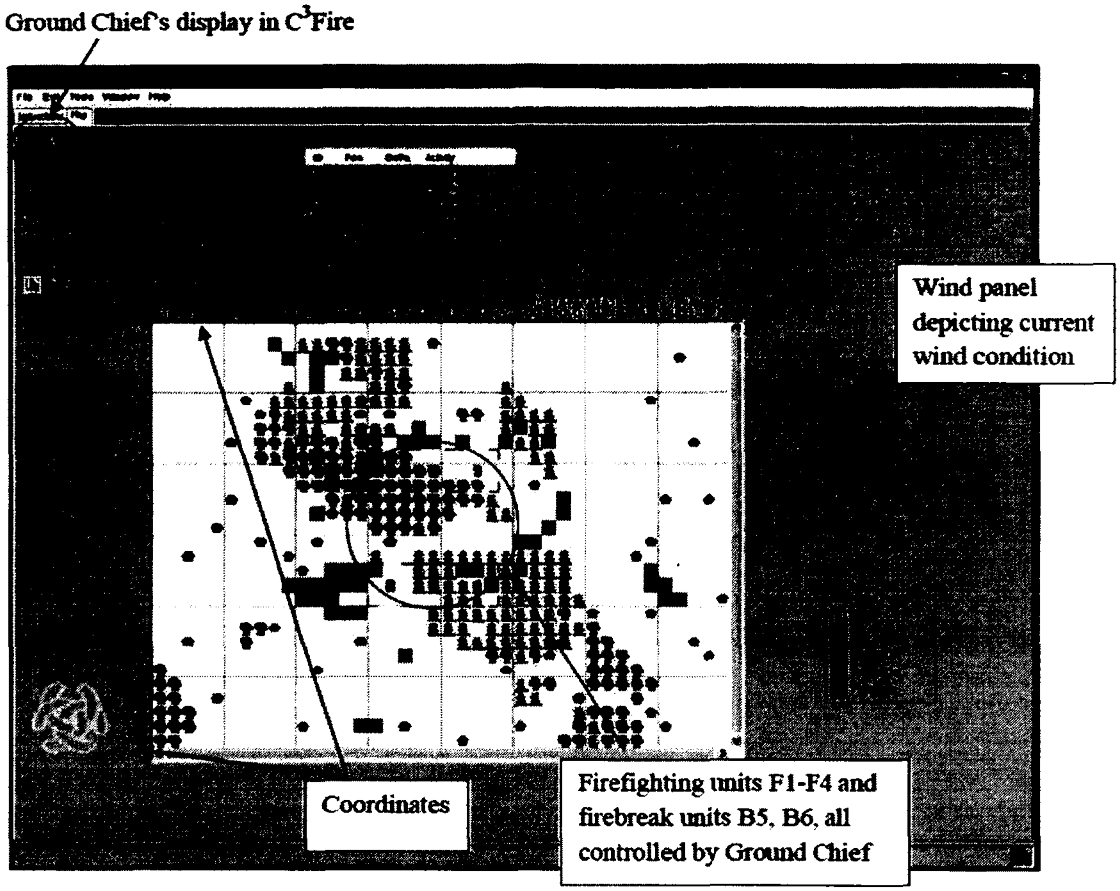


Figure 4. Screen capture of GC's display in C^3Fire.

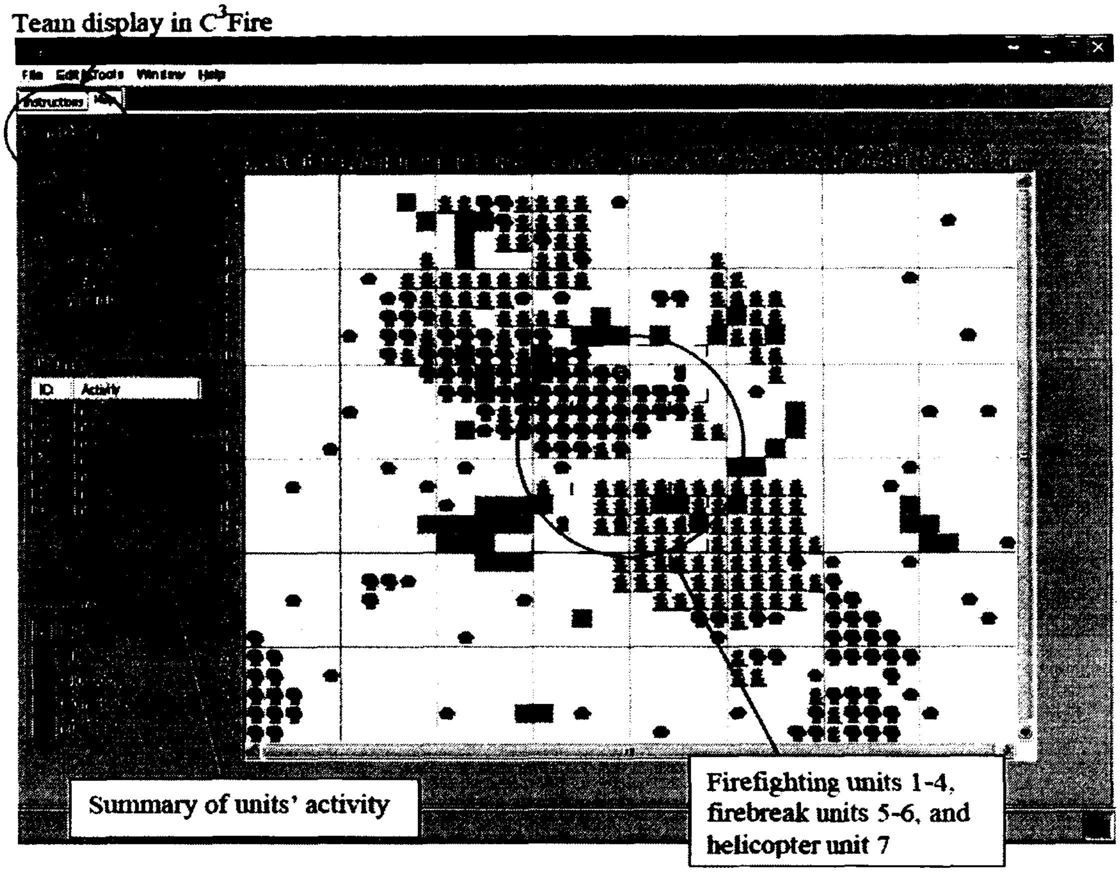


Figure 5. Screen capture of team display in C^{3}Fire.

Apparatus

All experiment sessions in this study were carried with a microworld simulation program called C^{3}Fire. It is a command, control, and communications simulation environment which basically resembles a strategy game and can be used for the investigation and the training experimentation of team decision-making and team situation awareness (Granlund, Johansson, &Persson, 2001). It has been created as a small and well-controlled simulation system which retains some important characteristics that are from the real world. The system generates a task environment that has complex, dynamic and opaque characteristics, similar to the cognitive tasks that people normally encounter in real-life systems.

The C^3Fire simulation was installed on four separate Windows based computers connected by an Ethernet LAN, with one being the server, two of the computers serving as command centers for each respective team member (i.e., individual displays), and the fourth running a communal display (i.e., team display). The user interface (UI) was adapted individually for two roles in each team as well as for the team display (also see Figure 3-5).

The displays. The resolution for both individual displays was 1280×1024 while the resolution for team display was 1024 × 768. All three consisted of a geographic information system (GIS) which was essentially a geospatial grid of 40 by 30 cells representing the map of the surrounding area. Each cell contained one and only one type of object, such as house, pine, birch, normal vegetation, or swamp.

Physical configuration. This study used the same physical configuration as previous study (Brandigampola, 2011). During the experiment, team members were seated side by side with such an angle that they were not able to see each other's display yet could still verbally communicate (see Appendix A).

Performance log. To be able to analyze the collaborative work in the C^3Fire system, computer-based logging was used. The logging was integrated in the simulation. For each session, the C^3Fire system would create a log with all the events in the simulation and all computer mediated activities (Johansson, Persson, Granlund, &Mattsson, 2003). Here is one example of an item in a log file:

<Event nr = "1660" time ="02:19:39" val = "11 3 33 3" />

Its corresponding meaning in natural language has been delineated with arrows below:

<Event nr = "1660" time ="02:19:39" val = "11 3 33 3" />

No. 1660 event happened at 02:19:39. It was a fire event: fire at (33, 3) was put out.

For each session, the log contains thousands of items like this one. Using *awk*, a programming language that permits easy manipulation of structured data and the generation of formatted reports (Dougherty & Robbins, 1997), a comma-separated values (*csv*) file was generated for each session which contained summarizing variables such as the total number of saved cells in a session.

SAGAT

This study measured participants' situation awareness with SAGAT (Situation Awareness Global Assessment Technique), one of the most widely used objective measurements of SA. The researcher developed SA queries that were predefined before the start of the experiment using hCTA, based on which a list of SA requirements for both roles in C^{3}Fire was constructed (see Appendix H). According to Ensley (2000a), SA requirements are dynamic information needs associated with the major goals or sub-goals of the operator in performing his or her job tasks or sub-tasks (as opposed to more static knowledge such as rules, procedures, and general system knowledge.) These SA requirements then formed the basis for determining the SA queries in C^{3}Fire. In each case the query was presented in paper-and-pencil form. An example SAGAT probe is provided in Figure 6 (see Appendix G for full lists of SA queries that were developed for the present study). This question would be presented together with an answer sheet (see Figure 7) to the participants so that they can write down answers on it.

Question ID	How many fire alarms are yet to be verified?				
1.1	0	1	2	3	4

Figure 6. Sample SAGAT question.

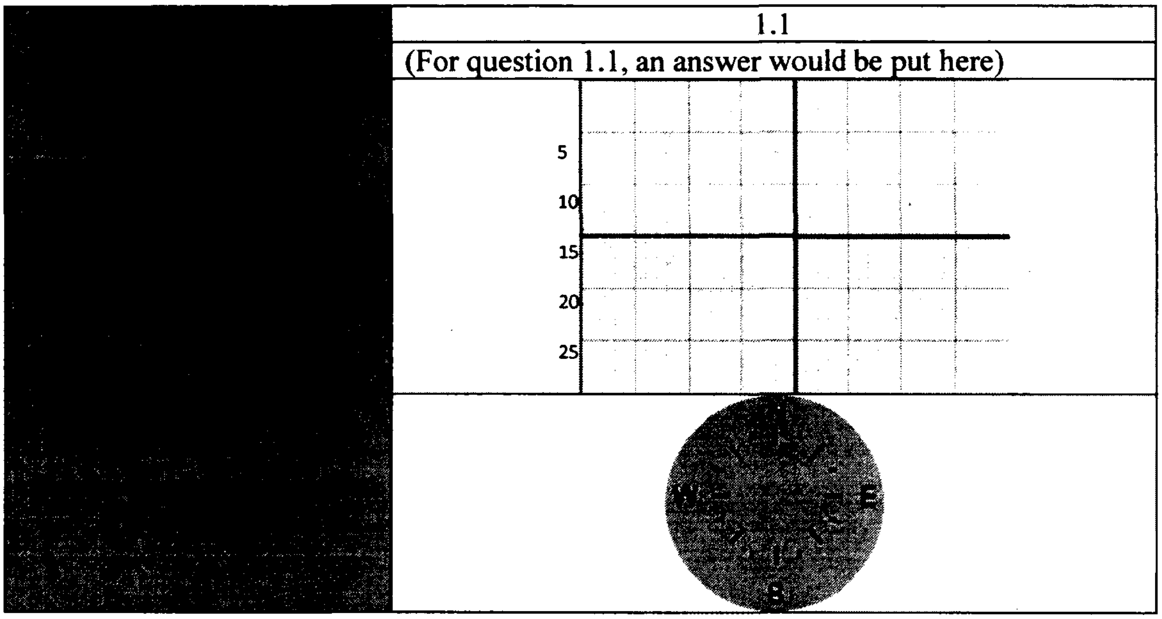


Figure 7. Sample answer sheet for SAGAT questions.

Procedure

Each session was based on two participants playing as a team. When the participants arrived, they received an informed consent form to read and sign. Next, the experimenter administered a demographic questionnaire designed to obtain pertinent background information, such as participants' native language, age, and computer experience (See Appendix E). The experimenter then randomly assigned the participants to either the role of Incident Commander or Ground Chief.

Before the experiment started, participants went through a training session which began with a series of video clips describing their individual tasks as well as of the other team member's tasks (see Appendix F for scripts). Whenever applicable, instruction regarding the team display was included.

After watching these videos, teams completed three practice scenarios, which essentially consisted of simplified and step-wise version of the experiment scenarios. This allowed participants to familiarize themselves with the simulator operations and interfaces, and it also gave them an opportunity to practice communication and coordinating strategies with their teammates. Throughout the training session, participants also were encouraged to ask the experimenter any questions concerning the simulation, and their roles in the scenarios, etc.

Shortly after the training session, the experiment began. In all four conditions, team members were allowed to communicate with one another verbally, and they were encouraged to determine what the other team member was doing, as well as work together on a joint strategy to improve performance. However, communication was artificially forbidden twice—for 1 minute and 2 minutes—amid each of the two sessions, creating the "communication breakdown" condition. During breakdowns, participants had to carry out their tasks despite no verbal communication.

In addition, each experimental session was stopped at two times during which all displays were frozen and blanked and three randomly selected SAGAT questions, one at each level, were asked for each participant (see Appendix G for the full list of questions). A random sampling provided consistency and statistical validity, thus allowing SA scores to be easily compared across scenarios, subjects, and conditions. Each freeze lasted about 1 minute. The timing of each freeze for SAGAT administration was predefined and was unknown to participants so they could not prepare for it in advance. To ensure that responses were independent, communication between participants were not allowed during the freeze. Participants received training on the SAGAT procedure during the second and third practice scenarios.

A total number of 3 (level) × 2 (freeze) × 2 (role) = 12 SAGAT probes were administered to each group for each experimental condition. Six of them were asked at 4 minutes 30 seconds into each 10-minute scenario (hence considered "1^{st}") and the other six at 8 minutes into the scenario (hence considered "2^{nd}").

Measures

Teamwork performance. To test the performance level under different experimental conditions, teams' performance was operationalized as the performance score in each C^3Fire scenario. This study examined both accuracy-based and time-based indices. Since the whole map of surrounding area was divided into 40×30 cells, accuracy-based indices examined how many cells each group lost/saved in a scenario. Mean while, time-based indices investigated both the total time each group spent on suppressing fires and the average time they spent on putting out fire in a burning cell. More details will be provided below. Throughout these analyses, cells that contained houses (referred to as "house") were singled out from cells containing other objects to study whether unique performance pattern existed for houses because participants were instructed to strictly prioritize saving houses over other objects (i.e., forests) when completing a scenario. Note that whenever "cells" is addressed in this paper, houses are also included.

Loss of cells. This index was based on the total number of cells that were lost by the end of each scenario irrespective of cell types (i.e., houses, forests). They include cells that burned out during a scenario and cells that were left burning by the end of the scenario.

Using the same index, this study examined how the performance level changed as the scenario unfolded. More importantly, this measure tried to discern the performance level near communication breakdown and thus to explore how the display type affected performance change. The duration of each 10-minute scenario was divided into five blocks, 2 minutes each. Note that two instances of communication breakdown happened during time block 2 and block 4, respectively. Total number of lost cells up to the end of each minute was first calculated. The average of every two numbers within a time block was then used as dependent variable (Figure 8 shows an example for the calculation).

Total number of lost cells up to the end of each minute	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
Average of every two numbers within a time block	$\frac{N1 + N2}{2}$		$\frac{N3 + N4}{2}$		$\frac{N5 + N6}{2}$		$\frac{N7 + N8}{2}$		$\frac{N9 + N10}{2}$	
	Block 1		Block 2		Block 3		Block 4		Block 5	

Figure 8. Illustration of segmenting 10-minute scenario into five blocks.

Loss of houses. Similar measures were carried out for houses. Number of houses that burned out during a scenario or was left burning by the end of a scenario was counted. Also, using the same rationale as with cells, this measure further broke down the duration of 10 minutes of each scenario into five time blocks. Average number of lost houses within each time block was used to reflect performance change as scenario unfolded.

Saved cells. Instead of using the absolute number of saved cells, this study used the ratio between the number of saved cells and the number of cells that caught fire in each scenario. The reason of doing this is based on the consideration that fewer saved cells cannot be linked to worse performance; vice versa. It may as well be because that more cells have been prevented from catching fire in the first place. However, a small proportion of saved cells out of cells that caught fire would suggest poor performance, hence the using of ratio.

Saved houses. Similarly, number of saved houses relative to number of fires on houses was calculated for each scenario.

Average time each cell was on fire. This index reflects the average duration (in seconds) from the time a cell starts burning until it is put out/burned out/the end of a scenario. Because fire in a burning cell will spread to its neighbouring cells if this burning cell is not put out after a certain amount of time (e.g., 80 seconds), faster suppression of fire on average will lead to less spreading of fire and hence less damage. To have a more "zoomed in" understanding of this index, another similar index—"the average time to put out fire on each cell"—was also examined.

Total active time working on fire suppression. This index reflects the total time that the four firefighting units spent on suppressing fires, which are controlled by the Ground Chief. For each firefighting unit, the 10-minute scenario can be decomposed into three parts: being idle, moving towards and/or travelling between different fires, and actually fighting fires. This index includes the time each unit spent on mobilizing and actually fighting fires. Less idle time and therefore more active time could indicate that participants had better deployment of resources (firefighting units).

Situation awareness. SAGAT probes in this study can be divided into two types based on how their answers were scored—continuous and true/false. Examples of both types of probes were provided below (*Figure 9*). Scoring of continuous probes ranges from 0 to 1 with any possible values in between. In contrast, true/false probes only have two possible scores 0 or 1.

a.

Question ID	Which fire(s) are about to burn houses?	
3.2	N/A	*Mark fires on scaled-down map with Δ*

b.

Question ID	Are there any fire breaks being built?		
1.7	Y	N	Not sure

Figure 9. Sample SAGAT question of continuous type (a) and of true/false type (b).

For continuous probes, mean scores of each participant (across SA levels) within each experimental condition before/after communication breakdown were used for analysis. For true/false probes, a tabulation of the frequency of correctness was made within each experimental condition for each participant before/after communication breakdown. As data scored as correct or incorrect are binomial, the assumption of normality for analysis of variance was violated. A transformation ($Y' = 2 \arcsin(\sqrt{Y})$) was applied to binomial data, which allowed analysis of variance to be used (Kutner, Nachtsheim, Neter, &Li, 2004, p. 789).

For both continuous and true/false SA questions, each type of SA questions were further differentiated between team questions (teamQs) and individual questions (individualQs). To answer teamQs, participants do not necessarily have certain information and need it from his/her teammate (e.g., Question for the GC: "where are these burning fires?"). Hypothetically, teamQs tapped into information that necessitates communication and thus participants' scores on teamQs could better reflect the joint impact of team display and communication breakdown. Therefore, this subset of data was used for further analysis. Restricted by the sample size, true/false teamQs were not analyzed (see Appendix D for number of SA probes distributed across types).

Subjective workload. The level of workload experienced by participants in each condition was measured via NASA Task Load Index (TLX, Hart & Staveland, 1988). It is a multi-dimensional rating procedure that provides an overall workload score based on a weighted average of ratings on six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort, and Frustration (see Appendix I). Due to time limits in this experiment, weights were collected only from four teams of participants and then arithmetic average of them was used later; each time15 possible pair-wise comparisons between these six subscales were presented (see Appendix I). Ratings on these six subscales were collected from all teams and weighted average was calculated afterwards.

This measurement was used as a check that C^3Fire scenarios were sufficiently cognitively demanding. Also, it could offer some insights as to the benefits of team display in this experiment setting.

Results

This chapter is organized by the three measurements—performance, SA, and workload. It begins with several performance-based measures, all of which were derived from the log files generated by the C^3Fire simulation. This is followed by the analysis of situational awareness within teams. The chapter concludes with the subjective workload analysis.

Performance

Loss of cells. Preliminary statistical analyses were conducted for cells irrespective of cell types (i.e., houses, forests) to test for possible order effect and to determine if there was an interaction among order and the two independent variables (i.e., display type and communication breakdown). The total number of lost cells by the end of each scenario were subjected to a 2 (display type) × 2 (communication breakdown) × 4 (order of scenarios; i.e., first, second, etc.) within ANOVA. The main effect for the display type was significant ($F(1, 7) = 50.56, p < .001, \eta_p^2 = .878$), as was the effect for order ($F(3, 21) = 4.702, p = .02, \eta_p^2 = .402$). The main effect for communication breakdown and the four interaction effects were non-significant. The analyses indicate that the extent of loss was consistently smaller under the condition of "individual + team display" ($M = 167.45$, $SE = 7.06$) comparing to "individual display only" condition ($M = 215.02$, $SE = 6.04$). The main effect for order indicates that participants had fewer losses in later sessions than in earlier sessions ($M_{First} = 229.31$, $SE_{First} = 9.07$; $M_{Second} = 192.47$, $SE_{Second} = 10.50$; $M_{Third} = 174.69$, $SE_{Third} = 14.82$; $M_{Fourth} = 168.47$, $SE_{Fourth} = 13.90$), but, critically, neither display type nor communication breakdown interacted significantly with experimental order. In short, the predicted "individual display only" versus "individual + team display" effect was observed for number of lost cells, and this effect was not significantly moderated by order.

In addition, a 2 (display type) ×5 (time block) within ANOVA revealed main effects on both factors on the mean number of lost cells ($F(1, 31) = 10.33, p = .003, \eta_p^2 = .250$; $F(4, 124) = 339.29, p < .001, \eta_p^2 = .916$) and a significant interaction ($F(4, 124) = 8.69, p = .006, \eta_p^2 = .219$). It should be pointed out that given the central interest here is the impact of the team display on the performance level when communication breakdown happened, only data from the two conditions that introduced communication breakdown were analyzed. The result indicates that the extent of cell loss accumulated throughout the

10 minutes of a scenario as a result of fire spreading faster than the speed it was put out. In addition, the result shows that the number of lost cells in the later blocks of the scenario exhibited larger differences between the display conditions relative to the earlier blocks in the scenario. For example, in the fourth block, about 30 more cells on average were lost under the condition of "communication breakdown without team display" compared to when the team display was present; this difference increased to around 50 in the fifth block (see Figure 10). Note that although it is the conventional degrees of freedom that are provided for all of the statistical results reported here, all of the corresponding statistical tests were actually based on significance levels that were determined by the (more conservative) Greenhouse-Geisser, epsilon-adjusted degrees of freedom.

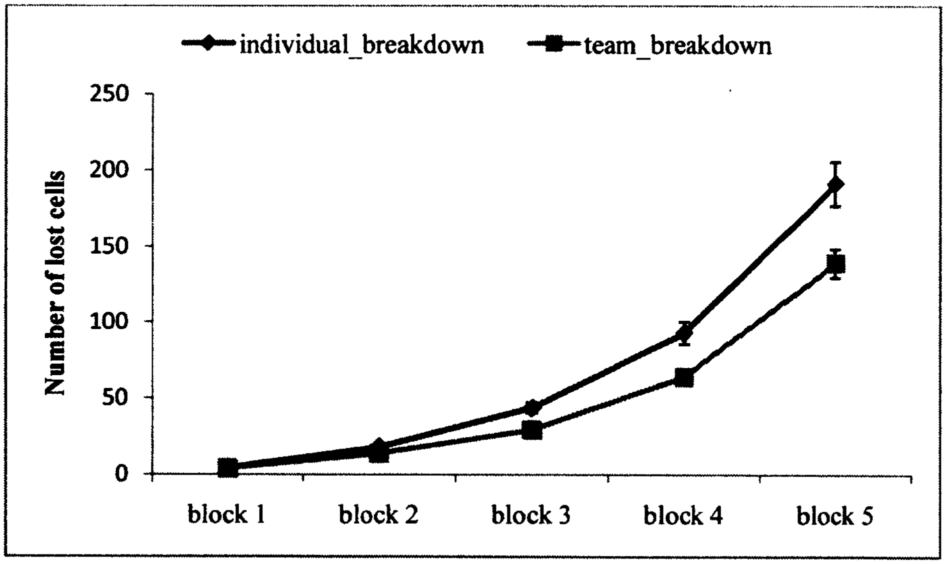


Figure 10. Mean number of lost cells across time block and display type.

Loss of houses. A 2 (display type) × 2 (communication breakdown) within ANOVA revealed a significant main effect of display on the mean number of lost houses ($F(1, 31) = 5.29, p < .001, \eta_p^2 = .330$) and significant interaction between display and communication breakdown ($F(1, 31) = 4.28, p = .047, \eta_p^2 = .121$). The main effect of communication breakdown did not reach significant level ($F(1, 31) = .70, p = .408$). These results indicated that the extent of houses loss was consistently less when the team display was present ($M = 1.61, SE = .20$) compared to when it was absent ($M = 2.72, SE = .29$). Moreover, communication breakdown tended to cause larger extent of loss when team display was not present ($M = 3.16, SE = .38$) compared to no communication breakdown ($M = 2.28, SE = .39$); this trend was reduced or even slightly reversed when team display was present ($M = 1.41, SE = .25$; compared to no communication breakdown: $M = 1.18, SE = .25$; see Figure 11).

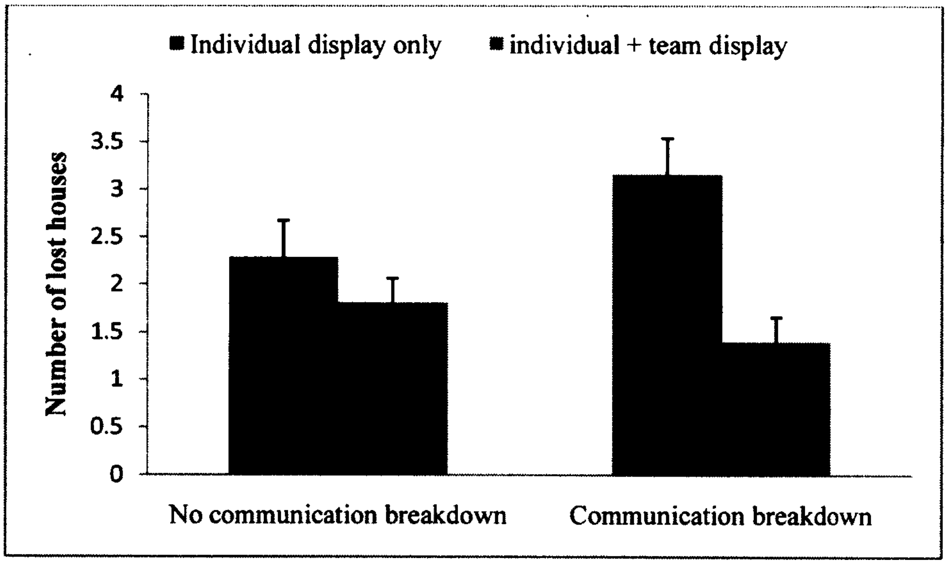


Figure 11. Mean number of lost houses across display type and communication breakdown.

A 2 (display type) ×5 (time block) within ANOVA resulted in main effects on both factors ($F(1, 31) = 12.51, p = .001, \eta_p^2 = .288$; $F(4, 124) = 52.317, p < .001, \eta_p^2 = .628$) and a significant interaction ($F(4, 124) = 11.09, p = .001, \eta_p^2 = .263$). Again, all of the corresponding statistical tests were based on significance levels that were determined by the (more conservative) Greenhouse-Geisser, epsilon-adjusted degrees of freedom. These results suggest that as the number of lost houses changed throughout the 10 minutes of a scenario, display type moderated such change resulting in the increased differences between the display conditions with respect to number of lost houses as a function of time block. More specifically, although there were always more houses lost when the team display was absent (except for in the 2nd block where no house was lost under either condition), this difference became larger in the later blocks of the scenario relative to the earlier blocks in the scenario (see Figure 12). Note that a downward line here is because some burning houses from last minute were put out in the next minute.

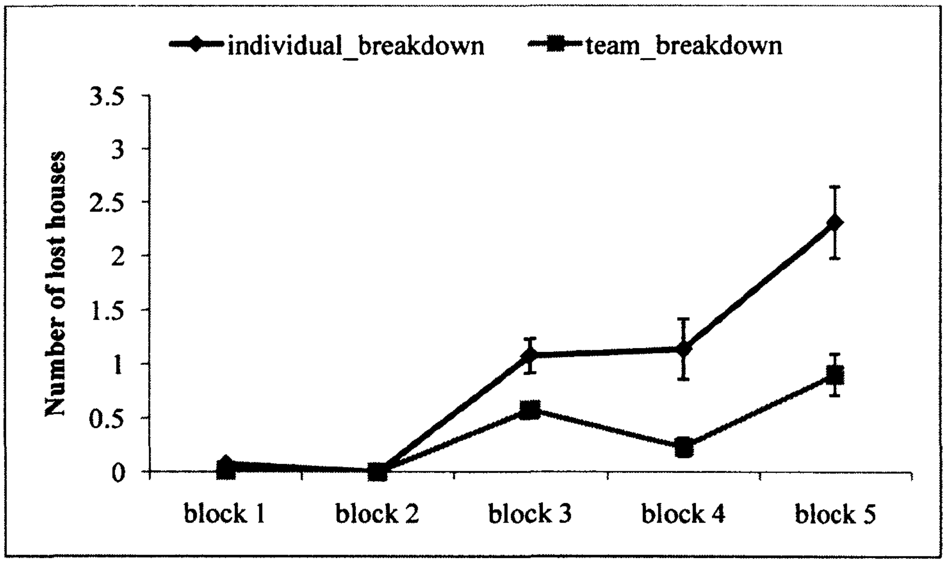


Figure 12. Mean number of lost houses across time block and display type.

Saved cells. A 2 (display type) × 2 (communication breakdown) within ANOVA was run on the ratio between number of saved cells and number of cells on fire irrespective of cell types. This analysis yielded a significant main effect of display type ($F(1, 31) = 14.87, p = .001, \eta_p^2 = .324$). With team display, participants managed to save more cells relative to the number of fires ($M = 27.8\%$, $SE = .02$) compared to when the team display was absent (*M* = 23.2%, *SE* = .02). Note that although it is the untransformed mean ratios and standard errors reported here, all of the corresponding statistical tests were actually based on log transformed data to restore error constancy (Kutner et al., 2004, p. 789).

Saved houses. A 2 (display type) × 2 (communication breakdown) within ANOVA on the ratio between number of saved houses and number of houses on fire revealed a significant interaction ($F(1, 31) = 7.44$, $p = .01$, $\eta_p^2 = .194$). This result indicated that the negative impact of communication breakdown on performance was moderated by the presence of the team display (see Figure 13). Without the team display, 49.7% (*SE* = .06) of burning houses were saved on average when no communication breakdown happened during a session comparing to a smaller proportion of 33.1% (*SE* = .04) when communication breakdown did happen. With the team display, the proportion of saved houses did not become smaller, but even increased when communication breakdown was introduced (*M* = 47.7%, *SE* = .06; comparing to no communication breakdown: *M* = 36.1%, *SE* = .06).

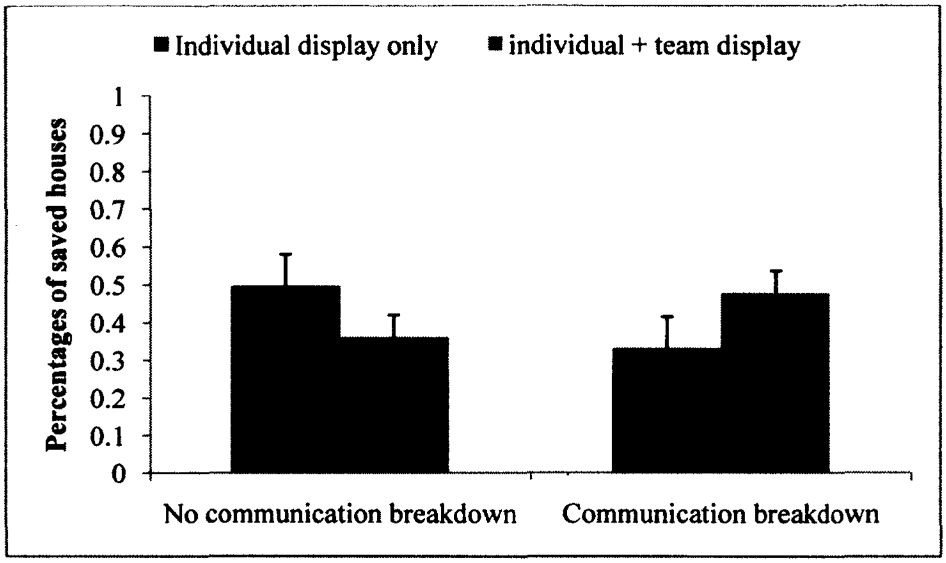


Figure 13. Mean percentages of saved houses across display type and communication breakdown.

In summary, significantly fewer cells/houses were lost in the conditions with the team display compared to conditions without team display. Similarly, significantly more cells/houses on fire were put out when the team display was present. The introduction of communication breakdown tended to negatively affect performance in the form of more lost cells/houses and smaller proportion of saved cells/houses. However, this trend was either reduced or slightly reversed with the presence of the team display.

Average time each cell was on fire (in seconds). A 2 (display type) × 2 (communication breakdown) within ANOVA revealed a significant main effect of display type ($F(1, 31) = 11.91, p = .002, \eta_p^2 = .278$). On average, cells were on fire for a shorter period of time when the team display was present ($M = 77.65$, $SE = .86$) compared to when it was absent ($M = 80.63$, $SE = .89$).

Considering that the "time" in the index "average time on fire" was composed of three parts: time that cells start burning until extinguished; time that cells start burning until burned out; and time that cells start burning until the end of scenario, a more specific index was also explored and is reported below.

Average time to put out fire on a cell (in seconds). A 2 (display type) × 2 (communication breakdown) within ANOVA revealed no significant main effect in average seconds to put out a burning cell between the "individual + team display" (M = 62.86, SE = .77) and the "individual display only" condition (M = 62.66, SE = 1.01). In addition, there was no significant main effect between the communication breakdown condition (M = 62.71, SE = .90) and the no communication breakdown condition (M = 62.82, SE = .96). No interaction ($F(1, 31) = .69$, *ns.*) was revealed.

Total active time working on fire suppression (in seconds). A (display type) × 2 (communication breakdown) within ANOVA revealed a significant main effect of display type ($F(1, 31) = 10.55$, $p = .003$, $\eta_p^2 = .254$). Significantly longer mean active time was observed when the team display was present (M = 1668.94, SE = 29.19) compared to when it was absent (M = 1601.27, SE = 27.63). This analysis did not reveal significant main effect in total active time between the communication breakdown condition (M = 1618.61, SE = 29.23) and the no communication breakdown condition (M = 1651.59, SE = 26.36). Nor was there an interaction ($p > .1$).

Situation Awareness

Separate analyses were carried out for the two types of SAGAT probes—continuous (Cont.) and true/false (T/F)—due to the intrinsic difference between these two types of data.

SAGAT probes (continuous). For subjects who had zero continuous probes asked during one measurement, regression equation was first established using cases that have both continuous & true/false data (T/F as X, Cont. as Y), then missing values were imputed using predicted values. 19 values out of 256 values were imputed for Incident Commander and 11 values were imputed for Ground Chief. The mean scores on SAGAT probes (continuous) for each participant were analyzed by a 2 × 2 × 2 × 2 mixed repeated measures ANOVA, with measurement time (1st, 2nd), display type and communication breakdown as repeated measures and team member role (IC vs. GC) as the between-participants variable. Using a more liberal alpha level, the main effect of display type was significant ($F(1, 62) = 3.16, p = .081, \eta_p^2 = .048$). So were the main effect of measurement time ($F(1, 62) = 3.63, p = .061, \eta_p^2 = .055$) and the three-way interaction between measurement time, communication breakdown, and role ($F(1, 62) = 3.19, p = .079, \eta_p^2 = .049$). No other main effect or interaction was significant (*ps* > .1).

With the team display, participants tended to have higher scores on SA probes ($M = .74, SE = .02$) in comparison with no team display ($M = .71, SE = .02$). In addition, participants on average scored higher in the 1st measurement ($M = .74, SE = .02$) compared to the 2nd ($M = .71, SE = .02$). However, this main effect should be qualified with the three-way interaction between measurement time, communication breakdown, and roles. More specifically, the extent how SA scores changed from 1st to 2nd measurement was moderated by whether communication breakdown happened during a session; such moderating relationship also differed across two roles (see Figure 14). For example, for IC, the mean SA score slightly increased from 1st to 2nd measurement when no communication breakdown happened ($M_{1st} = .67, SE_{1st} = .04; M_{2nd} = .69, SE_{2nd} = .04$); however, the mean SA score drastically decreased between two measurements when communication breakdown happened ($M_{1st} = .72, SE_{1st} = .03; M_{2nd} = .62, SE_{2nd} = .03$).

This contrasted with GC whose mean SA score barely changed between two measurements when communication happened during a session ($M_{1st} = .77$, $SE_{1st} = .03$; $M_{2nd} = .76$, $SE_{2nd} = .03$), although a noticeable decrease was observed from 1st to 2nd measurement when no communication breakdown happened ($M_{1st} = .82$, $SE_{1st} = .04$; $M_{2nd} = .76$, $SE_{2nd} = .04$). Separate graphs of SA scores (continuous) for IC and GC across display type, communication breakdown and measurement time are presented in Figures 15 and 16.

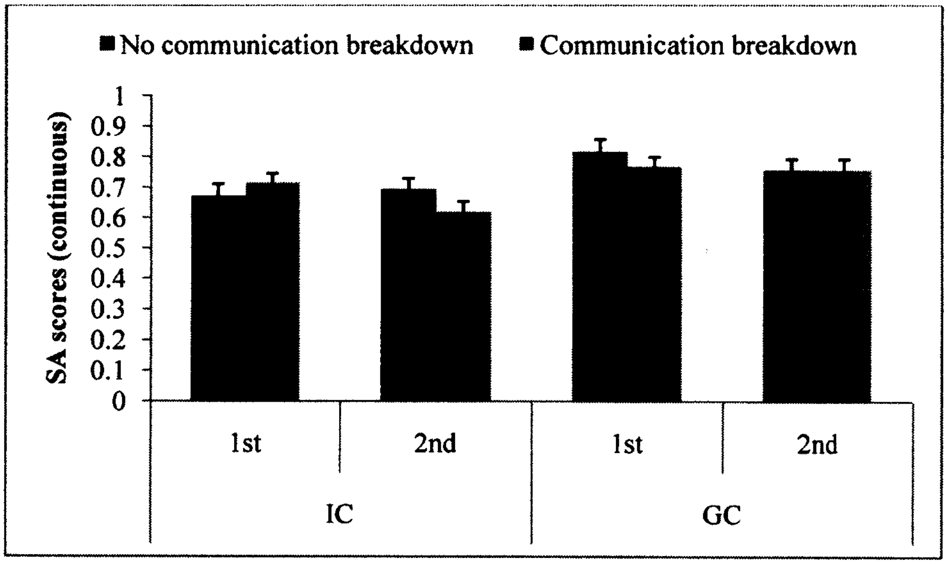


Figure 14 Mean SA scores (continuous) across roles, measurement time, and communication breakdown.

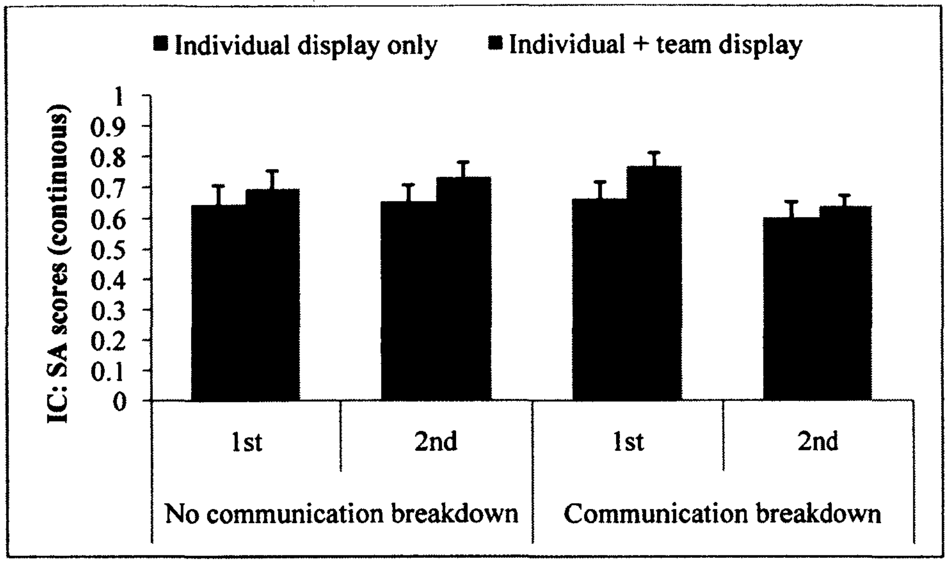


Figure 15. Mean SA scores (continuous) for IC across display type, communication breakdown, and measurement time.

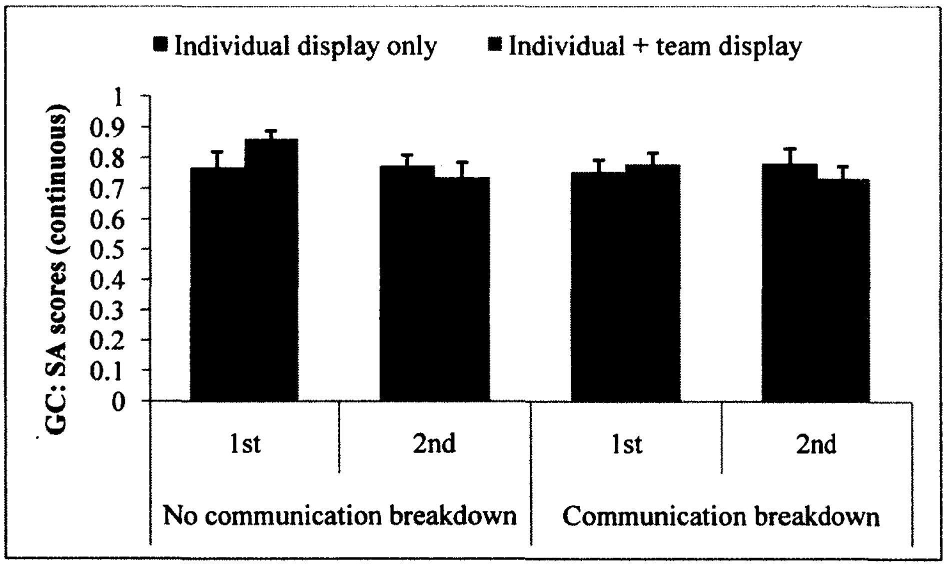


Figure 16. Mean SA scores (continuous) for GC across display type, communication breakdown, and measurement time.

SAGAT team probes (continuous). The mean scores on continuous SAGAT team questions (teamQs) for each participant were analyzed by a 2 × 2 × 2 × 2 mixed repeated measures ANOVA, with measurement time (1st, 2nd), display type and communication breakdown as repeated measures, and team member role (IC vs. GC) as a between-participants variable. For subjects that had zero continuous teamQs asked during one measurement, data was imputated using an additive model based on the subject and cell effects (Kutner et al., 2004, p. 964). 34 values out of 256 values were imputed for IC and 57 out of 256values for GC.

The two-way interaction between display and role was significant ($F(1, 62) = 11.01, p = .002, \eta_p^2 = .151$), indicating that the presence of the team display had different impact on two roles (see Figure 17). For ICs, their mean SA score was .73 ($SE = .03$) when the team display was present in comparison to .62 without the team display ($SE = .03$). For GCs, their mean SA score was .72 ($SE = .03$) when the team display was present in comparison to .76 without the team display ($SE = .03$). No other main effect or interaction effect was significant ($ps > .1$).

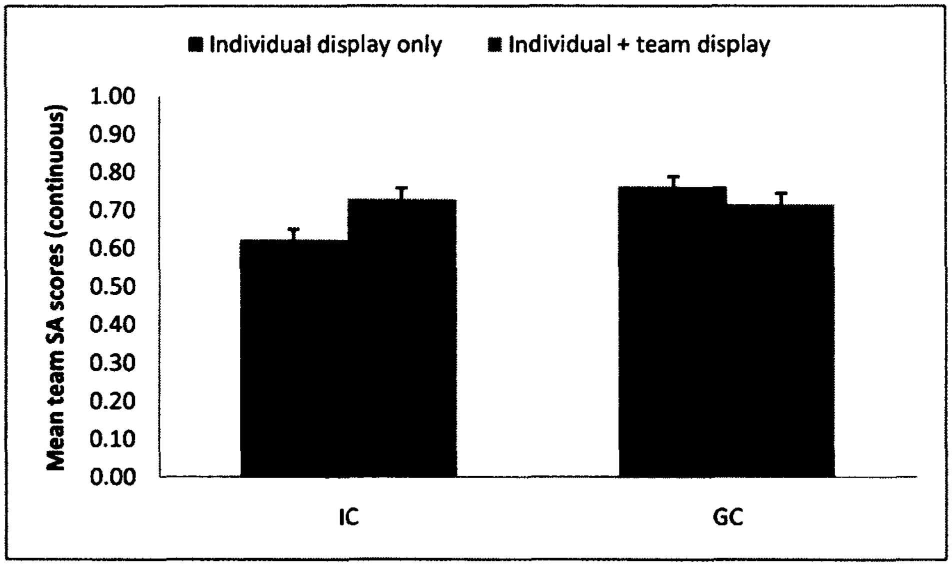


Figure 17. Mean team SA score (continuous) across role and display type.

SAGAT probes (true/false). The transformed mean scores on SAGAT probes (T/F) for each participant were imputed (Cont. as X, T/F as Y) and then subjected to a 2 ×

$2 \times 2 \times 2$ mixed repeated measures ANOVA, with measurement time (1^{st}, 2^{nd}), display type and communication breakdown as repeated measures and team member role (IC vs. GC) as the between-participants variable. 82 values out of 256 values were imputed for GC; there was none missing value for IC. This analysis revealed a significant main effect of display type ($F(1, 62) = 6.14, p = .016, \eta_p^2 = .09$), indicating that participants tended to have higher SA scores with the team display ($M = .74, SE = .03$) in comparison with no team display ($M = .65, SE = .03$). No other main effect or interaction was significant ($ps > .1$). Note that although all the statistical tests reported here were based on transformed data, all the mean scores and standard errors were based on untransformed data.

Workload

Weighted mean scores on NASA-TLX from each IC and GC under each condition were analyzed in two 2 (display type) × 2 (communication breakdown) within ANOVAs. The analyses revealed no significant main effect or interaction for IC or GC ($ps > .1$), indicating that both team members experienced similar workload level across four conditions. Table 2 presented mean workload scores for both roles under each condition.

Table 2

Weighted average TLX scores *for both roles across four conditions*

		Without Communication breakdown	With Communication breakdown
IC	Individual display only	11.474	11.327
	Individual + team display	11.240	10.786
GC	Individual display only	12.740	12.601
	Individual + team display	12.194	12.288

* The scores were measured out of 20

Discussion

This chapter begins with summarizing the main findings in this study, and proceeds with discussing implications of these findings to the research of team oriented displays and teamwork in a C2 context. This is followed by an outline of the limitations of this study, and a description of the potential for future research in this field.

As a follow-up of an empirical study on forest firefighting command and control teamwork and SA (Brandigampola, 2011), the goal of this study was to test the effectiveness of a team-oriented information display in supporting teamwork. It was hypothesized that the team display could enhance teamwork in a C2 context by improving team situation awareness and hence overall performance, and particularly by facilitating recovery from communication breakdown. To examine these hypotheses, both situation awareness and performance were measured in a simulated wildland firefighting C2 context with or without the presence of a team display. Upon analyzing the data, it is reasonable to suggest that the team display can facilitate performance and situation awareness even with communication breakdown.

Performance

Both the smaller number of lost cells/houses and the increased proportion of saved cells/houses under the "individual + team display" condition indicate that the team display did facilitate team performance. Given the task interdependency between the team members in this study, communication breakdown could pose difficulty for their information exchange and interrupt the teamwork. This has been confirmed by the lowest performance scores observed in the "individual display only with communication breakdown" condition. However, the interaction between display type and communication breakdown with number of lost houses and proportion of saved houses implies that when the needed information was continuously updated in a specially tailored team display such as the one in the present study, the negative impact of communication breakdown was reduced.

From both perspectives—loss and saving, team display facilitated overall performance even with communication breakdown. The only exception is the smaller proportion of saved houses when team display was present but without communication breakdown. Unfortunately, the current study does not have enough data to account for this exception.

A question arises where the effectiveness of the team display came from. One possible explanation is that, with team display, participants deployed their vehicles more wisely within a 10-minute scenario so that more fires were put out but not necessarily by being faster. This hypothesis was supported by analyzing total active time of the four firefighting units under different experiment conditions. Units spent more time fighting fires when the team display was present. With the introduction of communication breakdown under the "individual display only" condition, firefighting units idled on average as long as 80 seconds longer than when no communication breakdown happened. This negative impact of communication breakdown was reduced by the presence of the team display. This time-based index offers some insights for the effectiveness of the team display observed repeatedly in this study: participants consistently managed to take better advantage of their resources (firefighting vehicles) when the team display was present and therefore put out more fires. This result also agrees with what has been found by Tremblay and colleagues (2011). In their study, monitoring effectiveness (measured in terms of non-idle time of ground units) was translated into better performance.

From another perspective, the presence of team display could have shortened participants' reaction time, i.e., faster suppression of fire and therefore would have resulted in less spreading of fire and hence less damage. While results from examining the index "average time each cell was on fire" seemed to support such a hypothesis because less burning time on average was observed when the team display was present, caution is required in interpreting these results. A shorter average time on fire can have resulted from any one or a combination of the following three cases: (a) fewer cells were burned out throughout a session. Considering that the time a cell starts burning until it is burned out is a constant and is always longer than the time to put out fire on a cell, the index "average time on fire" would be partially a reflection of the number of burned out cells; (b) the average burning time for cells that started burning toward the end of the scenario was shorter than the average time to put out fire on a cell. In this case, "average time on fire" is at best an indicator of a firefighting team's efficiency for the first 8-9 minutes[1] out of a 10-minute scenario; (c) on average, fire on each cell was put out within a shorter time. However, nonsignificant results upon analyzing the average time to put out fire on a cell indicates that this case alone cannot explain the effectiveness of firefighting teams with the team display. Caution is also required in interpreting this result. Given that fires have different priorities, longer reaction time may be still appropriate with those that have low priorities.

In short, the hypothesis that team performance will be significantly better when a team display is present compared to absent was supported. Adding to this result is the observation of a larger difference on number of lost cells/houses between different display conditions as a function of time. This result did not directly answer the question whether the team display supported performance recovering from communication breakdown or not. It could be because participants maintained a relatively higher performance level all the time with the team display. While the negative impact of communication breakdown was reduced in the "individual + team display" condition, it had a larger negative impact when the team display was absent, thereby resulting in larger and larger difference between the two conditions. Or performance recovery did happen, however, the time required to recover may be shorter than the interval set in this analysis (2 minutes), especially with the team display, so the recovery became indiscernible. In short, the team display supported teamwork especially during communication breakdown, either by preventing performance from getting worse so that

---

[1] In the present experimental setting, it takes about 1 minute for a cell from being ignited until burned out.

it could maintain a relatively higher level, or by enabling the performance to recover quickly after breakdown.

To answer the fundamental question whether improved SA due to the team display is the reason for improved performance, the next section will discuss it in view of the results from the present study.

Situation Awareness

The hypothesis that the team display could improve participants' SA was generally supported by the results. Participants consistently scored higher on SA accuracy for both continuous and true/false types of questions when the team display was present in comparison when it was absent.

The interaction between role and display type on team SA accuracy (continuous teamQs) indicated that the team display did not always improve SA for the GC. Since the GC did not experience higher workload with the team display, it could be ruled out that GC's decreased SA at the presence of the team display was caused by higher workload for processing additional information on the team display (Brandigampola, 2011). This result may be because that IC has more of a C2 type role and this role definition had benefited from the team display more than the GC. Due to the different role definitions of the two, GC may also tend to develop dependence on the team display for access to relevant information in fighting fires (Hutchins & Lintern, 1995; Stanton, Salmon, Walker, &Jenkins, 2010). In another words, GC were less likely to register information coming from IC in his/her memory because it was available on the team display (Stanton et al., 2010). When the team display was absent during SAGAT measurement, GC lost access to the information and therefore had lower scores on those memory-based probes.

However, when the team display was absent from the beginning of a scenario, i.e., sessions under the condition "individual display only", GC had to rely more on his/her memory, based on which s/he could easily provide answers when probed.

The second SA measurement in the two scenarios that introduced communication breakdown was supposed to measure "post-breakdown SA". It was hypothesized that, with the team display, participants would score more similarly in this measurement and the first than those that did not have the team display when the communication breakdown happened. It was further reasoned that participants maintained better SA level during communication breakdown with the team display and/or recovered their SA faster from post-breakdown with the team display. However, the actual results did not support such hypothesis. The team SA scores (continuous) of IC[1] showed a larger decrease from 1st to 2nd measurement when the team display was present (M_{1st} = .759, M_{2nd} = .690) comparing to when it was absent (M_{1st} = .623, M_{2nd} = .611), although the absolute values were always higher with the team display (also see

Figure 15). This result raised the question "how long would it take to recover SA from interruption/breakdown." According to Tremblay (2011), recovery from interruption for people working in dynamic systems, which change automatically and/or as a consequence of decision making, may require more than a dozen seconds. Given the fact that the 2nd measurement was implemented 15 seconds after a communication

---

[1] The SA scores of GC maintained approximately the same from 1st to 2nd measurement when the team display was present (M_{1st} = .698, M_{2nd} = .703). However, there was an increase when the team display was absent (M_{1st} = .710, M_{2nd} = .758). This result may have been complicated by the fact that GC scored lower on team SAGAT probes (teamQs) when the team display was present (see the beginning of this section).

breakdown, the results agreed with their findings. But the author also acknowledges that the present study used different paradigm from interruption studies and the results may not be directly comparable.

Another relevant question is whether the time to recover SA from breakdown varies between different roles. The three-way interaction between measurement time, communication breakdown, and role on the SA scores (continuous), suggest that when the post-breakdown SA was measured 15 seconds after the communication breakdown, IC's SA decreased from the pre-breakdown SA while GC's SA did not. This result can be interpreted either as a reflection that IC and GC had differing recovery rate of SA, or that IC's and GC's SA had different degree of vulnerability to communication breakdown, with IC's SA more vulnerable to a communication breakdown. Future study could use more sensitive SA measures to answer this question.

SA and Performance

Combining the results that both IC's SA accuracy scores and the team performance were consistently improved when the team display was present, it is reasonable to conclude that IC's SA played a more important role in teamwork. However, no correlation was examined between SA and performance scores. Therefore, we cannot reach this conclusion, although SA has been recognized as one causal variable of performance (Durso, 1998).

If we were to accept that the SA scores represented approximately true SA levels of participants, then the result also implied some disconnection between SA and performance. For instance, significant deterioration of performance was observed under the conditions with communication breakdown but without the team display. However, such negative impact of communication breakdown on participants' SA was not significant. Previous research has also provided mixed results with regards to the link between SA and performance (Brandigampola, 2011; Berggren & Johansson, 2010).

There are several possible reasons. It may suggest that performance was not solely driven by SA (Pew, 2000). Actually, it has been shown that many other factors also came into play in turning good situation awareness into successful performance (Endsley, 1995b). Another reason could be that the second SA measure was either too close to the end of the breakdown or not early enough and thus was not sensitive enough to possible changes and mitigations. Using the current SA measurement, it is practically impossible to "catch" the point when SA was most affected by communication breakdown and/or when SA recovered from communication breakdown. Future research could study this question by using fine-grained measurement so that any subtle change of cognition will be recorded.

To summarize, the team display seemed to have a larger positive impact on IC's SA than GC's SA, although the overall team performance was consistently better with the team display even when communication breakdown happened.

Practical Implications

Supportive information display. This study replicated and extended findings from the previous study that a team-oriented display had demonstrated benefits to SA (Brandigampola, 2011). This study found that the team display could enhance SA and also aid performance. When adding communication breakdown to the scenario, the team display also reduced the negative impact of communication breakdown on performance. Although the team display probably facilitated performance by facilitating teamwork throughout each scenario regardless of the condition, it was not meant to replace communication but to function as a backup during communication breakdown. The author also acknowledges that this team display was specifically designed with the unanticipated overheads caused by communication breakdown in mind (Garbis, 2004). It is entirely possible that firefighting C2 team need additional supportive information displays for daily operations.

One of the concerns in introducing a team display into a C2 center is that it may support teamwork at the expense of increasing users' workload (Endsley, Bolté, &Jones, 2003). The team display in this study improved performance and SA level without increasing workload. This result also confirmed that SA and workload are essentially independent constructs (Durso, 1998; Endsley, 1993; Wickens, 2008). In addition, anecdotal observations suggested that the team display was beneficial as it was commented many times as "useful" by participants in this study.

Design principles of team display. This study successfully instantiated the design principles proposed in previous studies (Parush et al., 2011b; Parush et al., 2009). Design principles for a TSA augmentative display that were established first in healthcare have been tested in forest firefighting with initial success. The team display was designed by identifying situation-related information elements which are critical for both team members and presenting them on the display in an integrated, context-sensitive, dynamic, and continuous manner. Improved SA and performance as well as no higher workload at the presence of the team display suggest that the design principles are sound and generalizable. Future search could apply these principles in other safety-critical organizations.

Using microworld to study teamwork. C^3Fire microworld created a dynamic and complex environment that, in the most important aspects, represented the real world. According to a previous study using this simulation, it created a large motivational appeal and user acceptance was high with the professional subjects (Johansson et al., 2003). In their study, the professional subjects quickly adopted analogies to their own field of expertise. This, and the fact that many of the teams in this study clearly stated that they found the simulation to be very engaging, indicates that the microworld, even though the simulation is fairly simple, reflects some of the crucial aspects of team work in dynamic settings. It is believed that the C^3Fire system can be used as a test-bed for future studies to further examine the role of TSA and team displays in extreme C2 circumstances.

Using SAGAT to measure SA. Given the instrumental role of TSA in decision making in a C2 team context, results from this study implies that (a) SAGAT may not be appropriate /adequate for measuring SA in a dynamic team context (Pew, 2000). Salmon (2009) made comments that the SAGAT approach can be classified as deterministic and linear. For more dynamic, collaborative, and changeable tasks, it may not be appropriate. It has also been suggested that SAGAT is useful for assessing aggregate individual differences in SA (Pew, 2000). However, Because of the randomness of the questions and limited time for answering them, one could not assure that questions asked at a particular point could reflect the concurrent SA level. Increasing number of probes asked each time could increase the chance of tapping into both TSA and individual SA. However, given the duration of each session in this study (10 minutes), number of measurements and hence number of probes were restricted. Otherwise, measurement would have distracted participants' attention too much; (b) if SAGAT is to be used in future research in dynamic team settings, it may require minor adjustments. For example, it maybe necessary to combine random selected and fixed probes at each measurement so that statistical validity and content validity can both be maximized. Moreover, instead of using paper and pencil, SAGAT questions can be embedded into the simulation so that SA measurement becomes part of the tasks and participants would be less likely to be distracted from the real tasks (i.e., fire suppression). This may increase the ecological validity of the whole experiment implementation.

Limitations of This Study

Design of SA questions. Mixing two types of questions—true/false and continuous—could pose difficulty for statistical analysis as has been shown in this study. Due to intrinsic difference between these two types of data, separate analysis needs to be run on each dataset. Moreover, all SAGAT probes for each measurement were randomly selected, thus it was not guaranteed that these probes would be distributed evenly between two types. For example, if a participant received zero true/false probes during one measurement, it was as if there were a missing value. When there are too many missing values, imputation became impossible, which is the case with true/false teamQs in this study.

Generability. This study used novice participants instead of professional firefighting commanders. Therefore, care needs to be taken when generalizing findings reported here to actual forest firefighting C2 and other C2 fields such as intensive care units and military operations. It is understandable that professional commanders hold special knowledge, attitude and sills comparing to novice participants. For example, lack of prioritizing when there were more than two fires on the ground was observed in many teams in this study. Instead, these teams responded to fires on a "first come, first serve" fashion. It was reasoned that prioritizing among more than two fires on the ground can be a difficult task for non-professionals, especially under considerable time constraints. One needs to take several factors into account simultaneously such as wind speed and direction, fires' proximity to houses, concurrent location of ground units, etc. Therefore, results of this study are open to questions such as whether professional users will interact with the team display in a different way so that its impact on their performance would differ accordingly. While these questions warrant further examination, findings of this study still have a certain degree of generability, especially considering that C^3Fire has good fidelity and has received acceptance from professional participants in previous study (Johansson et al., 2003).

Rater vs. researcher. Ideally, rate of SA probes and the researcher should be different people. However, due to practical limitations, they were the same person in the present study. Because objective criteria were used for rating the answers, source of experimenter's bias was strictly limited.

Future Studies

Advanced training design. Order effect was found in this study, though it did not interact with experimental variables. Such order effect was largely ensued by restricted training session which lasted approximately 30 minutes with three 5-minute hands-on practice sessions interposed with video-based training. In another words, participants' performance level was still unstable by the end of the training and therefore practice effect extended into the first one or even two sessions. Although counterbalanced Latin square design helped to control this confounding factor, it may still have compromised the generability of findings in this study because, ideally, professional users would have reached stable performance level in real life. Future studies could improve training strategy and/or increase the training session if time allows so that participants could reach stable performance level before real experimental sessions start.

Improved measurement of team cognition. SAGAT was used to measure participants' cognition in this study. As informative as it was, certain aspects of team cognition were still missed out by using this measurement, which was implied by the disconnection between performance and SAGAT accuracy scores. It has been shown that communication analysis could provide a better indicator of SA in team settings, especially those between professionals (Cooke et al., 2004; Foltz et al., 2008; Gorman et al., 2006), in part because communication and SA share a dynamic nature. For example, using a system called "TeamPrints" (a combination of Latent Semantic Analysis and Natural Language Processing techniques to automatically analyze team communications), Foltz and colleagues (2008) studied communication exchange and its potential in predicting SA of team members. Future research could recruit professional participants (e.g., forest firefighting commanders) and record their communication while they carry out tasks in a simulated context such as C^3Fire. A previous study has shown that professional users of C^3Fire often used their professional "language" when interacting (Johansson et al., 2003). The fact that some behavioural patterns could be preserved when the professional subjects were taken from their actual work to the laboratory suggests that analysis of their communication would be greatly informative and findings thereof have better external validity.

Collecting behavioural evidence of team display usage. Although findings in this study support the idea that a team display is beneficial to both SA and performance, it is still unknown whether and/or when team members actually used the display. Before such behavioural evidence has been collected, one cannot easily draw the conclusion of causal relationship between the team display and improved SA and performance, though strict experimental control was administered to ensure that the only difference between two conditions was the presence of the team display. Future studies in replicating findings of this study could include camera recording of participants so that behavioural evidence (actual usage of the team display) could be collected which would strengthen findings in this study.

Significance of This Study

This study added empirical evidence to previous studies on the benefits of team displays in a C2 context such as forest firefighting. It was found that the team display improved performance as well as reduced the negative impact of communication breakdown on teamwork. Preliminary findings also revealed the underling mechanism for such benefits, i.e., improved SA due to the team display facilitated teamwork. Given that wildland fires are always located in remote area, commanders are more likely operating from distance, making it harder for them to track fire ground and making them more vulnerable to communication breakdown. Once applied to the field, such a team display may have the potential to reduce property loss and increase safety, or even save lifes. Research findings in this domain could also be extrapolated to similar domains such as air traffic control, nuclear power plant, and other similar circumstances.

Reference

Alvarez, G. & Coiera, E. (2006). Interdisciplinary communication: An uncharted source of medical error? *Journal of Critical Care, 21*(3), 236-242. doi: 10.1016/j.jcrc.2006.02.004

Annett, J. (2003). Hierarchical task analysis. In E. Hollnagel (Ed.), *Handbook of cognitive task design* (pp. 17-35): Routledge.

Artman, H. & Garbis, C. (1998). *Situation awareness as distributed cognition.* Paper presented at the Proceedings of ECCE'98. Limerick Ireland.

Baker, D. P., Day, R., & Salas, E. (2006). Teamwork as an Essential Component of High-Reliability Organizations. *Health Services Research, 41*(4p2), 1576-1598. doi: 10.1111/j.1475-6773.2006.00566.x

Bartels, R., Herskovic, V., Monares, A., Ochoa, S., Pino, J., & Borges, M. (2010). A Simple and Portable Command Post to Coordinate Search and Rescue Activities in Disaster Relief Efforts. In G. Kolfschoten, T. Herrmann & S. Lukosch (Eds.), *Collaboration and Technology* (Vol. 6257, pp. 337-344): Springer Berlin / Heidelberg.

Berggren, P. & Johansson, B. J. E. (2010). *Developing an instrument for measuring shared understanding.* Paper presented at the The 7th International ISCRAM Conference, Seattle, USA.

Blandford, A. & Wong, B. L. W. (2004). Situation awareness in emergency medical dispatch. *International Journal of Human-Computer Studies, 61*(4), 421-452.

Blickensderfer, E., Cannon-Bowers, J. A., & Salas, E. (1998). Cross-training and team performance *Making decisions under stress: Implications for individual and team* *training.* (pp. 299-311): Washington, DC, US: American Psychological Association.

Bolstad, C. A. & Endsley, M. R. (2000). The Effect of Task Load and Shared Displays on Team Situation Awareness. *Human Factors and Ergonomics Society Annual Meeting Proceedings, 44*, 189-192.

Brandigampola, S. R. (2011). *Team situation awareness displays: an empirical evaluation of team performance. (Unpublished master thesis).* Carleton University, Ottawa, Canada.

Canadian Interagency Forest Fire Centre Inc. (2010). Canada Report 2010 Retrieved from http://www.ciffc.ca/images/stories/pdf/2010_Canada_Report.pdf

Cannon-Bowers, J. A., Salas, E., & Converse, S. (1993). Shared Mental Models In Expert Team Decision Making. *Individual and group decision making: Current issues*, 221.

Cannon-Bowers, J. A., Tannenbaum, S. I., Salas, E., & Volpe, C. E. (1995). Defining competencies and establishing team training requirements. *Team effectiveness and decision making in organizations*, 333-380.

Cooke, N., Salas, E., Kiekel, P., & Bell, B. (2004). Advances in measuring team cognition. In E. F. Salas, Stephen M. (Ed.), *Team cognition: Understanding the factors that drive process and performance.* (pp. 83-106): Washington, DC, US: American Psychological Association.

Cooke, N. J., Gorman, J. C., Duran, J. L., & Taylor, A. R. (2007). Team cognition in experienced command-and-control teams. *Journal of Experimental Psychology: Applied, 13*(3), 146.

Curts, R. J. (2006). Rethinking Command & Control: DTIC Document.

Darling, E. a. C. D. M. (2004). *A methodology for unobtrusively determining the usage of C2 Data Walls*. Paper presented at the 10th International Command and Control Research and Technology Symposium: The Future of C2.

Davenport, C. E. (1997). Displays for Spatial Situation Awareness: The Use of Spatial Enhancements to Improve Global and Local Awareness: DTIC Document.

Domínguez, C. (1994). Can SA be defined. *Situation awareness: Papers and annotated bibliography*, 5-15.

Dominguez, C., Long, W. G., Miller, T. E., & Wiggins, S. L. (2006). *Design directions for support of submarine commanding officer decision making*. Paper presented at the 2006 Undersea HSI Symposium: Research, Acquisition and the Warrior, Mystic, CT, USA.

Dougherty, D. & Robbins, A. (1997). *Sed & awk*: O'Reilly Media, Inc.

Douglas, L., Aleva, D., & Havig, P. (2007). *Shared Displays: An Overview of Perceptual and Cognitive Issues*. Paper presented at the 12th International Command and Control Research and Technology Symposium: Adapting C2 to the 21st Century.

Dudfield, H. J., Macklin, C., Fearnley, R., Simpson, A., & Hall, P. (2001). *Big is better? Human factors issues of large screen displays with military command teams.* Paper presented at the Human Interfaces in Control Rooms, Cockpits and Command Centres, 2001. People in Control. The Second International Conference on (IEE Conf. Publ. No. 481).

Durso, F. T. (1998). Situation Awareness As a Predictor of Performance in En Route Air Traffic Controllers. *Air Traffic Control Quarterly, 6*(1), 1-20.

Durso, F. T. & Sethumadhavan, A. (2008). Situation awareness: Understanding dynamic environments. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 50*(3), 442.

Durso, F. T., Truitt, T. R., Hackworth, C. A., Crutchfield, J. M., & Manning, C. A. (1998). En Route Operational Errors and Situational Awareness. *The International Journal of Aviation Psychology, 8*(2), 177-194. doi: 10.1207/s15327108ijap0802_6

Dyer, J. L. (1984). Team research and team training: A state-of-the-art review. *Human factors review, 26*, 285–323.

Endsley, M. R. (1993). *Situation awareness and workload- Flip sides of the same coin.* Paper presented at the 7th International Symposium on Aviation Psychology, Columbus, OH; UNITED STATES.

Endsley, M. R. (1995a). A taxonomy of situation awareness errors. *Human factors in aviation operations*, 287-292.

Endsley, M. R. (1995b). Toward a theory of situation awareness in dynamic systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 37*(1), 32-64.

Endsley, M. R. (2000a). Direct measurement of situation awareness: Validity and use of SAGAT. In M. R. Endsley & D. J. Garland (Eds.), *Situation awareness analysis and measurement* (pp. 147-173): Routledge.

Endsley, M. R. (2000b). Theoretical underpinnings of situation awareness: A critical review. *Situation awareness analysis and measurement*, 3-32.

Endsley, M. R., Bolté, B., & Jones, D. G. (2003). *Designing for situtation awareness: an approach to user-centered design*: Taylor & Francis Group.

Endsley, M. R., Jones, W., Schneider, K., & McNeese, M. (2001). A model of inter-and intrateam situational awareness: implications for design, training, and measurement. *New Trends in Cooperative Activities Understanding System Dynamics in Complex Environments*, 46-67.

Farley, T. C., Hansman, R. J., Amonlirdviman, K., & Endsley, M. R. (2000). Shared information between pilots and controllers in tactical air traffic control. *Journal of Guidance, Control, and Dynamics, 23*(5), 826-836.

Federal Aviation Administration. (2010). *ORDER JO 7110.65T.* Retrieved from http://www.faa.gov/air_traffic/publications/atpubs/atc/Index.htm.

Foltz, P. W., Bolstad, C. A., Cuevas, H. M., Franzke, M., Rosenstein, M., & Costello, A. M. (2008). Measuring situation awareness through automated communication analysis. In M. Letsky, N. Warner, S. Fiore & C. Smith (Eds.), *Macrocognition in teams: theories and methodologies* (pp. 259- 275). Aldershot, England: Ashgate Pub Co.

Furuta, K. & Shu, Y. (2004). *Team Situation Awareness and Its Assessment.* Paper presented at the The Seminar of JSPS-KOSEF Core University Program on Energy Science & Technology Subtask CR04-2-2 "Advancement on Operation & Maintenance for Nuclear Power Plant", Tohoku University, Sendai, Japan.

Gibson, J., Orasanu, J., Villeda, E., & Nygren, T. E. (1997). *Loss of situation awareness-Causes and consequences.* Paper presented at the 9th International Symposium on Aviation Psychology, Columbus, OH.

Gibson, J. A. (1997). An Investigation of Situation Awareness Using Aviation Incident Reports: DTIC Document.

Goin, D., Vernik, R., & Wark, S. (2010). *Using Large Group Displays to Support Intensive Team Activities in C2*. Paper presented at the 16th Command and Control Research and Technology Symposium International: Collective C2 in Multinational Civil-Military Operation, Quebec City, Canada.

Gorman, J. C., Cooke, N. J., & Winner, J. L. (2006). Measuring team situation awareness in decentralized command and control environments. *Ergonomics, 49*(12), 1312-1325.

Granlund, R., Johansson, B., & Persson, M. (2001). C 3 Fire a Micro-world for Collaboration Training and Investigations in the ROLF environment. *Proceedings of 42nd Conference on Simulation and Modeling: Simulation in Theory and Practice*.

Gutwin, C. & Greenberg, S. (2004). The importance of awareness for team cognition in distributed collaboration. In E. Salas & S. M. Fiore (Eds.), *Team cognition: Understanding the factors that drive process and performance.* (pp. 177-201): Washington, DC, US: American Psychological Association.

Harmer, M. (2005). Independent Review on the care given to Mrs Elaine Bromiley on 29 March 2005. Retrieved from http://www.chfg.org/wp-content/uploads/ElaineBromileyAnonymousReport.pdf

Hart, S. G. & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research *Human mental workload.* (pp. 139-183): Oxford, England: North-Holland.

Hutchins, E. & Lintern, G. (1995). *Cognition in the Wild* (Vol. 19): MIT press Cambridge, MA.

Jenkin, C. (2004). *Team Situation Awareness: Display Technologies in Support of Maritime Domain Awareness.* Paper presented at the 7th Marine Transportation System Research & Technology Coordination Conference, Washington, DC, USA.

Jiang, X., Hong, J. I., Takayama, L. A., & Landay, J. A. (2004). *Ubiquitous computing for firefighters: field studies and prototypes of large displays for incident command.* Paper presented at the Proceedings of the SIGCHI conference on Human factors in computing systems, Vienna, Austria.

Johansson, B., Persson, M., Granlund, R., & Mattsson, P. (2003). C3Fire in command and control research. *Cognition, Technology & Work, 5*(3), 191-196. doi: 10.1007/s10111-003-0127-x

Jones, P. E. & Roelofsma, P. H. M. P. (2000). The potential for social contextual and group biases in team decision-making: biases, conditions and psychological mechanisms. *Ergonomics, 43*(8), 1129-1152. doi: 10.1080/00140130050084914

Klein, G. A., Calderwood, R., & Clinton-Cirocco, A. (1988). Rapid Decision Making on the Fire Ground: KLEIN ASSOCIATES INC YELLOW SPRINGS OH.

Kutner, M. H., Nachtsheim, C. J., Neter, J., & Li, W. (2004). *Applied linear statistical models* (5th ed.): Irwin.

Lafond, D., Vachon, F., Rousseau, R., & Tremblay, S. (2010). A cognitive and holistic approach to developing metrics for decision support in command and control. In

D. B. Kaber & G. Boy (Eds.), *Advances in Cognitive Ergonomics* (pp. 65–73): Danvers, MA: CRC Press.

Landgren, J. (2005). Shared use of information technology in emergency response work: Results from a field experiment. In B. V. d. Walle & B. Carlé (Eds.), *Proceedings of the 2nd International ISCRAM Conference* (pp. 35-41). Brussels, Belgium.

Lim, B. C. & Klein, K. J. (2006). Team mental models and team performance: A field study of the effects of team mental model similarity and accuracy. *Journal of Organizational Behavior, 27*(4), 403-418.

Lingard, L., Espin, S., Whyte, S., Regehr, G., Baker, G. R., Reznick, R., . . . Grober, E. (2004). Communication failures in the operating room: an observational classification of recurrent types and effects. *Quality and Safety in Health Care, 13*(5), 330-334. doi: 10.1136/qshc.2003.008425

Mathieu, J. E., Heffner, T. S., Goodwin, G. F., Cannon Bowers, J. A., & Salas, E. (2005). Scaling the quality of teammates' mental models: equifinality and normative comparisons. *Journal of Organizational Behavior, 26*(1), 37-56.

Mathieu, J. E., Heffner, T. S., Goodwin, G. F., Salas, E., & Cannon-Bowers, J. A. (2000). The influence of shared mental models on team process and performance. *Journal of Applied Psychology, 85*(2), 273.

McKinsey & Company. (2002). McKinsey report: Increasing FDNY's preparedness. New York.

McLennan, J., Holgate, A. M., Omodei, M. M., & Wearing, A. J. (2006). Decision Making Effectiveness in Wildfire Incident Management Teams. *Journal of*

Contingencies and Crisis Management, 14(1), 27-37. doi: 10.1111/j.1468-5973.2006.00478.x

Morgan, B. B., Jr. (1986). Measurement of team behaviors in a Navy environment: DTIC Document.

Nählinder, S., Berggren, P., & Svensson, E. (2004). Reoccurring LISREL patterns describing mental workload, situation awareness and performance. *Human Factors and Ergonomics Society, New Orleans.*

Neef, N. A., Trachtenberg, S., Loeb, J., & Sterner, K. (1991). Video-based training of respite care providers: an interactional analysis of presentation format. *Journal of Applied Behavior Analysis, 24*(3), 473.

Nehme, C. E., Scott, S. D., Cummings, M. L., & Furusho, C. Y. (2006). Generating Requirements for Futuristic Hetrogenous Unmanned Systems. *Human Factors and Ergonomics Society Annual Meeting Proceedings, 50*(3), 235-239.

Neville, S. A. (2006). Hierarchical task analysis: Developments, applications, and extensions. *Applied Ergonomics, 37*(1), 55-79. doi: 10.1016/j.apergo.2005.06.003

Nofi, A. A. (2000). Defining and measuring shared situational awareness: DTIC Document.

Nonose, K., Kanno, T., & Furuta, K. (2010). An evaluation method of team situation awareness based on mutual belief. *Cognition, Technology & Work, 12*(1), 31-40.

Paris, C. R., Salas, E., & Cannon-Bowers, J. A. (2000). Teamwork in multi-person systems: a review and analysis. *Ergonomics, 43*(8), 1052-1075.

Parush, A., Campbell, C., Hunter, A., Ma, C., Calder, L., Worthington, J., . . . Frank, J. R. (2011a). *Situational Awareness and Patient Safety*. Ottawa, Canada: The Royal College of Physicians and Surgeons of Canada.

Parush, A., Kramer, C., Foster-Hunt, T., Momtahan, K., Hunter, A., & Sohmer, B. (2011b). Communication and team situation awareness in the OR: Implications for augmentative information display. *Journal of Biomedical Informatics, 44*(3), 477-485. doi: 10.1016/j.jbi.2010.04.002

Parush, A., Momtahan, K., Foster-Hunt, T., Kramer, C., Hunter, A., & Nathan, H. (2009). A Communication Analysis Methodology for Developing a Cardiac Operating Room Team-Oriented Display. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 53*(11), 728-732. doi: 10.1177/154193120905301120

Patrick, J. & James, N. (2004). A Task-Oriented Perspective of Siutation Awareness. In S. Banbury & S. Tremblay (Eds.), *A cognitive approach to situation awareness: theory and application* (pp. 61-81): Ashgate Pub Ltd.

Patrick, J., James, N., Ahmed, A., & Halliday, P. (2006). Observational assessment of situation awareness, team differences and training implications. *Ergonomics, 49*(4), 393-417.

Pew, R. W. (2000). The state of situation awareness measurement: Heading toward the next century. *Situation awareness analysis and measurement*, 33–47.

Pyne, S. J., Andrews, P. L., & Laven, R. D. (1996). *Introduction to wildland fire*: John Wiley & Sons Inc.

Resch, B., Schmidt, D., & Blaschke, T. (2007). Enabling geographic situational awareness in emergency management *Proceedings of the 2nd Geospatial Integration for Public Safety Conference* (pp. 1-8). New Orleans, Louisiana, US.

Rohde, M. (2002). *Command decisions during catastrophic urban-interface wildfire: A case study of the 1993 Orange County Laguna Fire.* MA thesis. California State University, Long Beach, CA.

Roscoe, S. N. & Williams, A. C. (1980). *Aviation psychology*: Iowa State University Press.

Ross, E. W., Chief Investigator & Forest, T. N. (1990). Dude Fire Accident Investigation Report. Payson, Arizona, U.S.

Roth, E. M., Lin, L., Thomas, V. M., Kerch, S., Kenney, S. J., & Sugibayashi, N. (1998). *Supporting situation awareness of individuals and teams using group view displays.* Paper presented at the Human Factors and Ergonomics Society 42nd Annual Meeting, Santa Monica, CA.

Roth, E. M., Multer, J., & Raslear, T. (2006). Shared situation awareness as a contributor to high reliability performance in railroad operations. *Organization Studies, 27*(7), 967.

Rousseau, R., Tremblay, S., & Breton, R. (2004). Defining and modeling situation awareness: A critical review. In S. Banbury & S. Tremblay (Eds.), *A cognitive approach to situation awareness: theory and application* (pp. 3-21): Ashgate Publishing, Ltd.

Salas, E., Burke, C. S., & Samman, S. N. (2001). Understanding Command and Control Teams Operating in Complex Environments. *Inf. Knowl. Syst. Manag., 2*(4), 311-323.

Salas, E., Dickinson, T. L., Converse, S. A., & Tannenbaum, S. I. (1992). Toward an understanding of team performance and training. In R. W. Swezey & E. Salas (Eds.), *Teams: Their training and performance.* (pp. 3-29): Westport, CT, US: Ablex Publishing.

Salas, E. & Fiore, S. M. (2004). *Team cognition: Understanding the factors that drive process and performance*. DC, US: American Psychological Association: Washington.

Salas, E., Prince, C., Baker, D. P., & Shrestha, L. (1995). Situation awareness in team performance: Implications for measurement and training. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 37*(1), 123-136.

Salas, E., Stagl, K. C., & Burke, C. S. (2004a). 25 Years of Team Effectiveness in Organizations: Research Themes and Emerging Needs. In C. L. Cooper & I. T. Robertson (Eds.), *International Review of Industrial and Organizational Psychology 2004, Volume 19* (pp. 47-91). Chichester, UK: John Wiley & Sons, Ltd.

Salas, E., Stagl, K. C., & Burke, C. S. (2004b). 25 years of team effectiveness in organizations: research themes and emerging needs. *International Review of Industrial and Organizational Psychology 2004*, 47-91.

Salmon, P., Stanton, N., Walker, G., Jenkins, D., Baber, C., & McMaster, R. (2008a). Representing situation awareness in collaborative systems: A case study in the energy distribution domain. *Ergonomics, 51*(3), 367-384.

Salmon, P. M., Stanton, N. A., Walker, G. H., Baber, C., Jenkins, D. P., McMaster, R., & Young, M. S. (2008b). What really is going on? Review of situation awareness models for individuals and teams. *Theoretical Issues in Ergonomics Science, 9*(4), 297-323.

Scott, S. D., Wan, J., Rico, A., Furusho, C., & Cummings, M. (2007). *Aiding team supervision in command and control operations with large-screen displays.* Paper presented at the HSIS 2007: ASNE Human Systems Integration Symposium, Annapolis, MD, USA.

Shu, Y. & Furuta, K. (2005). An inference method of team situation awareness based on mutual awareness. *Cognition, Technology & Work, 7*(4), 272-287.

Smith, K. & Hancock, P. A. (1995). Situation Awareness Is Adaptive, Externally Directed Consciousness. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 37*(1), 137-148. doi: 10.1518/001872095779049444

South Canyon Fire Accident Investigation Team, United States. Bureau of Land Management, United States. Forest Service, & United States. National Weather Service. (1994). *South Canyon Fire investigation of the 14 fatalities that occurred on July 6, 1994 near Glenwood Springs, Colorado*. Washington, DC: U.S.: US Dept. of the Interior, Bureau of Land Management.

Stanton, N. A. (2010). Situation awareness: Where have we been, where are we now and where are we going? *Theoretical Issues in Ergonomics Science, 11*(1-2), 1-6. doi: 10.1080/14639220903009870

Stanton, N. A., Chambers, P. R. G., & Piggott, J. (2001). Situational awareness and safety. *Safety Science, 39*(3), 189-204. doi: 10.1016/s0925-7535(01)00010-8

Stanton, N. A., Salmon, P. M., Walker, G. H., & Jenkins, D. P. (2010). Is situation awareness all in the mind? *Theoretical Issues in Ergonomics Science, 11*(1-2), 29-40.

Stanton, N. A., Stewart, R., Harris, D., Houghton, R. J., Baber, C., McMaster, R., . . . Young, M. S. (2006). Distributed situation awareness in dynamic systems: theoretical development and application of an ergonomics methodology. *Ergonomics, 49*(12), 1288-1311.

Stout, R. J., Cannon-Bowers, J. A., Salas, E., & Milanovich, D. M. (1999). Planning, Shared Mental Models, and Coordinated Performance: An Empirical Link Is Established. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 41*(1), 61-71. doi: 10.1518/001872099779577273

Sulistyawati, K., Chui, Y. P., & Wickens, C. D. (2008). Multi-method Approach to Team Situation Awareness. *Human Factors and Ergonomics Society Annual Meeting Proceedings, 52*, 463-467.

Sundstrom, E., de Meuse, K. P., & Futrell, D. (1990). Work teams: Applications and effectiveness. *American Psychologist, 45*(2), 120-133. doi: 10.1037/0003-066x.45.2.120

Tenney, Y. J. & Pew, R. W. (2006). Situation Awareness Catches On: What? So What? Now What? *Reviews of human factors and ergonomics, 2*(1), 1-34. doi: 10.1177/1557234x0600200102

Toups, Z. O., Kerne, A., Hamilton, W. A., & Shahzad, N. (2011). *Zero-fidelity simulation of fire emergency response: improving team coordination learning.* Paper presented at the Proceedings of the 2011 annual conference on Human factors in computing systems, Vancouver, BC, Canada.

Tremblay, S., Vachon, F., Lafond, D., & Kramer, C. (2011). Dealing With Task Interruptions in Complex Dynamic Environments: Are Two Heads Better Than One? *Human Factors: The Journal of the Human Factors and Ergonomics Society.* doi: 10.1177/0018720811424896

Varone, J. C. & Dept, P. F. (1996). *Fireground Radio Communications and Firefighter Safety*: National Fire Academy.

Vidulich, M. A. (2000). Testing the sensitivity of situation awareness metrics in interface evaluations. In M. R. Endsley & D. J. Garland (Eds.), *Situation awareness: analysis and measurement* (pp. 227-246): Routledge.

Vidulich, M. A. (2003). Mental workload and situation awareness: Essential concepts for aviation psychology practice. In P. S. Tsang & M. A. Vidulich (Eds.), *Principles and practice of aviation psychology.* (pp. 115-146). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

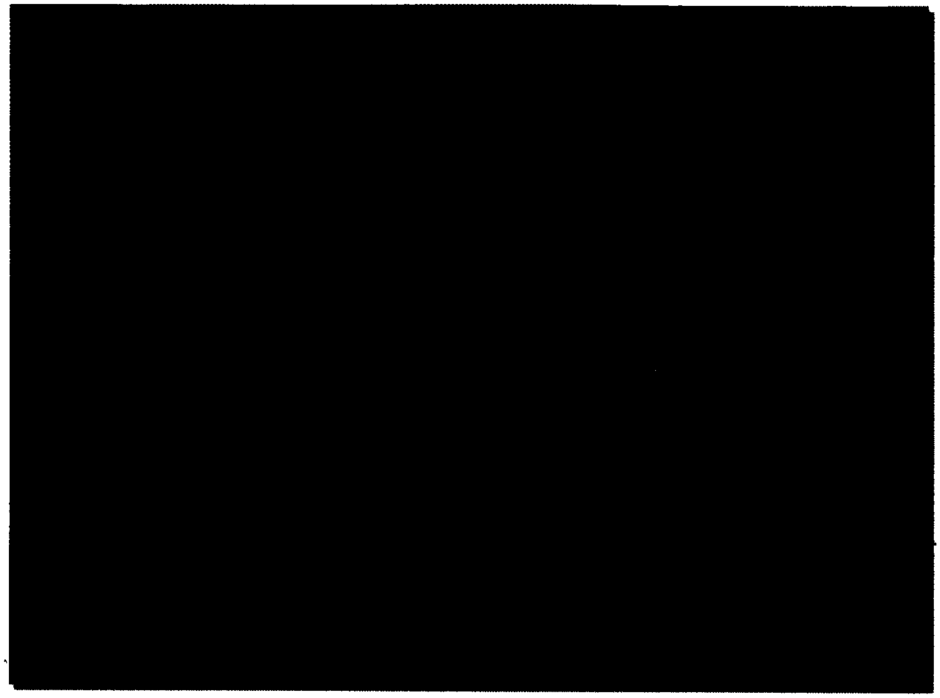
Wellens, A. R. (1993). Group situation awareness and distributed decision making: From military to civilian applications. *Individual and group decision making: Current issues*, 267-287.

Wickens, C. D. (2008). Situation Awareness: Review of Mica Endsley's 1995 articles on Situation Awareness theory and measurement. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 50*(3), 397.

Wilson, K. A., Salas, E., Priest, H. A., & Andrews, D. (2007). Errors in the Heat of Battle: Taking a Closer Look at Shared Cognition Breakdowns Through Teamwork. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 49*(2), 243-256. doi: 10.1518/001872007x312478

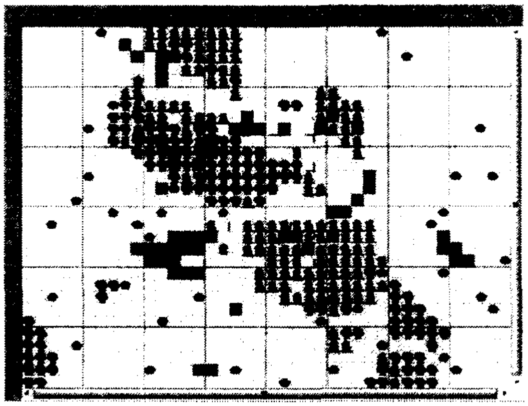
Wright, M. C. & Kaber, D. B. (2005). Effects of Automation of Information-Processing Functions on Teamwork. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 47*(1), 50-66. doi: 10.1518/0018720053653776

Appendix A Physical Layout of Experiment

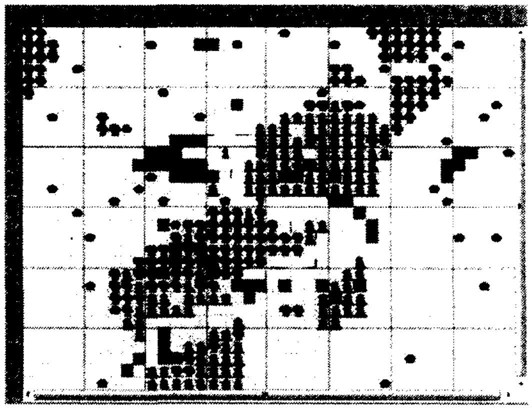


Appendix B Flipped Maps for Four Scenarios

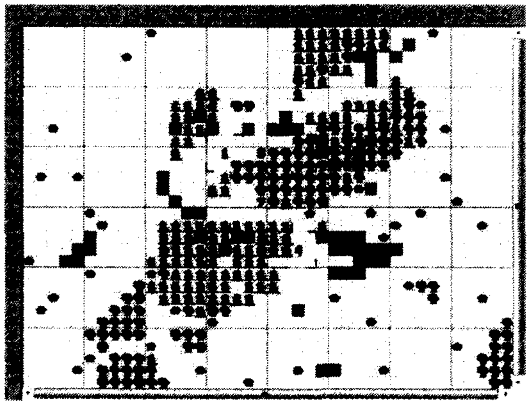
Non-flipped:



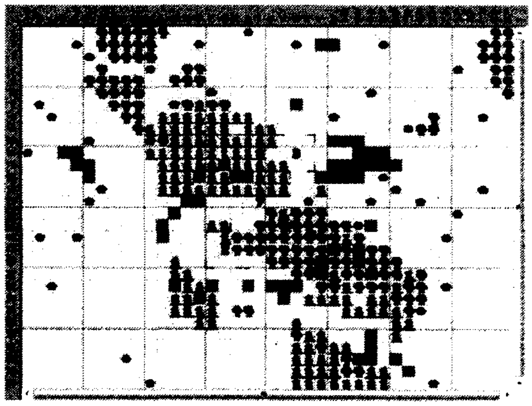
Horizontally flipped:



Vertically flipped:



Diagonally flipped:



Appendix C Counter-balancing of Experiment Conditions and Scenarios

Team Number	Experiment scenarios	1	2	3	4
Teams 1, 17	Condition	Individual	Individual-Breakdown	Team-Breakdown	Team
	Scenario	Normal	Horizontal	Diagonal	vertical
Teams 2, 18	Condition	Individual	Individual-Breakdown	Team-Breakdown	Team
	Scenario	Horizontal	Vertical	Normal	Diagonal
Teams 3, 19	Condition	Individual	Individual-Breakdown	Team-Breakdown	Team
	Scenario	Vertical	Diagonal	Horizontal	Normal
Teams 4, 20	Condition	Individual	Individual-Breakdown	Team-Breakdown	Team
	Scenario	Diagonal	Normal	Vertical	Horizontal
Teams 5, 21	Condition	Individual-Breakdown	Team	Individual	Team-Breakdown
	Scenario	Normal	Horizontal	Diagonal	vertical
Teams 6, 22	Condition	Individual-Breakdown	Team	Individual	Team-Breakdown
	Scenario	Horizontal	Vertical	Normal	Diagonal
Teams 7, 23	Condition	Individual-Breakdown	Team	Individual	Team-Breakdown
	Scenario	Vertical	Diagonal	Horizontal	Normal
Teams 8, 24	Condition	Individual-Breakdown	Team	Individual	Team-Breakdown
	Scenario	Diagonal	Normal	Vertical	Horizontal
Teams 9, 25	Condition	Team	Team-Breakdown	Individual-Breakdown	Individual
	Scenario	Normal	Horizontal	Diagonal	vertical
Teams 10, 26	Condition	Team	Team-Breakdown	Individual-Breakdown	Individual
	Scenario	Horizontal	Vertical	Normal	Diagonal
Teams 11, 27	Condition	Team	Team-Breakdown	Individual-Breakdown	Individual
	Scenario	Vertical	Diagonal	Horizontal	Normal
Teams 12, 28	Condition	Team	Team-Breakdown	Individual-Breakdown	Individual
	Scenario	Diagonal	Normal	Vertical	Horizontal
Teams 13, 29	Condition	Team-Breakdown	Individual	Team	Individual-Breakdown
	Scenario	Normal	Horizontal	Diagonal	vertical
Teams 14, 30	Condition	Team-Breakdown	Individual	Team	Individual-Breakdown
	Scenario	Horizontal	Vertical	Normal	Diagonal
Teams 15, 31	Condition	Team-Breakdown	Individual	Team	Individual-Breakdown
	Scenario	Vertical	Diagonal	Horizontal	Normal
Teams 16, 32	Condition	Team-Breakdown	Individual	Team	Individual-Breakdown
	Scenario	Diagonal	Normal	Vertical	Horizontal

Appendix D Number of SA questions distributed across types

Table 1

Number of SA probes distributed across types: Incident Commander

	true/false				continuous				
	level 1	level 2	level 3	Subtotal	level 1	level 2	level 3	Subtotal	total
	11	2	3	16	0	7	5	12	28
teamQs	3	1	3	7*	0	6	5	11	18

Table 2

Number of SA probes distributed across types: Ground chief

	true/false				continuous				
	level 1	level 2	level 3	Subtotal	level 1	level 2	level 3	Subtotal	total
	5	1	3	9	6	4	3	13	22
teamQs	1	1	1	3*	4	1	3	8	11

* There were too few true/false teamQs for either IC or GC. Therefore they were not analyzed in the present study.

Appendix E Demographic Questionnaire

Background Information

What is your sex?

- ☐ Male
- ☐ Female

What is your age? __________

What is your first language?

- ☐ English
- ☐ French
- ☐ Other (Please specify) ______________________________

How often do you use maps (digital and/or paper)?

- ☐ Several times a day
- ☐ Once a day
- ☐ Several times a week
- ☐ Once a week
- ☐ Once/twice a month
- ☐ Every few months
- ☐ Once/twice a year
- ☐ Never

You are working with a teammate in this study, how familiar are you with him/her?

- ☐ I have never met him/her before
- ☐ I have met him/her before, but we are not well acquainted
- ☐ I am well acquainted with my teammate

Experience with Technology

How often do you use a computer?

- ☐ Several times a day
- ☐ Once a day
- ☐ Several times a week
- ☐ Once a week
- ☐ Once/twice a month
- ☐ Every few months
- ☐ Once/twice a year
- ☐ Never

How often do you play video games on a computer?

- ☐ Several times a day
- ☐ Once a day
- ☐ Several times a week
- ☐ Once a week
- ☐ Once/twice a month
- ☐ Every few months
- ☐ Once/twice a year
- ☐ Never

How often do you play video games on a video game console (e.g., wii, xbox, playstation)?

- ☐ Several times a day
- ☐ Once a day
- ☐ Several times a week
- ☐ Once a week
- ☐ Once/twice a month
- ☐ Every few months
- ☐ Once/twice a year
- ☐ Never

How often do you play strategy games?

- ☐ Several times a day
- ☐ Once a day
- ☐ Several times a week
- ☐ Once a week
- ☐ Once/twice a month
- ☐ Every few months
- ☐ Once/twice a year
- ☐ Never

Appendix F Scripts for Training Clips

Scripts for Incident Commander

***************What's this game about?*****************

This is a strategy game in which you and your teammate have just been called in to command and control the suppression of a series of forest fires. The overall goal is to suppress fires as soon as possible with minimal loss of forests and houses, and houses always have the first priority.

Your role in the team will be incident commander and your teammate will be the ground chief.

The game allows you to command and control three kinds of units: firefighting, fire break, and helicopter unit.

As the incident commander, you have control over the helicopter unit, while your teammate controls the ground units consisting of firefighting and fire break units.

***************What's this game like? ***************

Before the game starts, let's take a quick look at your display. Here is the map. The map is composed of cells with coordinates.

At the beginning of game, your helicopter unit will always be here, the center of map. With the helicopter unit you can "see" an area of 5by5 cells.

On the map, you can see pine, birch, houses, swamp, and normal vegetation. During a fire, normal vegetation and houses burns at the same speed, while birch burns at a slower rate and pine burns at a faster rate. Swamp never burns. Remember that when putting out a fire, houses are the most important property to protect.

***************How do I start to play the game? ***************

Now let's take a tour of the game. The game always starts at 02:15:00. Once it starts, you can track the time by looking at the time panel.

Usually, your firefighting tasks begin with receiving one or more fire alarms from the emergency center. Once it arrives in your mail box, the mail window turns into pinkish and the button here lights up. Now you can click to open and read the message. The number here indicates how many mails are unread. Old mails can be viewed again by scrolling up and down in the viewer panel.

Remember that not all fire alarms are true. Therefore, it is your responsibility to verify each fire alarm. Once you receive a fire alarm through the message, the first thing you do is send out the helicopter to the designated location to verify the alarm. You do this by selecting its white number in the unit panel, and then push the left mouse button on the intended cell on the map. Now you can see the helicopter starts moving toward the location of fire alarms. Note that the unl current position is exposed with a colored number, and its intended position is exposed with a white number. Here, as the helicopter approaches the location of fire alarm, you see cells in red, which means the fire alarm is true. Now you can tell your teammate about this fire alarm so that s/he could dispatch ground units to start suppressing this fire.

Sometimes, you also receive false alarms…in a case of false alarms you would not see any red cells, which means the alarm is false.

In the following practice session, you will receive two alarms from emergency center, one at a time. Please proceed to read the messages and verify if they are true or false.

***************Wind monitoring***************

It's also critical to monitor wind conditions to predict how the fires will progress and affect surrounding terrain. The wind panel is at the upper right corner of your display. The arrow indicates the direction the wind blows **from.** So here, the wind is blowing **from** North to South. The number here indicates the wind strength. The higher the number, the stronger and faster the wind blows.

Wind direction and/ or strength could change during the game. Before it changes, you'll get a message in your mail box from the emergency center. It specifies the estimated time of wind change and forecasted wind condition...Now you can see at 02:17, the wind changed into East with a faster speed.

Remember that your teammate won't get wind forecast message. It's your responsibility to warn him/her about upcoming wind changes at certain time as you see appropriate | so that s/he could plan ahead when fighting fires.

***************How does my teammate do his/her job on the ground? ***************

When your helicopter flies over the area where your teammate is working, you can see his/her units. Here is unit 1 firefighting...when the red cell turn into brown, it means fire has been put out at this location and no fire could be ignited here again. Now it's moving towards the next position. ..here is unit 5 building firebreaks...and it just built a firebreak in this cell so no fire could be ignited here anymore. The black cells are places that have been burnt out due to lack of fuel. They can't be ignited either.

***************How is my teammate doing on that fire? ***************

You map won't update itself automatically. Instead, the helicopter updates you with fire information falls into its visible area as it flies over a certain area. This way, you can check out your teammate once in a while to make sure everything is under control. Besides, you can also require verbal update from your teammate, especially when your helicopter is otherwise occupied. Such communication could be as specific as units' locations (e.g., where are your firebreak units now?) or as general as evaluating a fire's progression (e.g., Have you put the fire under control?)

********* Collaboration and communication *********

Sometimes, more than one fire burns at the same time, yet your teammate doesn't have enough workforces to suppress all of them at once. In such a situation, you and your teammate need to draw up together a strategy of priority. Always put houses first on your priority list. Also take advantage of property of different terrains and vegetation. Remember, both of you can make contributions to this strategy by exchanging information.

In the following practice session, you will receive several alarms from the emergency center, some of them true while others false; you need to verify them one by one before notifying your teammate of only TRUE alarms. Besides, you will also receive wind forecasts; you need to inform your teammate about its upcoming. At a certain point in this session, you will see more than one fires burning on the ground. This is when you and your teammate need to collaborate, communicate and draw up a strategy so that damage could be minimized. Don't hesitate to solicit update from your teammate about fire progression and status of ground units.

*************** ***************

Now you're almost ready to start playing! Remember that the overall goal is to suppress fires as soon as possible with minimal loss of forests and houses, while houses always have first priority. Your tasks include:

Receive fire alarms and wind forecasts from the emergency alarm center.

Verify fire alarms and make dispatch orders to your teammate.

Warn your teammate about upcoming wind changes at a certain time as you see appropriate.

If you team mate fails to update you about the location and activity of the ground units under his/her control, remember to ask for this information so you don't waste time flying your helicopter to check on it.

Determine priority of fires together with your teammate when there are too many for your teammate to fight at once.

***************Team display***************

During two of the four sessions in this game, you'll have access to the team display mounted on the wall in front of you. Now let's take a look at it.

This is wind panel for current wind conditions. Wind forecasts will appear here in the orange panel when there is an upcoming wind change. This is the time when the wind will likely change.

In this table, you have a quick overview of current activities for all units under your teammate's and your control.

The map is similar to that on your own display, except that you can also see your teammate's units on the team display. Each of them has a smaller visible area relative to your helicopter. As they move over the map, they update the team display with fire information inside their visible area.

When there is more than one fire burning at the same time, another way to draw the attention of your teammate to a certain area, in addition to communication, is to use a priority icon. Select the icon in the 'Symbol Palette' panel and push the left mouse button on the map. The icon will flash on the intended cell. Remember that this icon is only visible on your display and team display.

To cancel a priority, select "None" in the "Symbol Palette" and push the left mouse button on the intended cell. The icon will disappear from your display and team display

When the team display is on, you can also inform your teammate of the wind forecasts by pressing Ctrl+Tab that will cause a window to pop-up and appear on the team display.

In the following practice session, you and your teammate will both have access to the team display. Please use Ctrl+Tab together when notifying your teammate of wind changes. You may also use the priority icon when you want to draw his/her attention to a certain area of imminent danger. Note that this time you can see vehicles under both of your control on the team display.

Scripts for Ground Chief

***************What's this game about? ***************

This is a strategy game in which you and your teammate have just been called in to command and control the suppression of a series of forest fires. The overall goal is to suppress fires as soon as possible with minimal loss of forests and houses, while keeping in mind that houses always have the first priority.

Your role in the team will be the ground chief and your teammate will be the incident commander.

This game allows you to command and control three kinds of units: firefighting, fire break, and the helicopter unit.

As the ground chief, you have control over the ground units including fire fighting and fire break units, while your teammate controls the helicopter unit.

***************What's this game like? ***************

Before the game starts, let's take a quick look at your display. Here is the map. The map is composed of cells with coordinates.

At the beginning of game, your units will always be here, in the center of map. With each of your ground units you can "see" an area of 3by3 cells.

On the map, you can see pine, birch, houses, swamp, and normal vegetation. During a fire, normal vegetation and houses burn at the same speed while birch burns at a slower rate and pine burns at a faster rate. Swamp never burns. Remember that when putting out a fire, houses are the most important property to protect.

***************How do I start to play the game? ***************

Now let's take a tour of the game. The game always starts at 02:15:00. Once it starts, you can track the time by looking at the time panel.

Usually, your firefighting tasks begin when your teammate who is playing the incident commander receives fire alarms from the emergency center. Once s/he has verified the alarm, s/he'll inform you of this so that you can dispatch ground units to the designated location.

***************How do I control my workforce? ***************

You have a total of 6 ground units: 4 firefighting units F1, F2, F3, and F4, and 2 fire break units, B5 and B6. You may command a unit by dragging-and-dropping the colored number to the intended position. Now you can see the units starting to move. Note that the unit's current position is displayed with a colored number, while its intended position is displayed with a white number.

You see only what your units see. Also, the map doesn't update itself automatically – therefore, information regarding fire in cells out of the visible range of your units only gets updated when you send units over there.

***************How does a firefighting unit work? ***************

A fire-fighting unit that is placed in a burning cell will automatically start to fight the fire...Here is unit 1 firefighting...when the red cell turn into brown, it means that the fire has been put out at this position and no fire can start here again. The black cells are areas that have been burnt out due to lack of fuel. They can't be ignited either.

Remember that putting two fire-fighting units on the same burning cell will cause conflicts and thus slow down both units.

***************How does a fire break unit work? ***************
By placing a fire break unit anywhere, you can create a fire break at that location by double clicking the mouse...here is unit 5 building firebreaks...when the cell turns into grey, it mean a firebreak has been built in this position and no fire can start here anymore.

***************Firefighting strategies***************
A fire in one cell can spread to all eight surrounding cells. Therefore, it's a good idea to always keep firefighting units one next to the other. Otherwise, fires will spread between the fire fighters and will eventually surround them. Another strategy is to always put your workforce onto the outermost cells to try and contain the fire. This will create a perimeter line around the fire to prevent the fire from escaping and spreading beyond this line.

Now imagine that your teammate has just verified a fire at _J,6_ and communicated this information to you. In the following practice session, you will have six units under your control and you may dispatch any amount of units you deem necessary to this fire in order to suppress it. Please try what you have just learned in this tutorial.

***************Wind monitoring***************
It's also critical to monitor the wind conditions to predict how the fires will progress and affect surrounding terrain. The wind panel locates at upper right corner of your display. The arrow indicates the direction that wind blows **from**. So here, the wind is blowing **from** North to South. The number here indicates the wind strength. The higher the number, the stronger and faster the wind blows.
Wind direction and/or strength could change during the game. Prior to the change, your teammate will receive forecasts and inform you of them. Once the wind changes takes place, the wind panel on your screen will change correspondingly.

***************Collaboration and communication***************
What if there are too many fires on the ground to fight at once? Sometimes, more than one fire burns at the same time, yet you don't have enough workforce to suppress them all at the same time. In this situation, you and your teammate need to collectively determine a strategy of priority. Be sure to always put houses first on your priority list. Also take advantage of characteristics of different terrains and vegetation. Remember, both of you can make contributions to this strategy by exchanging information.

In the following practice session, you will work with your teammate to put out a series of fires. At a certain point in this session, you will see more than one fire burning on the ground. This is when you and your teammate need to collaborate, communicate and draw up a strategy so that damage could be minimized.

*************** ***************

Now you're almost ready to start the experiment! Remember that the overall goal is to extinguish fires as soon as possible with minimal loss of forests and houses, while keeping in mind that houses always have the first priority. Your main task is to control and to optimally coordinate your ground units to put out fires. At the same time, you need to monitor wind conditions and collaborate with your teammate on setting fire priorities.

***************Team display***************

During two of the four sessions in this game, you'll have access to the team display in front of you. Now let's take a look at it. This is the wind panel for current wind condition. Wind forecasts will appear here in the orange panel to notify you of upcoming wind changes. This is the time when the wind will likely change.

The map looks similar to that on your own display – however you can also see your teammate's helicopter on the team display. The helicopter has a broader view than your units. As the helicopter flies over the map, it updates the team display with fire information that is inside **its** visible area.

When your teammate detects a high priority fire, s/he may advise you through verbal communication OR, by placing a priority icon on the intended cell and causing it to flash on the team display. Ideally, area around the priority cell needs your immediate attention. However, if your units are occupied elsewhere, it is your responsibility to wisely distribute your units among different fires. You may make these types of decisions through discussion with your teammate when feasible.

In the following practice session, you and your teammate will both have access to the team display. Please be advised to pay notice to any changes in the wind panel as this will inform you of upcoming wind changes. Also, if you see the priority icon flashing on the map – this is a signal from your teammate to draw your attention to a certain area of imminent danger. Note that, at this time - you will be able to see vehicles under both of your and your teammate's control on the team display.

Appendix G List of SA Questions

SA questions for Incident Commander:

Question ID 1.1	How many fire alarms are yet to be verified?				
	0	1	2	3	4

Question ID 1.2	Where are the fires that need verification?	
	No alarms to be verified	*Mark on scaled-down map with "Δ"*

Question ID 1.3	Where is the helicopter?	
	N/A	*Mark on scaled-down map with "H"*

Question ID 1.4	What's the current wind direction?
	Draw arrow in the circle

Question ID 1.5	What's the current wind strength?				
	0	0.5	1.0	1.5	2.0

Question ID 1.6	Are there currently any houses caught in fires?		
	Y	N	Not sure

Question ID 1.7	Are there currently any forests caught in fires?		
	Y	N	Not sure

Question ID 1.8	Has your teammate reacted to your most recent suggestions (if any) on fire priority?			
	N/A	Y	N	Not sure

Question ID 1.9	Is there any forecast of wind change?		
	Y	N	Not sure

Question ID 1.10	What's the forecasted wind direction?	
	N/A	*draw arrow in the circle*

Question ID 1.11	What's the forecasted wind strength?				
	0	0.5	1.0	1.5	2.0

Question ID 1.12	When will wind direction and strength change?	
	hh__:mm__:ss__	Not sure

Question ID 1.13	How much time remains before wind direction and strength change?				
	N/A	A. less than 1 min	B. 2 mins	C. 3 mins	D. 5 mins	E. longer than 5 mins

Question ID 2.1	Indicate on which fire(s) the firefighting/firebreak units are working or moving towards?	
	N/A	*Mark on scaled-down map with Δ*

Question ID 2.2	Indicate location of helicopter relative to the to-be-verified fire alarm(s)	
	No alarm to be verified	Mark on scaled-down map with "H" for helicopter and "A" for alarm(s)

Question ID 2.3	Is the very last alarm that you've investigated true?		
	Y	N	Not sure

Question ID 2.4	Which kinds of forest in the entire area is (are) on fire?				
	A. Pine	B. Birch	C. Both	D. No forest has been on fire so far	E. Not sure

Question ID 2.5	How many fires are there yet to be suppressed?				
	0	1	2	3	4

Question ID 2.6	Where are the fires that are yet to be suppressed?	
	N/A	*Mark on scaled-down map with Δ*

Question ID 2.7	If there is more than one fire on the ground right now, indicate their relative sizes	
	N/A	*Mark fires on scaled-down map with circles. Use circle size to indicate fire sizes*

Question ID 2.8	Are units working on the fire(s) that is (are) deemed highest priority?		
	Y	N	Not sure

Question ID 2.9	Which fire(s) is your teammate aware of?	
	N/A	*Mark on scaled-down map with Δ*

Question ID 3.1	Are there any houses in the entire area about to catch fire?		
	Y	N	Not sure

Question ID 3.2	Which fire(s) are about to burn houses?	
	N/A	*Mark fires on scaled-down map with Δ*

Question ID 3.3	Are there any forests about to catch fire?		
	Y	N	Not sure

Question ID 3.4	Which kind of forests will be caught in fires?				
	A. Pine	B. Birch	C. Both	D. None	E. Not sure

Question ID 3.5	Which fire(s) are about to burn forests?	
	N/A	*Mark fires on scaled-down map with Δ*

Question ID 3.6	If there is more than one fire yet to be suppressed, please indicate the one(s) with high priority	
	N/A	*Mark fire(s) on scaled-down map with Δ*

Question ID 3.7	Indicate the area that you think needs your teammate's instant attention	
	N/A	*Mark area on scaled-down map with Δ*

Question ID 3.8	Will the upcoming wind change affect firefighting priority? (If "Y", please indicate the fire(s) with high priority after wind change with △ on the scaled-down map)		
	Y	N	Not sure

SA questions for Ground Chief:

Question ID	What's the current wind direction?
1.1	*Draw arrow in the circle*

Question ID	What's the current wind strength?				
1.2	0	0.5	1.0	1.5	2.0

Question ID	Where are these burning fires?	
1.3	N/A	*Mark locations on scaled-down map with Δ*

Question ID	How many <u>firefighting</u> units are working on each of the fires that you're attending to?	
1.4	N/A	*Mark fires on scaled-down map with Δ and number of units*

Question ID	How many <u>firebreak</u> units are working on each of the fires that you're attending to?	
1.5	N/A	*Mark fires on scaled-down map with Δ and number of units*

Question ID	Where is firefighting unit F3 right now?	
1.6	N/A	*Mark the unit on scaled-down map with Δ*

Question ID	Are there any fire breaks being built?		
1.7	Y	N	Not sure

Question ID	For each fire that you're attending to, are there any houses caught in this fire?	
1.8	N/A	*Mark fires on scaled-down map with Δ and Y/N*

Question ID	For each fire that you're attending to, are there any forests caught in this fire?	
1.9	N/A	*Mark fires on scaled-down map with Δ and Y/N*

Question ID	Mark the latest fire which has been selected as of highest priority by your teammate	
1.10	N/A	*Mark the fire on scaled-down map with Δ*

Question ID	How much time remains before wind condition change?				
1.11	A. less than 1 min	B. 2 mins	C. 3 mins	D. 5 mins	E. longer than 5 mins

Question ID	Indicate which fire(s) the firefighting/firebreak units are working on or moving towards?	
2.1	N/A	*Mark on scaled-down map with Δ*

Question ID	Estimate the size(s) of the fire(s) you're working on (in total number of burning/burnt out cells)	
2.2	N/A	*Circle fires on scaled-down map and use circle size to indicate fire sizes*

Question ID	For each fire that you're attending to, indicate for how long you have worked on each of them	
2.3	N/A	*Mark fires on scaled-down map with Δ and* "1 min, 2 mins, 3 mins, etc."

Question ID	For each fire that you're attending to, what kind of forests has been caught in this fire?	
2.4	N/A	Mark fires on scaled-down map with Δ and "Pine, Birch, both, none"

Question ID	Are you currently working on the fire with the highest priority?			
2.5	N/A	Y	N	Not sure

Question ID	For each fire that you're attending to, are there any houses at risk of burning down due to this fire?	
3.1	N/A	*Mark fires on scaled-down map with Δ and Y/N*

Question ID	For each fire that you're attending to, are forests at risk of burning down due to this fire?	
3.2	N/A	*Mark fires on scaled-down map with Δ and Y/N*

Question ID	For each fire that you're attending to, what kind of forests will be caught in this fire?	
3.3	N/A	*Mark fires on scaled-down map with Δ and* "Pine, Birch, both, none"

Question ID	Do you have available workforce for the fire with the highest priority?		
3.4	N/A	Y	N

Question ID	For the fire marked with Δ on the scaled-down map, rate the likelihood of its spreading to the houses in its vicinity in the next 1 minute
3.5	Very unlikely ... Very likely ○ A ○ B ○ C ○ D ○ E

Question ID	For the fire marked with Δ on the scaled-down map, rate the likelihood of its spreading to the forests in its vicinity in the next 1 minute
3.6	Very unlikely ... Very likely ○ A ○ B ○ C ○ D ○ E

Appendix H Cognitive Task Analysis

Task-work	Required information	IC display	GC display	Info via team display	Info via comm.
Verify Fire Alarm	• Fire alarm location coordinate • Helicopter's location • Loc/size of fire	• Fire alarm location coordinate • Helicopter's location • Loc/size of fire		Alarm validity	Alarm validity
Situation Assessment – IC (global)	• Loc of property • Loc of helicopter • Wind direction • Wind strength • Fire locations • Size of fires	• Loc of property • Loc of helicopter • Wind direction • Wind strength • Fire locations • Size of fires		• Loc of property • Loc/size of fires	
Situation Assessment – GC (local)	• Loc of property • Loc/size of fire • Wind direction • Wind Strength • Units' position • Units' current activity • Units' intended coordinates		• Loc of property • Loc/size of fire • Wind direction • Wind Strength • Units' position • Units' current activity • Units' intended coordinates	• Loc of property • Loc/size of fire • Units' position • Unit's current activity • Units' intended coordinates	• Intermittent update of the working fire[1]

[1] A fire that is in the process of being suppressed

Assess Threat	IC (Global) Evaluate fire progression	• Loc of property • Wind direction • Wind Strength • Future wind condition • Estimated time of wind change • Loc/size of fires • Proximity of fires to high priority land	• Loc of property • Wind direction • Wind Strength • Future wind condition • Estimated time of wind change • Loc/size of fires • Proximity of fires to high priority land		• Loc of property • Future wind condition • Estimated time of wind change • Proximity of fires to high priority land	• Future wind condition • Estimated time of wind change • Warning of threat in near future
	GC(Local)	• Loc of property • Loc/size of fire • Proximity of fires to high priority land • Immediate wind direction • Immediate wind Strength		• Loc of property • Loc/size of fire • Proximity of fires to high priority land • current wind direction • current wind Strength	• Loc of property • Proximity of fires to high priority land • Future wind condition • Estimated time of wind change	

Select fire priority	• Loc of property • Locations of all the verified fires • Wind direction • Wind Strength • Future wind condition • Estimated time of wind change • Units' position • Unit's current activity • Units' intended coordinates	• Loc of property • Locations of all the verified fires • Wind direction • Wind Strength • Future wind condition • Estimated time of wind change		• Coordinates of prioritized fire(s) • Loc of property • Future wind condition • Estimated time of wind change • Units' position • Unit's current activity • Units' intended coordinates	• Coordinates of prioritized fire(s) • Suggestions on units to be dispatched
Dispatch units to high priority coordinate	• Units' position • Unit's current activity • Units' intended coordinates • Coordinates of higher priority fires		• Units' position • Unit's current activity • Units' intended coordinates • Coordinates of higher priority fires	• Units' position • Unit's current activity • Units' intended coordinates • Coordinates of higher priority fires • Location of units having been dispatched	• Confirmation or delay of dispatch • ID of units to be dispatched

Appendix I NASA-TLX Mental Workload Rating Scale

NASA-TLX Mental Workload Rankings

For each of the pairs listed below, circle the scale title that represents the more important contributor to workload in the last session.

Mental Demand	or	Physical Demand
Mental Demand	or	Temporal Demand
Mental Demand	or	Performance
Mental Demand	or	Effort
Mental Demand	or	Frustration
Physical Demand	or	Temporal Demand
Physical Demand	or	Performance
Physical Demand	or	Effort
Physical Demand	or	Frustration
Temporal Demand	or	Performance
Temporal Demand	or	Frustration
Temporal Demand	or	Effort
Performance	or	Frustration
Performance	or	Effort
Frustration	or	Effort

NASA-TLX Mental Workload Rating Scale

Please place an "X" along each scale at the point that best indicates your experience with the display configuration in the last session.

Mental Demand: How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Low High

Physical Demand: How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low High

Temporal Demand: How much time pressure did you feel due to the rate of pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and

Low High

frantic?

Performance: How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Low High

Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low High

Frustration: How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Low High