

TEAM SITUATION AWARENESS DISPLAYS: AN EMPIRICAL EVALUATION OF  
TEAM PERFORMANCE

by

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### **Abstract**

This study experimentally tested the use of a team-oriented display as a means of enhancing teamwork and situation awareness (SA) in both high and low workload environments. Teams were tested using a forest-fire simulation that incorporated features of a co-located command-and-control team architecture. As hypothesized, the presence of a team display was found to improve SA within team members and enhance team communication. Moreover, in high workload conditions, the significant benefits of the team display were even more apparent. Performance scores, however, were not affected by the presence of the team display. The incongruent relationship between SA and performance raises an interesting conceptual question and provides evidence of a non-direct relationship between these two variables. Findings from this study support the benefits of a team-oriented display; however, it also raises questions regarding the environment in which SA is most beneficial for teamwork, particularly with regards to team performance.

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## **Introduction**

### **Understanding the Need**

Canada has 244 million hectares of productive forest that produced \$27 billion in forest product exports in 1994, amounting to more income than agriculture, mining and fisheries combined (Canadian Council of Forest Ministry, 1994). The forested regions of the country provide resource-based economies, employment opportunities and recreational activities. However, the risk of wildfire to homes and communities can be significant, and Canada has a long history of evacuations and property destruction caused by wildfire events. On average, more than \$400 million is spent on fighting wildfires each year (1990-2001). In 1998, fire management costs were more than \$800 million, and costs in 2003 were near \$1 billion (Natural Resources Canada, 2009). However, this cost is far less than the impact of a forest fire, which includes loss of valuable timber and damage to private property or public infrastructure. Significant costs are also involved in the evacuation of communities threatened by fire and in the disruptions to economic activity resulting from road and rail closures. These are just some of the many significant economic losses to communities following a forest fire.

No civilian lives have been lost as a result of wildfires in Canada since 1938, however between 1986 and 2005, a total of 34 fire management personnel were killed either by fires or in the process of fighting fires (Natural Resources Canada, 2009). The hazards associated with firefighting are well documented but the risk involved with these hazards, and the frequency with which firefighters are unnecessarily exposed to these risks is a much more complex issue. The United States Fire Administration (2004) reports that firefighter fatalities have risen approximately 27% between 1992 and 2001. Furthermore, 21 injuries occur per 1000 fire incidents. In analyzing these troublesome events, it is evident that errors in communication and

decision-making processes are significant contributing factors. Although efforts have been made to address these factors and create learning opportunities following near-miss occurrences, the operational flaws and behavior patterns identified tend to be repeated during subsequent incidents.

Unfortunately, these trends do not appear to be unique to firefighting. Other high-risk organizations have displayed similar trends; for example, they are also observed in the field of health-care. A landmark report, titled: “To Err Is Human: Building a Safer Health System” states that errors cause between 44 000 and 98 000 deaths and over one million injuries every year in American hospitals (Kohn et al., 2000). Furthermore, current estimates of iatrogenic fatality rates in hospitals remain several times higher than fatality rates for automobile traffic accidents in many countries including the United States (NHTSA, 2008), Australia (AGDI, 2008), and the United Kingdom (UKONS, 2008).

Some theorists suggest that trends such as these in high-risk occupations, including health care and firefighting, are unavoidable; therefore, the losses involved in conducting such operations must simply be accepted. However, the research also gives evidence that certain organizations, referred to as High Reliability Organizations (HROs), are able to perform high-risk operations relatively error free over long periods of time, making consistently good decisions that result in higher quality, safer, and more reliable operations. These industries, including commercial aviation, nuclear power plants and the oil industry, have long been concerned with increasing safety by reducing error. The commercial aviation industry, for example, experienced no fatal accidents in 2002 and only two fatal accidents in 2003 resulting in 22 deaths (NTSB, 2003). This number is relatively small considering the millions of passengers who travel each year.

Due to their excellent safety records and continued effectiveness, HROs have received an increasing amount of attention over the past 10 years, and other organizations such as those in health care and firefighting have strived to evolve to high reliability status (Weick et al., 1999). One key element identified in the success of HROs is the coordinated work among individuals that have responsibility for different subsets of goals, different access to data, and different situation perspectives (Roberts & Rousseau, 1989). The process by which these individuals acquire information, understand it, and utilize it in a specific situation is often referred to as Situation Awareness (SA). Team Situation Awareness (TSA) is facilitated by team behaviors that allow shared knowledge to be constructed and maintained among team members. There has been growing interest in understanding the cognitive and collaborative factors that enable such teams to develop effective SA and TSA in HRO environments (VanFenema, 2005; Salas & Fiore, 2004), and in designing effective methods to support and maintain SA and TSA in order to improve safety in high-risk environments.

### **Research Overview**

Situation awareness is a critical part of an HRO; however, it is still not well understood. Sarter and Woods (1991), in referring to SA, noted, “situation awareness has thus become a ubiquitous phrase. Its use is most often based on intuitive understanding” (p.47). Due to this lack of concrete understanding, it has remained difficult to develop training and support methods to improve this construct in HROs.

The following introduction addresses situation awareness on two levels: 1. a brief summary of elements common to individual SA in order to provide a basis for examining team SA; and 2. an identification of critical variables that are associated with TSA, and a description

of processes and behaviors that have been proposed as contributors to its establishment and maintenance.

The goal of this thesis was to gain insight into the underlying relationship between SA and successful teamwork and communication, looking specifically at the impact that technological aids, such as a team display, can have on teamwork and TSA. The main research question addressed by this thesis was as follows: what is the impact of having a team display on teamwork and team situation awareness? It was hypothesized that the presence of a team display designed to provide continuous information would have a positive impact; i.e., improved situation awareness and effective teamwork. An additional goal was to investigate current principles for designing large screen team displays for organizations operating in high-risk domains. This was done by studying the efficacy of a team display and team situation awareness in the context of a forest fire fighting command-and-control center.

## **Background**

*Teamwork in High Reliability Organizations.* Organizations are increasingly using teams as a predominant strategy when faced with complex and ambiguous environments. These teams are typically defined as “a distinguishable set of two or more people who interact, dynamically, interdependently, and adaptively toward a common and valued goal/objective/mission, and who have each been assigned specific roles or functions to perform” (Salas et al., 1992, p.4). Teams are considered more suitable for complex tasks because they allow members to share workload, monitor work behaviors of other members, and develop and contribute expertise on subtasks (Swezey & Salas, 1992). Thus, many industries have been using teams as a means of improving organizational outcomes, such as productivity and safety. Conversely, the environments in which these teams work in are increasingly becoming dynamic and unstable (Baker et al., 2006). This

evolution has given rise to greater reliance on the effectiveness of teams and increased complexity in terms of team composition, skill requirements, and degree of risk involved.

Despite the proposed benefits of work teams, many real world examples have illustrated that they are not always effective (Hackman, 1990). Key reasons for this include a lack of coordinated teamwork (Wagner, 1995), as well as gaps in shared knowledge (Baker et al., 2006). To combat this, a subset of organizations has allocated time and resources to develop the ability to balance effectiveness and safety, despite the complexities of the environment. These organizations, such as those within the fields of aviation and nuclear power, have been termed high reliability organizations (HROs).

HROs are organizations that function essentially error-free for long periods of time despite their hazardous, fast-paced, and highly complex systems (Roberts, 1990). HROs are defined by their potential for causing failures that lead to catastrophic consequences. If the potential is high (elevated risk of error) but the actual number of failures is low, the team can be defined as an HRO (Roberts, 1990). For example, a nuclear power plant failure could result in horrific consequences for its surrounding community; however, such failures are extremely rare. The characteristics of HROs dictate that teamwork is essential: HROs will not achieve high reliability unless its members are able to effectively and efficiently coordinate their activities (Baker et al., 2006).

This thesis acknowledges the existence and importance of many factors in the development of an effective HRO, but focuses on the role of teamwork as an essential component leading to the effectiveness of HROs. The following study looked specifically at the roles of teamwork and team situational awareness in helping to promote effective performance, and investigated how team-oriented technology can support and facilitate such processes.

*Command and Control Teams in HROs.* As the complexities of HRO environments increase, it becomes less likely that any one agency or team will be able to manage the situation alone; resources from many different areas of expertise and organizational divisions will be needed. It is important that these resources are organized and managed so that all individuals are able to work together effectively: this is the role of a command-and-control team. Command-and-control teams have been defined as representing two or more individuals with specialized and interdependent roles, brought together to perform a complex, decision-rich task (Jones & Roelofsma, 2000). While initially used within the military community, these types of teams are increasingly being used to handle both emergency and non-emergency HRO circumstances (Bigley et al., 2001). More specifically, command-and-control teams are used to manage moderate to large-scale events within ill-defined situations, where resources are limited. Often the environment these teams operate in is fast-paced and members are required to deal with large amounts of ambiguous information that must be processed in limited amounts of time (Paris et al., 2000). Moreover, errors in decision-making and coordination within command-and-control teams can result in highly publicized, high stake outcomes (Jones & Roelofsma, 2000).

The primary tasks of a command-and-control team revolve around (a) situation assessment, (b) planning, (c) development of action plans/action selection, and (d) the implementation of these plans (Tolcott, 1992). During situation assessment, members of the command-and-control team must gather information from the environment. Key information is usually gained from a number of sources, including updates from those closest to the situation, archival information, communication channels, and information hardware devices (i.e., displays, sensors). Once the situation is assessed, planning, action selection, and implementation begin. The command-and-control team is constantly planning and revising strategies based on changing

situations and feedback from team members, as well as sub-teams below them in the organization. As the command-and-control team manages and coordinates the responses and information gathered from multiple contingencies, the team members must work together to overcome barriers such as non-standard terminology, lack of adaptability, non-integrated communications, and lack of consolidated action plans/decisions (Salas et al., 2004). As a consequence of these barriers, the effectiveness of the command-and-control team can be challenged.

Due to these challenges, there has been a great deal of work conducted to understand the factors that contribute to and detract from effective teamwork (Hackman, 1990; Swezey & Salas, 1992; Marks et al., 2000; Paris et al., 2000). Much has been learned over the past twenty years pertaining to what knowledge, skills, and attitudes are needed for teams operating in highly complex and dynamic environments, yet there remains a lack of prescriptive guidance for practitioners. Furthermore, technological advances are changing the environments within which teams operate and creating new challenges to the creation and maintenance of effective team performance. One field that faces said challenges is the area of command-and-control teams in forest fire command centers.

The command-and-control team in a forest fire command center faces many challenges in information processing and decision making for detecting potential fire threats, preventing them from occurring, and responding quickly and appropriately to fires that have already spread (Cardoso de Mura, 2006). First, the command-and-control team needs to process, interpret, and analyze a huge amount of highly dynamic information. Second, due to the broad scope of firefighting issues, the knowledge and expertise for interpreting and fusing information related to the fire is often distributed among individuals within a command center decision-making team.

For example, one member of the team may be an expert in predicting fire behaviour, while another is an expert in suppression techniques. Third, members of the team may have different access to various information sources due to their role and responsibility in the team. For example, an analyst may have access to satellite images while another analyst has access to intelligence reports. These three challenges can significantly hamper the quality and the timeliness of decision-making in the command center, which can have devastating consequences.

The identification of cognitive factors that contribute to high-performance teamwork is critical for investigating theories, models, and technological implementations that assist forest fire command teams. Psychological studies examining command teams have repeatedly pointed out that high performance teams share certain characteristics, which include a) Anticipating the needs of other teammates and b) Proactively helping teammates regarding their needs. One of the team cognition theories that attempts to explain these teamwork behaviors introduces the notion of “shared mental models” (Cannon-Bowers et al., 1993), which refers to an overlapping understanding among members of the team regarding their objectives, their structure, and their process. The following section outlines the role of shared mental models in improving teamwork in HROs.

### **Shared Mental Models.**

Critical performance in many HROs depends on the coordinated activity of a team of individuals. Cockpit crews, surgical teams, fire-fighting teams, and military teams are all examples of groups who operate in situations where ineffective teamwork can have disastrous consequences. Such teams are comprised of individuals who have high degrees of expertise in particular areas and require information contributed from different team members to converge in order for critical decisions to be made. Furthermore, the decision-making environments in which

these expert teams must operate are often characterized by severe time pressure; complex, multi-component decision tasks; rapidly evolving and changing information; high short-term memory demands; and high information ambiguity (Orasanu, 1993). In these complicated and error-prone environments, teamwork must be optimized in order to be effective.

One variable that has received much theoretical attention concerns the influence of team members' mental models on team-related processes and behaviors (Klimoski & Mohammed, 1994; Kraiger & Wenzel, 1997). Mental models are defined as organized structures of knowledge that allow individuals to interact with their environment (Veldhuyzen & Stassen, 1977). More specifically, mental models allow people to predict and explain the behavior of the world around them, to recognize and remember relationships among components of the environment, and to construct expectations for what is likely to occur next (Rouse & Morris, 1986). Shared mental models describe the degree to which mental models held by team members are aligned, such that substantial agreement exists between team members (Rouse et al., 1992). Cannon-Bowers et al. (1993) suggest that teams that must adapt quickly to changing task demands might be drawing on shared mental models. The rationale behind this assertion is that in order to adapt effectively, team members must predict what their teammates are going to do and what they are going to need in order to do it. The function of shared mental models is to allow team members to draw on their own well-structured knowledge as a basis for selecting actions that are consistent and coordinated with those of their teammates.

To refine this concept even further, Stout et al. (1996) suggested that the manner in which shared mental models operate is related to task demands. Specifically, these authors argued that under conditions that allow team members to freely communicate and strategize with one another, shared mental models will not be very important; that is, the team is able to discuss

strategies and does not need to rely on pre-existing knowledge. However, under conditions in which communication is difficult - due to excessive workload, time pressure, or some other environmental factor - teams are not able to engage in necessary strategizing. In this case, shared mental models become crucial to team functioning as they allow members to predict the information and resource requirements of their teammates.

To summarize, the literature on teamwork emphasizes that for effective teamwork to occur, individuals must share resources, as well as co-ordinate their activities in order to achieve their common goal. The development of shared mental models allows people to act on the basis of their understanding of the task, and how this will affect their team's response. This, in turn allows the team to act as a cohesive unit, and adapt quickly to be successful in dynamic environments.

This co-ordination is difficult, however, because each decision-maker has only a limited "window" on the task, and no one decision-maker has the overall view necessary for the required co-ordination. Hence the team members must still find means to achieve a common understanding of their environment, also known as team situation awareness. The following sections deal with the specifics of situation awareness and team situation awareness which are common elements of effective teamwork in HROs.

### **Situation Awareness.**

Situation awareness (SA) has received a great deal of attention over the past two decades because of its well-documented role in aviation and other complex environments. Endsley (1988) formally defined SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (p.97). Although the elements of SA vary widely between domains, the nature of SA and

the mechanisms used for achieving SA can be described generically. Level 1 of SA is the perception of relevant elements in the environment (Endsley, 1993). It is considered an active process whereby individuals extract salient cues from the environment. Level 2 SA is comprehension of the meaning of these cues, and involves integration of information in working memory (Salas et al., 1995) to understand how it will impact the individual's goals and objectives. Level 3 SA is projection, which consists of extrapolating this information forward in time to determine how it will affect future states of the operating environment (Endsley, 1993). Level 3 combines what the individual knows about the current situation with his or her mental model of similar events from previous experience to be prepared for what might happen next.

To this point, most explanations of SA have focused on individual SA and have not been concerned with determining what is necessary for developing SA for a team. Endsley (1995) even points out that whereas her theory of SA described cognitive processes that underlie individual SA (perception, comprehension, and projection), team SA involves unique activities such as coordination and information sharing. Team SA represents far more complexity than simply combining the situation awareness of individual team members (Schwartz, 1990) and requires study in its own right. The following section will outline research in team SA.

### **Team Situation Awareness.**

A growing focus in the literature on teamwork is the importance of shared contextual knowledge in supporting coordination and facilitating work (Bolstad et al., 2005). Effective team performance depends on shared information about both the shared environment and other team members involved (Salas et al., 1995). This information includes mutual knowledge and beliefs about the current situation, each other's goals, and current and future activities and intentions. Various labels have been used to denote this shared contextual knowledge including team

cognition (Espinosa et al., 2004); common ground (Klein et al., 2005); shared situation awareness (Endsley et al., 2000); team situation awareness (Endsley et al., 1996); and shared workspace awareness (Gutwin & Greenberg, 2004). This shared contextual knowledge, which will be referred to from here on as team situation awareness (TSA), allows team members to efficiently coordinate work by enabling them to understand the current status of the task, interpret what others are doing, and anticipate what will happen next. It enables team members to anticipate the information and support the needs of other team members, resulting in reduced need for explicit communication and improved coordination (MacMillan et al., 2004). Conversely, incorrect or incomplete mutual assumptions, knowledge, or beliefs can contribute to breakdowns in communication and coordination (Klein et al., 2000). If one team member has a certain piece of information, but another who needs it does not, the SA of the team has suffered and its performance may suffer as well unless the discrepancy is corrected. In this light, a major portion of inter-team coordination can be seen as the transfer of information from one team member to another.

Endsley and Jones (2001) describe a model of TSA as a means of conceptualizing how teams develop high levels of shared SA across members. Four factors act to build team SA:

1. **Team SA Requirements:** the degree to which the team members know which information needs to be shared, including their higher level assessments and projections (which are usually not otherwise available to fellow team members) and information on team member's task status and current capabilities.
2. **Team SA Devices:** the devices available for sharing this information, which can include direct communication (both verbal and non-verbal), shared devices (e.g., visual, audio displays, or tactile devices), or a shared environment.

3. Team SA Mechanisms: the degree to which team members possess mechanisms, such as shared mental models, which support their ability to interpret information in the same way and make accurate projections regarding each other's actions.
4. Team SA Processes: the degree to which team members engage in effective processes for sharing SA information which may include a group norm of questioning assumptions, checking each other for conflicting information or perceptions, setting up coordination and prioritization of tasks, and establishing contingency planning among others.

TSA can provide the foundation for cooperative team practices that contribute to system resilience to human error and unanticipated events, thereby increasing overall safety (Hollnagel, 2004). This is particularly important in the safety-critical work settings commonly present in High Reliability Organizations (HRO). Prince et al. (1997) discussed three reasons for the importance of measurement of team process; these concepts apply equally well to the measurement of team SA. First, theory cannot move beyond the conceptual stage without the development of psychometrically sound measurement tools. Measurement, in and of itself, will contribute to the building and validating of accurate models of team SA. Second, without quantifiable indicators of team SA, it is hard to articulate what constitutes good SA. Such information is particularly important for providing performance feedback during training. Finally, measurement is vital in evaluating TSA support techniques (such as team displays). Keeping these points in mind, the following section will outline some of the most prevalent strategies in the measurement of SA.

### **Situation Awareness Measurement**

The multivariate nature of SA continues to pose a considerable challenge to its quantification and measurement, and there remains a wide range of opinions concerning what

measurement techniques best capture the essence of SA (Durso & Gronlund, 1999). Methods of measuring SA are categorized as either direct measurement, or methods that infer SA based on user behavior or performance. Direct measures are considered to be “product-oriented,” and assess an SA outcome. Inferred measures are considered to be “process-oriented,” focusing on the underlying processes or mechanisms required to achieve SA (Matthews et al., 2002). The following is a brief overview of direct and inferred measurement techniques of SA, and their applicability to TSA.

*Direct measurement.* The most common measurement method in the study of SA has been direct experimental techniques such as queries or probes. Direct SA measurements can be either objective or subjective. Objective measures assess SA by comparing an individual’s perceptions of the situation or environment to what is actually happening in order to measure the accuracy of their SA at a given moment in time. Objective measures can be gathered in one of three ways: (1) real-time as the task is completed, (2) during an interruption in task performance, or (3) post-test following completion of the task.

Subjective measures assess SA by asking individuals to rate their own SA on an anchored scale. Subjective measures are appealing because they are relatively straightforward and easy to administer. However, there are several limitations to consider. Individuals making subjective assessments of their own SA are naïve to information they do not know, which limits the scope of their self-evaluation. Subjective measures also tend to be more generalized in focus, and as such, do not fully explore the multi-faceted nature of SA to provide the detailed diagnostics available with objective measures. Nevertheless, self-ratings may be useful in that they can provide an assessment of an individual’s degree of confidence in their SA and their own performance. Even if this information is skewed, it can prove to be extremely valuable: errors in

perceived SA quality may be equally as harmful to decision-making as errors in actual SA (Endsley, 1998).

One of the most popular methods of directly measuring SA was developed by Endsley (1995), titled: The Situation Awareness Global Assessment Technique (SAGAT). In this method a simulation is frozen at various points in time and workers are asked questions designed to assess their Level 1, Level 2 and Level 3 SA. Their answers are then compared to the real situation to provide an objective measure of SA. One important aspect of SAGAT is the development of queries for the experiment. This requires a fairly in-depth study of an individual's role to identify the SA requirements and appropriate phrasing of questions. Methods such as Goal Directed Task Analysis may be used to identify task goals, related decisions, and finally the SA requirements that are needed to make the decisions that allow operators to meet their goals (Endsley, 2000).

SAGAT has been criticized in the past because SA related questions are thought to shift participants' attention to SA requirements, thus influencing subsequent SA scores (McGowan & Banbury, 2004). However, several studies investigated this issue by comparing SAGAT to other methods of SA measurement and found no differences when SAGAT is used (Bolstad & Endsley, 1990; Endsley, 2000).

*Inferred Measurement.* Inferred measures utilize process indices to evaluate whether a person is actually making a situation assessment, which is an underlying process that should result in situation awareness. One commonly used set of process indices are psycho-physiological, such as EEG, transient heart rate, and eye-tracking, etc. Wilson (2000) found at least two advantages to the psycho-physiological measurement of SA. Firstly, these measures are continuous. Also, they do not require the freezing of an ongoing action. Wilson correctly

identified that these advantages are vital since SA is especially required in a constantly changing environment.

Inferred measurement techniques have also been effectively used to examine communication patterns between team members. This allows researchers to infer the development of TSA, since team communication supports the knowledge acquisition and information processing that leads to SA construction (Parush et al., 2009; Endsley & Jones, 1997).

*Performance based measures of SA.* A subtype of inferred SA measurement is performance-based measures, which rely on the assumption that improved performance on average indicates improved SA. Common performance metrics include quantity of output or productivity level, time to perform a task or to respond to an event, the accuracy of the response or, conversely, the number of errors committed. The main advantage of performance measures is that these can be collected objectively and without disrupting task performance. However, although evidence exists to suggest a positive relation between SA and performance, this connection is probabilistic and not always direct and unequivocal (Endsley, 1995). In other words, good SA does not always lead to good performance and poor SA does not always lead to poor performance (Endsley, 1990). For example, an expert participant may be able to achieve acceptable performance even when his SA is inadequate. Similarly, a novice participant may possess superior levels of SA but still achieve inferior performance due to other factors such as inexperience. Thus, it is recommended that performance measures be used in conjunction with others measures of SA that directly assess this construct.

## **Team Situation Awareness Measurement**

Although team SA would appear to complicate matters, many researchers have taken a simplistic approach by aggregating the SA of individuals to measure the SA of the team. This approach typically involves probing the projective mental states of team members during task performance in order to infer the knowledge, or model of the situation and then aggregating to the team level by assessing the degree of overlap across individual mental states (e.g. shared mental model) (Artman, 1999; Fowlkes et al., 2000).

However, Sarter and Woods (1991) suggest that team SA is better measured through the use of complex scenarios, a method that has already been applied to teams in a variety of settings. They recommended embedding events in the scenarios to elicit key situation assessment behaviors and processes. They also recommended that a number of such events be embedded in order to provide multiple opportunities to measure TSA. To make this measurement work, methods that allow observers to document and rate team SA and behaviors throughout the scenario need to be developed.

Measuring TSA does not however, imply that individual SA becomes irrelevant; rather, that the concept of SA includes both the individual and team aspects (Shrestha et al., 1995). According to Cannon-Bowers and Salas (1997), team competencies exist at different levels of measurement with corresponding units of analysis. Thus, it is clear that no single construct can effectively measure all elements of SA and TSA. This view is further supported in studies that demonstrate that different types of SA measures do not always correlate strongly with each other (Durso et al., 1998; Endsley et al., 1998). Accordingly, rather than rely on a single approach or metric, valid and reliable measurement of TSA should utilize a battery of distinct yet related measures that complement each other (e.g. Harwood et al., 1988). Such a multi-faced approach

to SA measurement capitalizes on the strengths of each measure while minimizing the limitations inherent in each.

The methods of measuring SA and TSA are not yet fully understood. A better developed area of knowledge is that of the factors that degrade SA and TSA. The following section will outline some of the key degraders of SA with the goal of identifying factors that can be supported and improved through augmentative technology such as a team-oriented display.

### **Degraders of SA in High Reliability Organizations**

For teams working in a Command-and-Control environment, such as a forest fire command center, maintaining a high level of situation awareness is one of their most critical and challenging responsibilities. A vast portion of effective teamwork in an HRO is dependent on members developing SA and keeping it up-to-date in a rapidly changing environment. Acquiring and maintaining SA becomes increasingly difficult as the complexity and dynamics of the environment increase (Salas et al., 1995). In HRO's, many decisions are required across a fairly narrow space of time and tasks are dependent on an ongoing up-to-date analysis of the environment. Unfortunately, this chaotic environment makes the acquisition of team SA a challenging task. Here, we will discuss five of the most common barriers that HRO teams are faced with when developing TSA.

1. *Data Overload* is a significant problem in many areas. Advances in technology have increased the amount of information available to HRO teams. Systems are now capable of producing a huge amount of data, both on the status of their own components and on the status of the external environment. Unfortunately, an increase in information does not necessarily dictate an improvement in performance (Bolstad & Endsley, 1999). It is becoming widely recognized that more data does not equal more information, and

issues of automation and “intelligent systems” have frequently only exacerbated the problem, rather than aided it (Endsley & Kiris, 1995; Sarter & Woods, 1995). Sorting through this data to derive the desired information and achieving a good picture of the overall situation is an important challenge. Overcoming this problem through better system designs for the presentation of integrated data is currently a major design goal in the realm of human factors and systems design.

2. *Attentional Tunneling*: Successful SA is highly dependent upon constantly juggling different aspects of the environment. Sometimes multiple pieces of information are simultaneously processed in order to perform one or more tasks. For example, monitoring the road while driving and monitoring the radio for traffic information. This is called attention sharing. People face numerous bottlenecks in attention sharing, however this is typically encountered within a single modality, like vision or sound, and thus can only reduce attention in a particular capacity (Wickens, 1992).

Good SA is highly dependent on switching attention between different information sources. Unfortunately, people often can get trapped in a phenomenon called attentional tunneling (Baddeley, 1972; Wickens et al., 1993). When succumbing to attentional tunneling, they lock in on certain aspects or features of the environment they are trying to process and either intentionally or inadvertently drop their attention-switching behavior. In this case, their SA may be very good with regards to the part of the environment they are concentrating on, but will quickly become outdated on the aspects they have stopped attending to.

3. *Attention control*: People generally seek out information that is relevant to their goals. For example, an automobile driver may search for a particular street sign among

competing signs and objects in the world. However, at the same time the driver's attention will be caught by information that is highly salient. Saliency, the compellingness of certain forms of information (Parkhurst et al., 2002), is largely determined by its physical characteristics. The perceptual system is simply more sensitive to certain signal characteristics than others. Natural salient properties can be used to promote SA or to hinder it. When used carefully, properties like movement or color can be used to draw attention to critical and highly important information and are thus important tools for designing to enhance SA. Unfortunately, these tools are often overused or used inappropriately. If less important information is flashing on a display, for example, it will distract the person from more important information.

4. *Limitations in working memory:* Working memory can be thought of as a central repository where features of the current situation are brought together and, along with knowledge in long-term memory, processed into a meaningful picture of what is happening. This memory bank is essentially limited. Miller (1956) formalized the proposition that people can hold approximately seven plus or minus two chunks (related pieces) of information in working memory. This has significant implications for SA. While we can develop the ability to hold substantial situational information in memory through the use of a process called chunking, working memory is a limited cache for storing information. SA failures can result from insufficient space in that cache and from a natural decay of information in the cache over time. In the absence of other mechanisms, most of a person's active processing of information must occur in working memory (Endsley & Smith, 1996). As a person attempts to scan different information from an environment, previously accessed information must be remembered and

combined with new information. Given the complexity and sheer volume of information required for SA in many systems, it is no surprise that memory limits create a significant SA bottleneck.

5. *Limitations in workload:* The concept of workload can be defined as the combination of task demands, or load factors, and a team's response to those demands (Endsley et al., 2000). High mental workload is a stressor of particular importance in HRO's that can negatively affect team SA (Taylor, 1990). First, it can act to reduce an already limited working memory by using up a portion of it. There are essentially fewer cognitive resources available for processing and holding information in memory to form SA. As reliance on working memory can be problematic, stressors such as these only exacerbate the problem. Second, people are less able to gather information efficiently under stress. They may pay less attention to peripheral information, become more disorganized in scanning information, and be more likely to succumb to attentional tunneling.

Poor SA can also occur under circumstances of extremely low workload. In this case the team may have inattentiveness, decreased vigilance, or low motivation. Relatively little attention has been paid to the effects of low workload on SA. However, this condition can pose a significant challenge for SA in many HRO environments and deserves further study.

These potential SA barriers represent just a few of the pitfalls that stem from the inherent limitations of human information processing which can severely undermine SA. The problem is no longer a lack of information, but finding what is needed, when it is needed. Thus when designing to support SA, it is vital to take these SA degraders into account. The objective of this

research is to study the problem of TSA degradation and to derive and test potential technological solutions to augment and facilitate TSA and teamwork. The following section will outline the challenges of designing a Team SA display intended to support TSA in a command-and-control HRO environment.

### **Team Situation Awareness Display**

*Design challenge.* The complex environment in many HROs puts a great demand on individuals working in these settings. Therefore, in order for HRO team members to be effective, they must rely on continuous coordination, communication, and information sharing with their teammates (Parush et al., 2011); in other words, team members must maintain a certain level of TSA. To achieve this adequate level of TSA, large team-oriented displays are becoming an integral part of HRO team environments. It is generally agreed that such large displays, often called team situation awareness displays, should provide information that enables team members to maintain awareness of the overall situation, of their role on the team, and of the roles of other team members (Dominguez et al., 2006). However, few guidelines currently exist to help determine precisely what information sources should be shown on these large displays or what interface techniques should be used to provide this information in an effective format. Also, it is not well understood how different HRO personnel should use these team SA displays, although anecdotal evidence suggests that, currently, they are commonly used by commanding personnel to gather status information (Dudfield et al., 2001).

Although there has been limited research on team displays supporting TSA, there has been substantial research conducted on the use of team displays in general, and several systems have been designed for the purposes of supporting work tasks or collaborative work. For example, projects such as BlueBoard (Russell & Gossweiler, 2001) and Tivioli (Pedersen et al.,

1993) offer whiteboard-type tools for collaborating on shared artifacts. Tools such as MessyBoard (Fass et al., 2002) and the Notification Collage (Greenberg & Rounding, 2001) support synchronous and asynchronous communication for collaboration. Projects like CoLab (Fass et al., 2002), ARIS (Biehl & Bailey, 2004) and iRoom (Johanson et al., 2002) focus on the architecture, system design, and interaction techniques of multi-systems and environments with a focus on how users can interact through displays. These systems however, are designed for non-HRO environments, where teams may not be faced with the same dynamic situations and small margin of error. Therefore, findings from this research may not be generalizable to high-reliability environments.

What research has been done on team displays in HRO environments has been limited and scattered. Investigations have been done into the use of team displays in the HRO domains of military command-and-control (Jedrysik et al., 2000; Scott et al., 2007; Wark et al., 2004), air traffic control (Bolstad & Endsley, 1999), surgical team environments (Parush et al., 2011 Bitterman, 2006; Lai & Spitz, 2006; Levine et al., 2005), and naval ship command (Jenkin, 2004). However, it is challenging to synthesize this body of research into design principles applicable to all co-located team interactions. Not only are different results produced by the variety of applications and environments, but also the vast differences of interpersonal interactions create unique and un-replicable collaborative situations. While the evaluations of these systems have yielded valuable findings regarding the application of team displays for supporting teamwork and situation awareness, the findings are circumstantial and difficult to replicate, and so we still lack a clear understanding of what role these systems play in HRO environments. Building on this previous research, the following study is directed towards developing and testing a team display in a controlled and replicable microworld environment,

which assists individuals in achieving a high level of TSA when involved in collaborative decision-making tasks such as those found in command-and-control team environments.

The goal of this project was to create and test a visual display that presented a data set in an effective format that would be easy to interpret and understand. Although appropriate data presentation holds the potential to make the team member's work more manageable, the possibility of data overload presented a significant problem. In these situations, the rapid rate at which data changes creates a need for information intake that quickly outpaces the ability of a person's sensory and cognitive system to supply that need. As people can only take in and process a limited amount of information at a time, significant lapses in TSA can occur. In order to evaluate the role that a team display played in supporting TSA during periods of potential data overload, the following research explored workload level and its affect on both team interaction and on the use of team displays.

*Design process.* An analytic approach was used to specify the design basis for the team-oriented display in this study. This began with an analysis of the requirements for situation awareness of both individuals and teams. The analysis drew on the existing research base to identify issues and lessons learned across various HRO domains about the factors that contribute to situation awareness and support cognitive and collaborative performance (Parush et al., 2011; Endsley et al., 2003; Cannon-Bowers & Salas, 1998; Endsley, 1995; Hutchins, 1996).

The present research draws from a list of principles for supporting SA, developed by SA Technologies (Endsley et al., 2003). Specifically, three of these principles can be drawn upon for designing team displays intended to support HROs. The first relevant design principal is to reduce display density (without sacrificing important information) in order to ensure data is displayed efficiently. One way to display data efficiently is to favor graphic data over written

data. In many cases an image or video of an event can replace many lines of written description; this reduces the display space needed. Another way to reduce overall display density is to favor data sources that filter out extraneous data, when available. However, the display should not be so sparse that the user must use additional data sources to find needed information (Endsley et al., 2003). The second relevant design principle is to “present level 2 data directly” (Endsley et al., 2003). Level 2 data is data that enhances the ability of the user to not only perceive relevant data, but also comprehend its meaning. At the very least, this requires using data that is a composite of multiple sources (e.g. overlaying multiple maps into one display) or data that has been processed by software. As much as possible, the team display should relay the meaning of crucial elements to the user, not just the status of those elements. The third relevant design principle is to assist the user in developing projections of the status of important data in the near future. This principle requires greater processing of data, and should be used with caution. An over-reliance on inaccurate projections will not enhance SA, nor performance. However, in some cases it may be appropriate for the team display to show projected information (e.g. weather forecasts, projected positions for vehicles of interest). As much as possible, the display should assist the user in not only perceiving relevant information, but also in comprehending the meaning and projecting the future status of that information. In summary, SA Technologies identifies that an SA support system should favor information that is 1) graphic in nature, 2) derived from multiple data sources, and 3) processed to enhance comprehension and projection.

In addition to the preceding design principles, this thesis addressed the need for an effective way to reduce the cognitive load of processing information. This could be achieved by reducing the search time for the data necessary to make a decision. In the past, good visualization has been achieved by grouping related information together. One of the better-known

visualization-techniques that implement this grouping was first identified by Edward Tufte (1991), and is known as small multiple designs. Small multiple designs use the same graphical depiction to portray information of different content. The consistent design of each graphical depiction facilitates the human mind's innate ability to compare and contrast each of the depictions rapidly and accurately. Based on this assertion, both the individual display and the team display were designed in the same format so that comparisons can be made at a glance. This poses a benefit by visually enforcing comparisons of change.

In order for operators to view and interpret all of the information available from an increasing number of information sources and sensors, the information must be displayed in a meaningful way. The machine-human interface must be as fluent and as efficient as possible for usage by operators at all levels. Operators need tools that help them gain situational awareness faster and thereby enable correct decisions with less risk. The information support system described in this paper aims to empirically test design concepts for TSA displays and yield faster situational awareness for operators in a variety of command-and-control industries. In order to assess the impact of a team display on teamwork and SA, the researcher needed to choose a domain that could be replicated in a laboratory setting. Furthermore, a domain was needed that would be easily understandable and intuitive for the non-expert test demographic. An effective option that met these requirements was the field of forest firefighting.

### **The Firefighting Domain**

Forest fire suppression refers to the firefighting tactics used to suppress forest fires. Firefighting efforts in wildland areas require different techniques, equipment, and training compared to the more familiar structure fire fighting found in populated areas. Working in conjunction with specially designed firefighting trucks and aircrafts, these forest fire-trained

crews suppress flames, construct fire lines, and extinguish flames and areas of heat to protect resources and natural wilderness. Forest fire suppression also addresses the issues of the wildland-urban boundary, where populated areas border with wildland areas.

For wildland forest fires, each response to an emergency call carries with it a variety of complex hazards and the protection of human life, both firefighters and civilians, is first priority. The challenge of engaging with the hazards of a forest fire requires a complex approach that ensures operational effectiveness, efficiency, and safety. The elements of such an approach include structured communication between crew members, timely adjustments to rapidly changing environments, pre-established systems for incident command, and the ability to make critical decisions with only limited or incomplete inputs. In such a complicated environment, it is not surprising that events often unfold in a way that can place firefighting personnel in peril.

The literature reveals an abundance of research on firefighting, on topics including organizational structure (Regehr, 2003; Weick, 1999), decision-making processes (Klein, 2005), and psychological and health conditions (Regehr et al., 2000). There have also been several studies of firefighting incident failures, some notable ones being procedural after the World Trade Center attacks (McKinsey, 2002) and a study of organizational and communication failures at Mann Gulch (Weick, 1993). Although this research is valuable, there is unfortunately little work that provides insight into teamwork among firefighting command crews. One reason for this is that researchers working in the forest fire domain face important methodological problems when trying to test their hypotheses and theories due to the dynamic and unpredictable environment in which forest firefighters work.

Although there is limited research on teamwork in firefighting command, one valuable review was conducted by the United States Forest Service (USFS), which found command-and-

control concepts, such as those used in many High Reliability Organizations, to be effective tools for improving operational effectiveness and firefighter safety. Findings from the 1995 Wildland Firefighters Human Factors Workshop (Putnam, 1995) suggest that HRO concepts should be used as a model for reorganization strategies in wildland fire agencies in order to reduce accident rates on fire incidents. HRO concepts were also identified as a mechanism to improve the efficiency of the forest service's prescribed firefighting operations (Weick et al., 2004). Similarly, forest fire professionals have recognized the need for a more organized form of command in the fight against wildfires (Phillips, 2003). Specifically, they realized that, during crisis situations, there is a diversity of people making strategic decisions in a complex environment, and a common terminology and a clear chain of command are needed. In light of this, a decision was made to implement a form of command control, the Incident Command System, as a global standard for fire management.

Unfortunately, the inflexible circumstances present in forest fire environments make it difficult to examine and improve the Incident Command System and the command-and-control teams operating within it. Most organizations learn and adapt through trial-and-error. However, in the domain of firefighting, the cost of experimental learning can far exceed the value of the lessons learned. Researchers cannot afford to study failure or to wait for accidents to occur and then investigate what components of the system failed. This poses a challenge for the study of command teams in forest firefighting. However, as researchers become increasingly interested in forest fire command, numerous novel research designs and strategies have emerged. One of the most popular research methods involves the use of Microworld simulations which will be further discussed in the methods section below.

## **Goals and Objectives**

The goal of this research project was to evaluate the effectiveness of a team display concept intended to assist individuals in achieving a high level of team situation awareness (TSA) when involved in collaborative monitoring and decision making tasks in a forest fire-fighting command-and-control context.

The objectives of this study were as follows:

1. To assess the impact of a team display on TSA
2. To evaluate the effects of varying team workloads on TSA
3. To identify patterns of communication reflecting teamwork processes and TSA

## **Research Questions**

To reach the research objectives, the proposed study addressed the following questions:

1. Can team displays effectively promote and support TSA in a command-and-control team context?
2. What effect does workload have in the development of effective TSA within a command-and-control team?
3. How will a team-oriented display affect communication (specifically information sharing) in a co-located command-and-control team?

## **Research Approach and Hypotheses**

In previous related research, shared displays have been provided for each team member as a complete replicate of the other team member's display. It has been found that this may not be the best way to provide a shared display of information to team members. The current study used a single large team-oriented display, which provided only the critical information elements

from the other team member's display based on an analysis of shared information requirements (see Appendix A).

Team performance was examined by comparing two conditions. The first condition involved teams of individuals working on separate workstation displays and using a team-oriented display that supported information sharing and communication. The second condition also involved teams working on separate displays. However, in this condition they were not provided with a team-oriented display, forcing the team to depend entirely on verbal communication. In addition, the workload level was manipulated to assess its effect on both team interaction and on the use of the team displays when performing critical tasks.

Three main hypotheses were tested in this study. First, it was hypothesized that the presence of a team-oriented display would improve performance in a team-based task. Secondly, it was expected that the presence of a team display would significantly improve the development and maintenance of situation awareness. Lastly, it was expected that a team-oriented display would reduce the frequency of verbal communication between team members, as essential information previously obtained using verbal communication would now be accessible through the team display.

## **Method**

### **Participants**

The following study included 64 research participants. For the purpose of this study, pairs of participants were considered as "teams" and their interaction assumed to reflect teamwork. With regards to analysis, each team was expressed as a single unit of measurement; therefore, the sample for this study was 32 teams. In order to maintain consistency it was ensured that all participants were paired alongside a team member with whom they had never interacted with

prior to this study. Participants consisted of individuals between the age of 17 and 41 and were recruited through SONA, the Carleton University Psychology Undergraduate student pool. The mean age of participants was 20.9 years, and the gender breakdown was nearly even with 47% males, and 53% females. All participants had either normal vision or corrected to normal vision. Although one participant identified himself as colour blind, this individual identified no problems perceiving all elements of both the team and individual displays. Furthermore, results for this participant revealed no outliers and therefore were not discounted. All participants received bonus credit towards a psychology course as an incentive for their participation.

### **Design**

Two factors served as independent variables in the study: display types and workload level (summarized in table 1).

1. Display types were a within-group manipulation including two conditions. One condition included an individual display for each team member with no ability to view the other member's display, thus requiring verbal interaction to accomplish team coordination (see Figure 1 for the information officer display and Figure 2 for the fire commander display). The second condition included individual displays for each team member with an additional co-located team display to support team communication, coordination, and situation awareness (see Figure 3). The team display incorporated situation-related elements that were unique to each participant role, yet simultaneously were required sometimes by the other team member to complete his or her tasks. These elements included sharing information about the fire location and the location and activity of simulation assets of each of the roles (see also Appendix A for a detailed breakdown of the information provided on the individual and team displays).

2. Workload level was also a within-group manipulation. Two workload levels (low and high) were based on the maximum number of fire fighting and surveillance tools (airplanes, trucks & helicopters) as well as the number of forest fires present in the scenario. These parameters (see Table 1) were verified in pilot tests to successfully vary the level of workload of the task.

There were three dependent variables in the study: Performance, Situation Awareness, and Communication.

1. Performance levels were calculated through the Networked Fire Chief simulation, serving as an indicator of teamwork as well as a possible indirect measure of team situation awareness.
2. Situation awareness among team members was measured using a derivative of the popular SAGAT method, called the Quantitative Analysis of Situation Awareness (QUASA).
3. Communication patterns were also analyzed to provide insight into effective teamwork using the conversation analysis approach (Pomerantz & Fehr, 1997)

Each method of measurement is further discussed and defined later in this section.

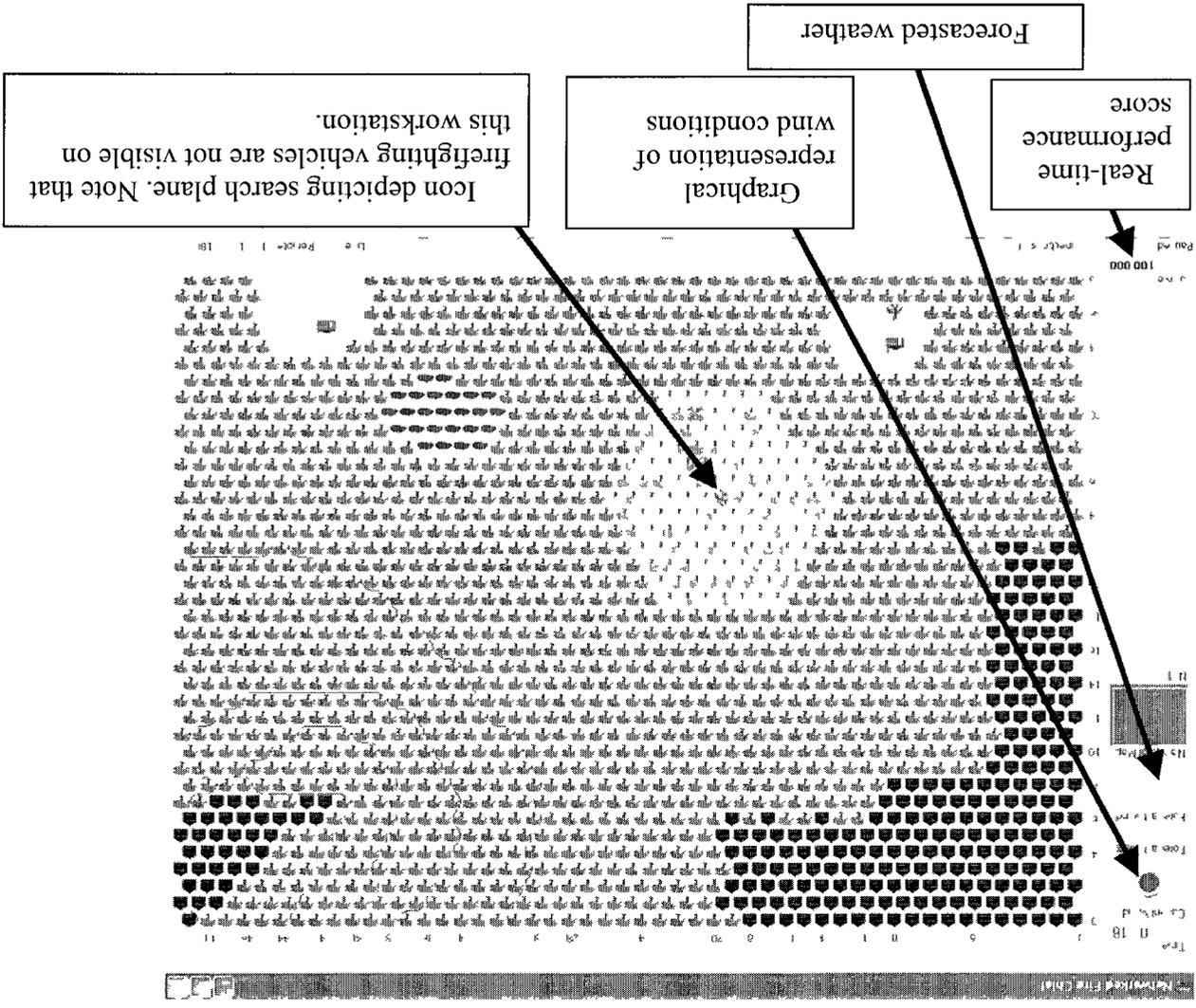
Randomized block design was used, such that subjects completed both workload conditions without a team display and then performed both conditions with the team display or vice versa. This design was used to reduce sources of variability caused by changes in display type. It should also be noted that the experimental scenario order was counterbalanced in order to eliminate fatigue or practice effects due to the order of presentation.

Table 1

*Experimental Conditions Identifying Manipulation of Workload and Display Variables*

	Individual displays only	Individual + Team display
Low-workload	Scenario I	Scenario III
	Search planes: 2	Search planes: 2
	Firefighting Trucks: 1	Firefighting Trucks: 1
	Firefighting Helicopters: 1	Firefighting Helicopters: 1
	Total Fires: 5	Total Fires: 5
High-workload	Scenario II	Scenario IV
	Search planes: 4	Search planes: 4
	Firefighting Trucks: 2	Firefighting Trucks: 2
	Firefighting Helicopters: 2	Firefighting Helicopters: 2
	Total Fires: 10	Total Fires: 10

Figure 1. Networked fire chief "information display" (individual display 1).



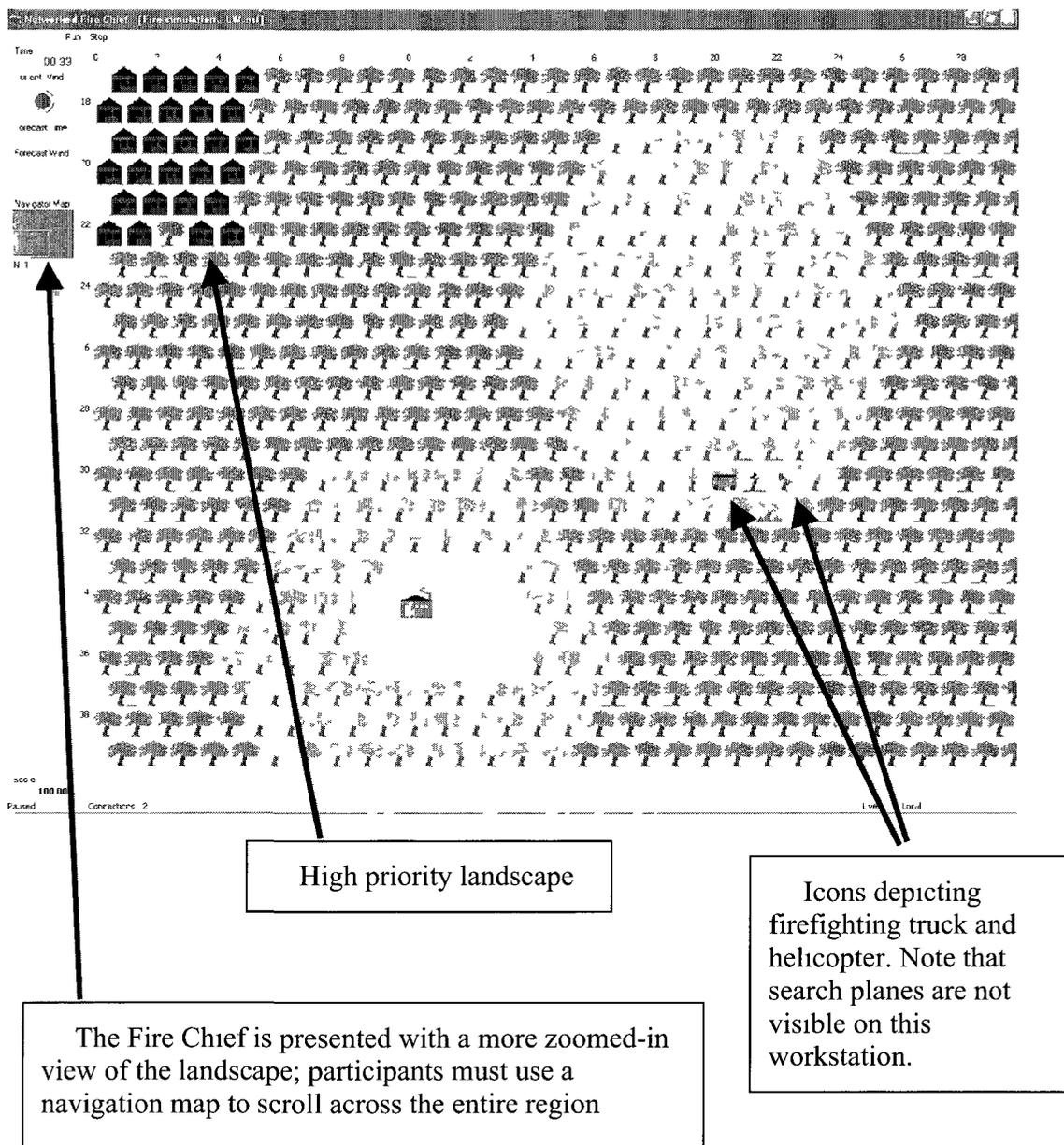
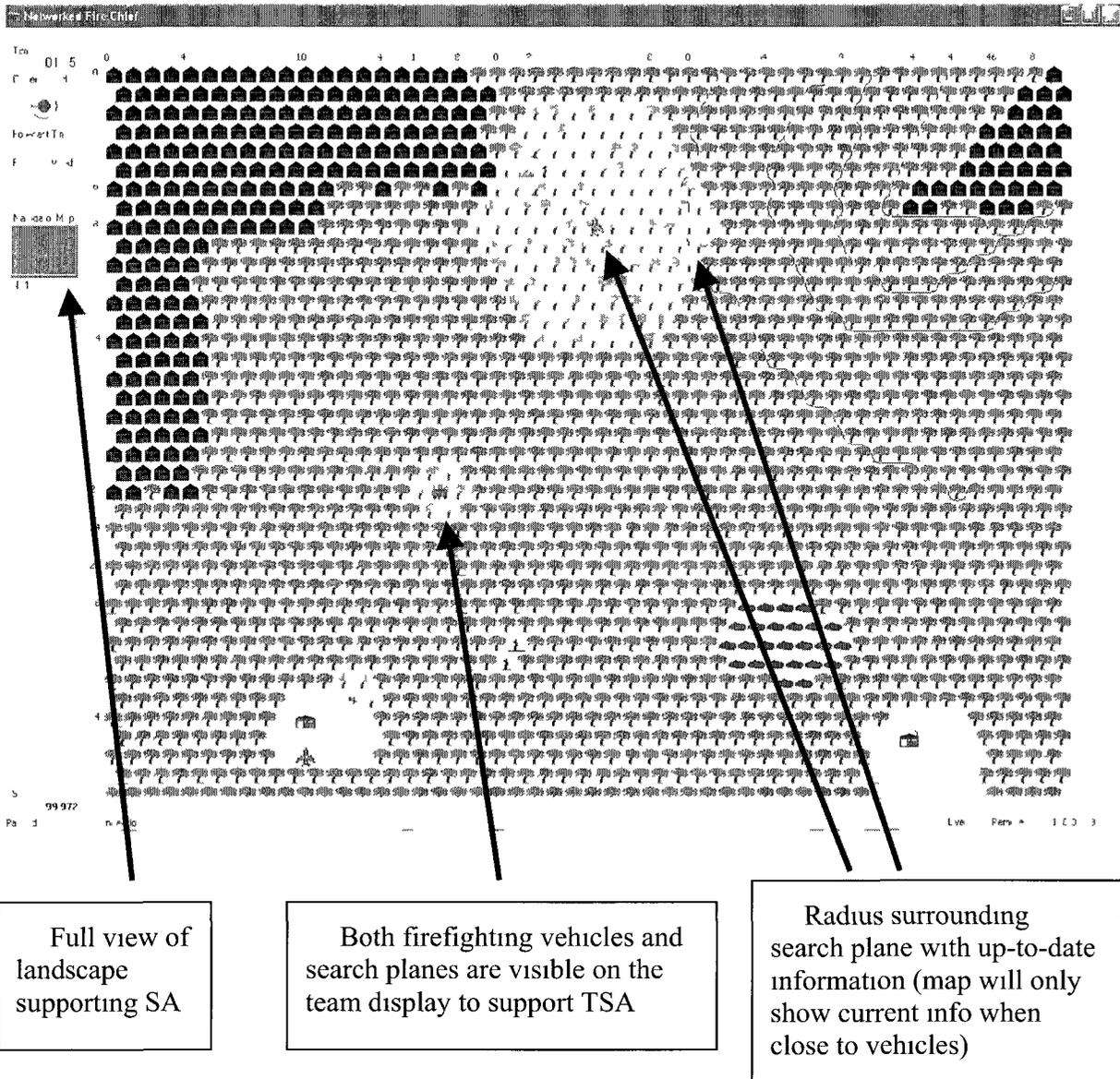


Figure 2. Networked fire chief “fire commander display” (individual display 2)



*Figure 3* Networked fire chief team display (see Appendix A for full list of team display elements)

### Experimental Tasks

The experimental task required two individuals to work together in a team setting, acting as members of a fire-fighting command-and-control unit in a forest fire computer simulation

The primary goal in the scenario was to extinguish all forest fires while limiting damage to the

landscape. The secondary goal was to protect high priority terrain, which consisted of regions of human populated areas. Each team member had separate but inter-related tasks. One team member acted as an Intelligence Officer, while the second team member assumed the role of a Fire-Crew Commander. The details of the two roles are elaborated below.

The tasks mimicked real world settings in which forest-fire commanders only receive updated information about fire status and location by sending reconnaissance planes to scout new fires (McAlpine, 2010). Participants viewed a map that only showed up-to-date information within a specified radius of a search plane. The Intelligence Officer was responsible for this aerial surveillance across the entire landscape. The primary objective of the Intelligence Officer was to navigate fixed wing aircrafts (2 search planes for low workload condition and 4 for high workload) across the site in order to monitor for the presence of fires. The secondary objective of this individual was to keep the teammate updated about the number and location of fires occurring at all times and to offer advice on a plan of attack (draw attention to high priority fires). Throughout the simulation there were periods where the number of fires exceeded what the fire crew could deal with at one time. In these situations it was the Intelligence Officer's directive to keep track of the actions of the Fire-Crew Commander and make recommendations about which fires should be regarded as high priority.

The Fire-Crew Commander was responsible for the navigation and firefighting command of firefighting trucks and helicopters (1 truck, 1 helicopter for low workload condition, and 2 trucks, 2 helicopters for high workload). This participant received information about the location of fires from the teammate and acted to suppress these fires. They needed to monitor several factors such as vehicle water levels, terrain elevation, and wind conditions as presented on their individual display, and deploy vehicles to put out the fires. Table 2 identifies the primary tasks

involved in the firefighting simulation, and provides a breakdown of team member requirements and responsibilities.

Table 2

*Firefighting Simulation Tasks and Associated Informational Requirements and Responsibilities*

Task/Event	Information Requirements	Responsibility
Identification of new fire	Location of new fire	Intelligence
	Number of fires	Officer
	Size of fires	
	Proximity of fires to vehicles	
	Wind conditions	
Prioritization of fires to extinguish	Location of all fires	Intelligence
	Number of fires	Officer
	Fire proximity to priority land	
	Status/availability of fire crew	
Extinguish fire	Location of fire	Fire Commander
	Water levels in tank	
Monitoring wind condition changes	Current wind conditions	Both team
	Forecasted wind conditions	members
	Projecting changes in fire behavior	
Re-fill water tanks	Water levels of each vehicle	Fire Commander
	Actions of each vehicle	
	Availability of water source	
Team member actions	Status of teammate	Both team
	Current actions of teammate	members
	Prioritization of teammate goals	
Navigation of vehicles	Status of vehicle	Both team
	Location of vehicle	members
	Future location of vehicle	

## **Apparatus**

The following research followed a growing trend in command-and-control research by utilizing a controlled microworld simulation. A microworld is a scenario simulated in a computer that changes dynamically and is designed to reproduce important characteristics of real situations while leaving open the possibility of manipulation and experimental control (Funke, 1993). The main purpose in using a microworld is that it should serve as a tool for research. The microworld provides researchers with the ability to investigate complex environments, while still giving them the flexibility of experimental manipulation and control. Most domains in command-and-control, such as forest fire fighting, are not amenable to experimental research where one factor at a time is varied in order to study its effects. Furthermore, field studies rarely permit researchers to interfere with the situation, especially in HRO type environments. Therefore a microworld that is relevantly designed might be able to provide insight into characteristics of a command-and-control system that have never before been systematically evaluated.

The term “microworld” suggests a miniature copy of the real world. This depiction captures important characteristics of a microworld: it is an abstraction of the real world that attempts to replicate features that are important to the decision-making process without replicating the real world environment. Microworlds include some important characteristics of the real system that are selected and simulated in a relatively small and well- controlled model (Brehmer, 1995).

To provide the participants with a complex environment, the following study used a forest fire fighting microworld, derived using freely available simulation software called Networked Fire Chief (NFC). The NFC is a microworld environment commonly used in command, control, and communication research, and in the training of team decision-making

(Omodei et al., 2004). The NFC was hosted on three identical Intel Core 2 Duo E6700 2.66 GHz IBM desktop computers running the Windows XP operating system. Each computer was connected via Ethernet LAN. Two of the computers were equipped 17-inch 1280x960 resolution monitor serving as workstations for each respective team member (see Figure 4), and the third computer was equipped with a 52 inch Samsung LCD serving as the wall mounted team display (see Figure 4).

The NFC fire-fighting simulator is operated by simple mouse point and click commands. Participants controlled their vehicles by selecting them with their cursor and then dragging the vehicle across the map to assign them a destination. The vehicles took a few moments to reach this assigned destination. When the projected location was on fire, fire fighting action was initiated. When the location was a water source, the water tank was refilled. This simple command interface minimized the need for extensive training and allowed users to focus on their required tasks.

### **Procedure**

Two individuals participated as a team. When participants first arrived, they received an informed consent form to read and sign. Next the experimenter administered a participant questionnaire designed to obtain pertinent background information, such as participants' native language, vision and computer experience (see Appendix B). The experimenter then randomly assigned the participants to either the role of Intelligence Officer or Fire-Crew Commander, and team members were presented with an instructional slideshow describing their individual tasks and a brief description of the other team member's tasks (see Appendix C). For the Team Display condition, information regarding the additional abstracted display was also included in the instructions.

During the experiment, team members were seated side-by-side. However their workstations were placed in a position that prevented them from seeing each other's display (see Figure 4). In all conditions, team members were encouraged to communicate with one another verbally during testing and it was further advocated that team members work together on a joint strategy to improve performance. Teams first completed a 5-minute practice trial, which consisted of a simplified version of the forest fire simulation. This allowed participants to familiarize themselves with the simulator controls and interface and also gave them the opportunity to practice communicating and coordinating with their teammate. Participants were then given a short break, during which they had the opportunity to ask the experimenter any questions regarding the simulation and their role in the scenario.

Following the short break, participants were asked to participate in four 5-minute firefighting simulator scenarios. During each of the four scenarios, questions designed to collect data regarding situation awareness were administered to participants. These questions are known as QUASA probes and are further explained in the *measurement* section. In order to administer the QUASA probes, each scenario was stopped at two random times, determined by a random number generator. As soon as the simulation was paused, all displays were immediately turned off in order to prevent participants from preparing for the questions by studying the screens. At each pause the experimenter administered two QUASA queries, along with a corresponding self-rating probes to each participant. The QUASA questions were administered by pencil and paper. Through pilot testing it was determined that it was most effective to present queries in a predetermined order. This prevented presenting questions to the participants that were inappropriate in a given situation. For example asking the following question at the very beginning of the simulation would be unsuitable: "Has your partner refilled water within the past

minute?” Thus, a set of fixed order questions was administered to negate this issue. It should be noted that although the order of questions was fixed, the order of experimental conditions was counterbalanced across the four scenarios; therefore specific questions were not linked with any given scenario.

Altogether, QUASA was administered 8 times – four scenarios, each stopped twice, with two questions being posed each time to each of the two participants. To ensure that responses were independent, communication among participants was not allowed during the pauses. In order to prepare participants for the administration of QUASA probes, the procedure was explained to them during training and a practice question was administered in order to familiarize them with the process.



*Figure 4.* The physical layout of the experiment, revealing two individual workstations in the bottom part of the photo along with the team display mounted on the wall in the top center of the image.

## Measurements

As noted earlier, the multivariate nature of SA complicates its quantification and measurement, and a single metric may have only tapped into one aspect of a user's SA. Accordingly, to gather a more broad view of the role between team members in a command-and-control environment, the following study utilized three distinct yet related measures that complement each other. The following section will elaborate on each method of measurement.

*Performance measures.* As indicated earlier, the team's performance goal was to control the fires as well as to protect high priority regions from the fires. Performance measures, therefore, were focused on the total amount of landscape burned or burning and the number of high priority regions burned or burning. High priority regions were assigned a higher value in the simulation; as a result, when this landscape was destroyed by fire, the firefighting score was more dramatically impacted, compared to other landscape. This measurement technique is commonly used in fire-fighting tasks (Svenmarck & Brehmer, 1991; Johansson et al., 2000). Each trial represented one measure with respect to performance. At the end of each of the four trials (outlined in table 1), the percentage of non-burned out cells was calculated and used as a performance measure (a high score is desired). This approach to performance measurement was selected with the belief that a successful team should be able to respond quickly to a situation, while at the same time coordinating effectively in order to minimize the impact of the forest fires.

The score was calculated through the simulation program in real-time using the following equation:  $S(g) = V(i) / [V(T) - S(p)] (100)$ , where  $S(g)$  represents time in seconds,  $V(i)$  represents the score value of all landscape elements (different elements of the landscape were assigned different values, for example the human populated areas were worth significantly more than

forested regions).  $V(T)$  is the total score value of all landscape elements at the start of the simulation, and  $S(p)$  is the score lost due to the initiation of fires (points were not deducted for landscape elements lost due to the initial inception of wildfires as this damage was not preventable).

*Situation Awareness Using QUASA.* The Quantitative Analysis of Situation Awareness assessment technique (QUASA) is a form of direct SA measurement largely based on the popular Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1988), one of the most widely used objective measures of SA. This method employs periodic, randomly timed freezes in the fire-fighting simulation scenario during which all system displays are temporarily blanked. At the time of the freeze, probes are posed to the participants to assess their knowledge of what was happening at the time of the freeze. These queries cover elements of all three levels of SA (perception, comprehension, and projection) as well participants' perceptions of TSA.

Queries were determined based on a cognitive task analysis conducted by the experimenter prior to testing. Task analysis is a term that encompasses ideas developed by Annett and Duncan (1967). It breaks down goals into a hierarchy of tasks that indicate the manual and mental activities required for both individuals and teams to perform said goal. This information also serves as the basis from which SA and TSA probes can be generated (see Endsley, 1995). In the current analysis (see example below), tasks were first broken down into sub-tasks based on the cognitive demands required to complete them. The information that is required to accomplish these sub-tasks was then identified, and categorized by information source. Once a full list of tasks was established (see Appendix A), they were evaluated through pilot testing. If it was determined that the complexity of several tasks caused excessive cognitive load for participants, these tasks were subsequently removed from the simulation.

The following is an example of one main task and two subtasks:

1. Identification of new fires
  - a. *Intelligence Officer* confirms to *Fire-Crew Commander* that 2 new fires are present in the landscape
  - b. *Intelligence Officer* specifies location of new fires, and instructs *Fire-Crew Commander* to send a firefighting vehicle to each new fire

The task analysis provided the researcher with a framework for identifying the critical tasks involved in the simulation and helped to identify scenarios where SA were in high demand. Questions were then derived from this analysis in order to evaluate the SA of each team member during the freeze, as per the QUASA method.

The QUASA method (McGuinness, 2004) uses a combination of true/false SA probes and self-ratings of confidence in each probe response to quantify not only actual SA (through the analysis of probe responses using signal detection theory) but also perceived SA (through confidence ratings) and, additionally, SA calibration, the extent to which perceived SA corresponds with actual SA. For example:

<u>Probe statement</u>	<u>Assessment</u>	<u>Confidence</u>
<i>There are 5 fires currently present across the landscape</i>	[ ] <i>True</i>	[ ] <i>Very High</i>
	[✓] <i>False</i>	[ ] <i>High</i>
		[✓] <i>Moderate</i>
		[ ] <i>Low</i>
		[ ] <i>Very Low</i>

Table 3 provides a list of examples QUASA probes along with the corresponding level of SA being evaluated (see full list in Appendix D).

Table 3

*QUASA Probe Examples and Corresponding Level of Situation Awareness*

QUASA True/False Probe	Level of SA
The fires are spreading south (downwards on map)	Level 1 SA
A fire will soon threaten a human populated area if it stays on its current course	Level 2 SA
There are currently 3 fires burning in the landscape	Level 1 SA
The current direction of the wind is up (north) on the map	Level 1 SA
A human populated (high priority) area will be threatened if the wind changes, and starts blowing north	Level 3 SA
A human populated (high priority) area is currently on fire	Level 1 SA
All firefighting vehicles are currently occupied (fighting/re-filling water/moving) (posed to Intelligence Officer)	Team SA
The box represents the entire landscape (box presented with probe); the fire indicated by the X is currently highest priority	Level 2 SA
The box represents the entire landscape (box presented with probe); there is currently a search plane in the location marked by an X (posed to Fire Commander)	Team SA

*Analysis.* Probe data was grouped into four categories:

- 1) “Hit” – a true statement which the participant agreed was true
- 2) “Miss” – a true statement which the participant thought was false
- 3) “False Alarm” – a false statement which the participant thought was true
- 4) “Correct Rejection” – a false statement which the participant correctly rejected

Once the data was categorized, the preliminary analysis evaluated SA accuracy by tallying the number of “Hits” and “Correct Rejections”. Data was then evaluated according to

Signal Detection Theory (SDT). SDT originated as a model of perceptual judgment that describes and analyzes how people perform in a task in which they must detect a signal, but not confuse it with non-signals and other irrelevant stimuli (noise). In the case of true/false SA probes, the signal is a valid description of the situation, and the noise is an invalid description. Three SDT statistics were applied: sensitivity ( $d'$ ), response bias ( $\beta$ ), and calibration bias.

Sensitivity ( $d'$ ) is defined by the SDT as an individual's actual ability to discriminate true signals from non-signals. In the case of true/false SA probes, SA sensitivity can be interpreted as an individual's ability to correctly discriminate between valid and invalid descriptions of the situation. The measure suggests that the greater the sensitivity, the better the individual is at making fewer misses and false alarms when responding to the true/false SA probes.

In order to measure Sensitivity participant Hit rates and False Alarm rates for each of the four experimental conditions were tabulated and normalized into Z-scores. The normalized False Alarm rates were then subtracted from the Hit rate to derive  $d'$  in accordance with the technique outlined in McGuinness (2004). A 2x2 repeated measures Analysis of Variance (ANOVA) design was then applied to evaluate the impact of both workload and display type on the level of SA and TSA.

Response bias ( $\beta$ ) specifies the setting of an individual's accept/reject criterion. This can be interpreted as an individual's leaning towards either more readily accepting or more readily rejecting information when he or she is uncertain as to its validity. A low  $\beta$  score suggests a "liberal or risk taking" strategy whereas a high  $\beta$  may represent a "conservative" approach. For example, if the stimulus is a metal detector searching for gold, then a miss (failing to detect the target) may cause you to miss out on hidden treasure, so a liberal bias is likely. In contrast,

sounding a false alarm too often may make people less likely to respond, grounds for a conservative bias.

Self-confidence ratings of responses to the SA probes were used to calculate calibration bias; this provided an indication of participants' SA calibration. The principle of calibration concerns the extent to which people are able to judge the correctness of their own observations or decisions. In other words, it assesses the degree of correspondence between self-perceptions of accuracy and actual accuracy (measured as a proportion of correct responses) (Koriat & Goldsmith, 1996). A well-calibrated judge is one who is highly confident about those responses that are in fact correct and unconfident about those responses that are incorrect. In a poorly calibrated judge, there is no systematic relationship between real and perceived accuracy. With respect to SA, a well-calibrated individual is one who has a high level of actual SA and correctly perceives this to be their SA state. The calibration bias score is a good measure of how well calibrated the participants with respect to SA and thus add an additional perspective on the potential impact and benefit of the team display. Calibration bias is measured by averaging confidence rating across all test items minus the proportion of the same items that were judged correctly. A positive bias score implies over confidence, while a negative bias score implies under confidence. This data was then plotted (Keren, 1991; Keren, 1997), presenting the mean confidence graphed against accuracy (proportion correct).

*Communication analysis of TSA and Teamwork.* Communication between the two participants was digitally recorded and used as a measure reflecting teamwork. There are various approaches reported in the literature of analyzing human communication in command-and-control contexts (Kiekel et al., 2004; Hess et al., 2006; Cooke, 2005). A study by Parush et al. (2009) identifies that the common aspects of most of these approaches contain elements from the

Conversation Analysis approach (Pomerantz & Fehr, 1997). Based on the key elements of Conversation Analysis, the following study took the full extent of verbal communication between team members and segmented them into utterances. An utterance is defined as a complete unit of speech in spoken language, generally but not always bounded by silence. Once utterances were identified, they were then coded into communication patterns based on two criteria: speech acts and domain-specific content. A speech act is defined as an utterance that serves a function in communication. It is rooted in the idea that individuals can use words not only to describe situations but also to perform communicative actions in conversation. Domain-specific content represents all utterances related to the simulation and team firefighting task. Coding was conducted by first identifying each individual utterance then categorizing them according to the appropriate speech act and content type. Coding categories were determined through an iterative process whereby categories were identified in a first pass, then re-evaluated and refined in an iterative process. This approach was in conjunction with previous HRO research (Foster-Hunt, 2009; Kramer, 2009). The main rationale of this method was to systematically and meaningfully reduce the scope of all information exchanged in teamwork into a minimal, but essential, subset of information required for effective teamwork. The overall objective of this coding approach was to identify communications that could reflect processes of coordination between the two team members as well as reflect the building and maintenance of TSA. Communication codes and categories were also counted in order to provide an indication of the scope and magnitude of communication patterns.

## **Results**

The presentation of the analyses and results is organized by each of the three measurement types. The analysis of the performance-based measures derived from the Network

Fire Chief simulation is presented first. This is followed by the analysis of situational awareness within teams, and finally, the analysis of communication patterns.

### **Performance-based measure**

The statistical assumptions of normality and compound symmetry were met as confirmed by the Shapiro-Wilk test of normality and Mauchly's Test of Sphericity, and no outliers were present in the performance data. Since the experimental conditions were counterbalanced and participants were randomly sampled from the population of Carleton's undergraduate students through the SONA system, the assumption of case independence was also met. Nevertheless, possible order effects were assessed and are presented later in this section.

The analysis of performance proceeded in two steps: 1. A two-by-two within participants ANOVA to assess the main question of this study: the effects of display type (team-display, no team-display) and workload (high, low) on performance; 2. Analysis of a possible impact of scenario order. The two-by-two ANOVA revealed a significant main effect between performance scores between the low workload condition ( $M = 78.19$ ,  $SE = 1.80$ ) and the high workload condition ( $M = 71.29$ ,  $SE = 2.84$ ),  $F(1,31) = 13.50$ ,  $p < .01$ , partial  $\eta^2 = .30$ , indicating significantly better performance in the low workload condition compared to the high workload condition. The analysis revealed no significant main effect in performance scores between the team display condition ( $M = 74.68$ ,  $SE = 2.31$ ) and the non-team display condition ( $M = 74.80$ ,  $SE = 2.44$ ),  $F(1, 31) = .004$ ,  $ns$ . The analysis also revealed no significant interaction between display type and workload,  $F(1, 31) = .155$ ,  $ns$ .

In order to assess whether there was any learning or practice effect while participants performed the four scenarios one after another, an ANOVA was conducted comparing performance across scenarios in the specific order that they were presented regardless of which

experimental condition was used. The analysis revealed that there was indeed a significant effect as participants performed better as they progressed through the four scenarios,  $F(1,31) = 21.15$ ,  $p < .01$ , partial  $\eta^2 = .42$ . A comparison using the Bonferroni correction revealed that there was a significant difference between performance on the first scenario in comparison with performance in each of the second, third, and fourth scenarios, with means and standard errors of 67.68 (3.06), 74.93 (2.21), 77.41 (2.43), and 79.36 (2.16) respectively, indicating participants performed better following the first trial. Two additional between-subjects ANOVAs were conducted in order to evaluate the impact of workload and display conditions while minimizing the impact of the learning effect. One ANOVA evaluated performance across only the first scenario while teams were still adapting to the task and the second ANOVA looked at the final scenario where the learning effect had completely diminished. The ANOVA for the first scenario revealed a significant main effect for workload  $F(1,31) = 8.99$ ,  $p < .01$ , but no significant main effect for the display factor  $F(1,31) = .10$ , *ns*. The ANOVA for the fourth scenario revealed no significant main effect for either the display factor  $F(1,31) = 1.40$ , *ns*. or for workload  $F(1, 31) = 1.34$ , *ns*. This suggests that the main effect on performance due to workload level took place in the very first scenario participants performed. The implications for the practice effect and the possible development of strategies are discussed later.

A second analysis was also conducted looking specifically at how teams performed in each of the four experimental conditions (high workload & team display; high workload & no team display; low workload & team display; low workload & no team display) comparing differences in performance across each of the 4 experimental orders (1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup>). This revealed no significant three way interaction between the presentation order, workload and display conditions  $F(3,18) = .50$ , *ns.*, as well as no significant interaction between presentation

order and the display condition  $F(3,18) = 0.46, ns$ . However, it did reveal a significant interaction between presentation order and workload  $F(3,18) = 3.36, p < .05$ , partial  $\eta^2 = .36$ .

Although each of the four experimental conditions were presented to participants in a counterbalanced order, an additional question that arose with regards to performance scores was whether any specific sequence of presentation affected the scores. In order to investigate this impact, a three-way ANOVA was conducted evaluating the impact of workload and display conditions across each of the four counterbalanced scenarios orders. The analysis resulted in a significant interaction between workload and scenario orders  $F(3, 26) = 5.77, p < .01$ , partial  $\eta^2 = .40$ , and between display and scenario order  $F(3, 26) = 12.85, p < .01$ , partial  $\eta^2 = .60$ . This indicates that the scenario sequence may have played a role in the performance results. The implications of these analyses are discussed later in the Discussion chapter.

### **Situation Awareness Probes (QUASA) Analysis**

The analysis of the situation awareness of the participants throughout the study and as a function of the two key variables - display and workload – includes the following: 1. Analysis of overall accuracy in responding to the SA probes; 2. SDT-driven analysis of sensitivity ( $d'$ ) and response bias ( $\beta$ ); and 3. SA calibration.

*Overall SA accuracy.* The initial QUASA analysis involved a comparison of participant accuracy (proportion of correct responses) across experimental conditions. Eight questions were posed for each of the four scenarios, and the total score from each scenario was aggregated. A two-by-two within subjects ANOVA was conducted to compare the effects of display type (team-display, no team-display) and workload (high, low) on SA. The assumption of sphericity, normality, and independence were met.

The ANOVA revealed a significant interaction between workload and display type,  $F(1, 29) = 4.98, p < .05, \text{partial } \eta^2 = .14$ . As well as significant main effects of workload,  $F(1, 29) = 51.84, p < .001, \text{partial } \eta^2 = .63$ , and display type,  $F(1, 29) = 47.81, p < .001, \text{partial } \eta^2 = .61$ . This indicates that participants' SA was better during low workload scenarios compared to high workload situations, and was better during the presence of the team display compared to when the team display was not available. However, the main effects should be interpreted with caution since they are influenced by the interaction. Figure 5 depicts the interaction, indicating that with team display there were no differences in SA accuracy due to workload, in contrast to the condition without team display where there was a larger SA difference due to workload level, with high workload level reducing accuracy.

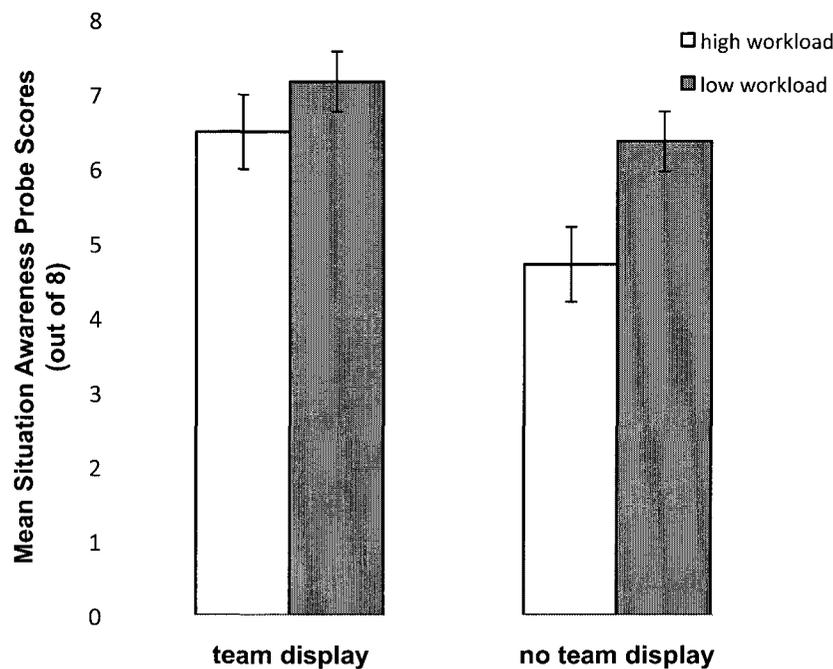


Figure 5. Mean situation awareness accuracy levels (along with *SE*) as a function of display type and workload showing the significant impact of both variables on SA.

SA was further investigated by looking specifically at whether any specific sequence of presentation affected the scores. In order to investigate this impact, a three-way ANOVA was conducted evaluating the impact of workload and display conditions across each of the four counterbalanced scenarios orders. The analysis found no significant three-way interaction between display, workload and scenario orders  $F(3, 25) = 0.71, ns$ , or any significant interaction between display and scenario orders  $F(3, 25) = 1.42, ns$ . However the analysis did reveal a significant interaction between order and workload,  $F(1, 25) = 6.05, p < .01, partial \eta^2 = .99$ . This analysis did not contribute to the goal of this study therefore it was not evaluated in depth, however it does imply that teams that started in the low workload condition performed significantly better. This is perhaps because they were initially presented with a less challenging scenario and thus had the opportunity to build more effective team strategies.

*SDT-driven analysis.* The next step in the evaluation of QUASA probes examined Sensitivity ( $d'$ ). Based on the analysis for Signal Detection Theory, the number of hits, misses, false alarms, and correct rejections were tallied for each true/false QUASA probe. Sensitivity scores, which are considered as the most accurate index of SA (e.g., Salmon et al., 2006), were computed using the following equation  $d' = Z(\text{hit rate}) - Z(\text{false alarm rate})$  as outlined in McGuinness (2004). False alarm scores for participants in each condition were transformed to Z-scores and were then subtracted from the Z-score of hit rates. A within subjects 2x2 ANOVA was then conducted to compare the effects of both display type (team-display, no team-display) and workload (High, Low) on sensitivity scores.

The ANOVA revealed a significant difference in sensitivity across display and non-display conditions,  $F(1,29) = 20.53, p < .001$ , partial  $\eta^2 = .41$ , indicating that participants had a higher Sensitivity score in the team display condition ( $d'=2.56$ ), compared to the non-team display condition ( $d'=1.08$ ) (see Figure 6). This suggests that participants in the display condition were able to more effectively discriminate between true and false descriptions of the situation, compared to participants in the non-display condition.

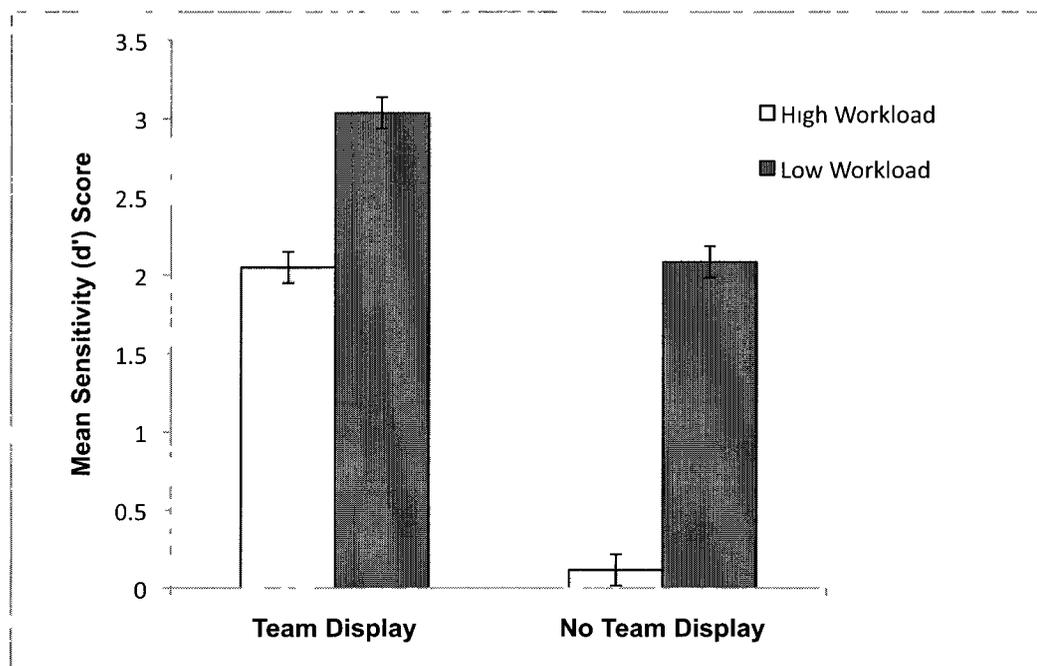


Figure 6. Mean SA probe Sensitivity scores (along with *SE*) across display and non-display conditions

The within-subjects ANOVA also revealed a significant difference in sensitivity across the high and low workload conditions,  $F(1,29) = 25.90$ ,  $p < .001$ , partial  $\eta^2 = .47$ , indicating that participants had a much higher Sensitivity score in the low workload condition ( $d' = 2.56$ ), compared to the high workload condition ( $d' = 1.08$ ). This suggests that participants in the low workload condition were able to more effectively discriminate between valid and invalid descriptions of the situation, compared to participants in the high workload condition. The ANOVA did not reveal a significant interaction between workload and display type,  $F(1, 29) = 2.84$ , *ns*.

Responses to the QUASA probes were also examined through the evaluation of response bias ( $\beta$ ) scores, which quantifies an individual's response strategy for dealing with ambiguous stimuli (McGuinness, 2004; Stanislaw & Todorov, 1999). Because the  $\beta$  calculation is based on

a ratio, the natural logarithm of  $\beta$  is often analyzed in place of  $\beta$  itself (McNicol, 1972). A conservative bias leans toward rejecting and is expressed by a positive value. A liberal bias leans toward accepting and is expressed by a negative value. Response bias was computed using the following equation  $\ln \beta = d' * (k - d' / 2)$ , where  $k$  represents the negative Z-score of False Alarm rates (Harvey, 2003). When looking at the response biases of the team display and non-team display conditions, participants in the non-team display condition demonstrated a liberal response bias ( $\ln \beta = -0.40$ ) (see Figure 7). Thus, teams in the non-display condition had a consistent tendency to over-accept statements as true, and thus held a much higher false alarm rate (see Figure 8). In comparison, participants in the team display condition had a relatively neutral response bias ( $\ln \beta = -0.09$ ), indicating that teams in the display condition employed a less biased strategy when responding to ambiguous probes.

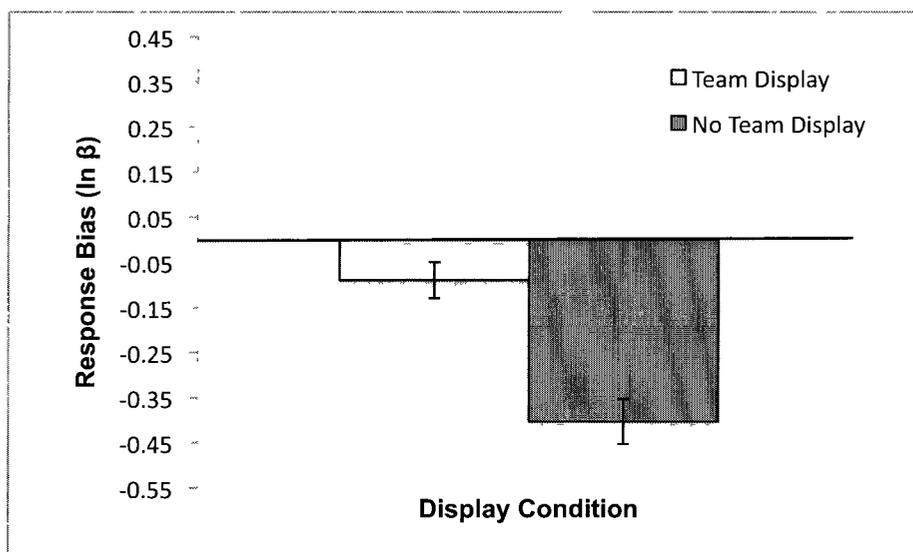


Figure 7. Mean SA probe Response Bias ( $\ln \beta$ ) across display and non-display conditions

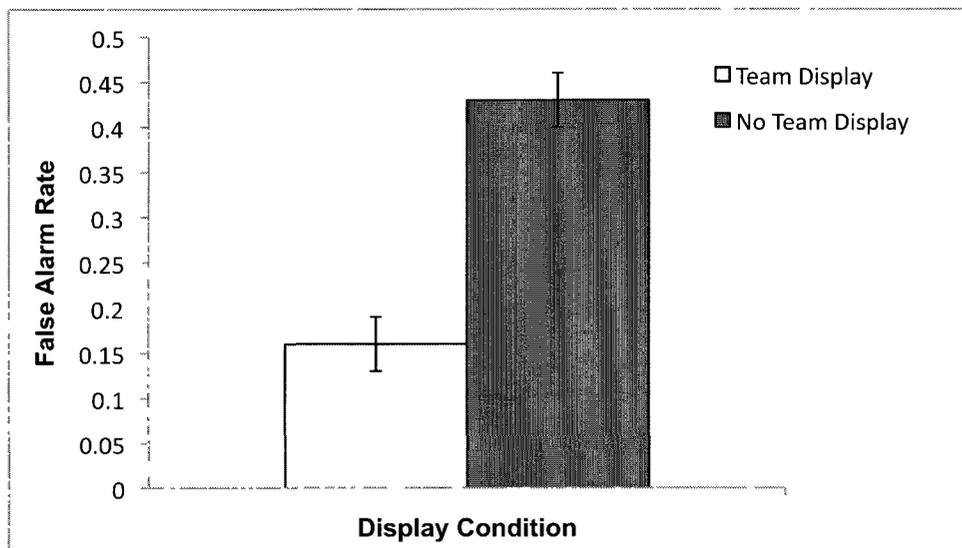


Figure 8. Mean SA probe False Alarm Rates across display and non-display conditions

Response biases scores were also examined as a function of high and low workload conditions, revealing comparable scores across conditions. Participants in both the high and low workload conditions displayed a liberal bias ( $\ln \beta = -0.31$  and  $\ln \beta = -0.22$ , respectively) (see Figure 9). These findings suggest that response bias may not have been impacted by the level of workload.

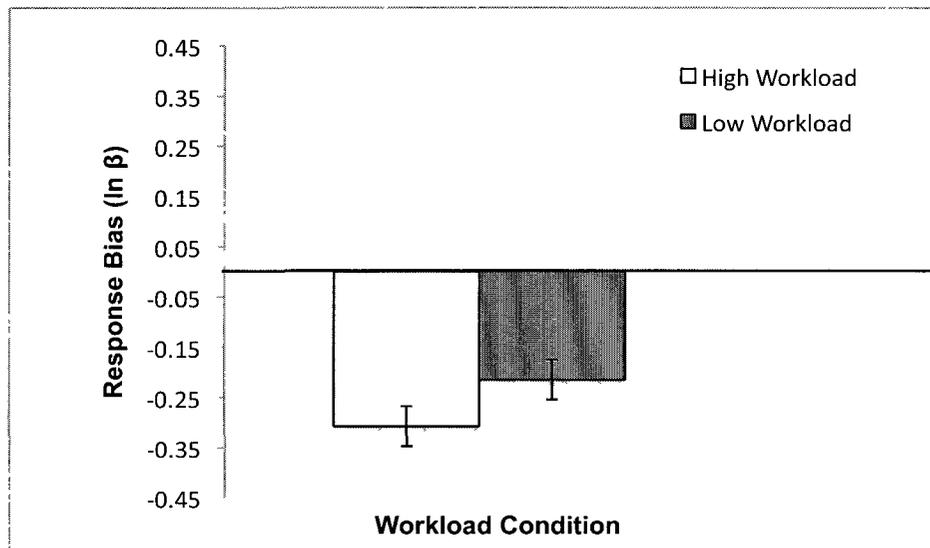


Figure 9. Mean SA probe Response Bias ( $\ln \beta$ ) across high and low workload conditions

*Calibration of SA.* The principle of calibration concerns the extent to which people are able to judge the correctness of their own observations or decisions. This metric helps to assess the degree of correspondence between self-perceptions of accuracy and actual accuracy (Koriat & Goldsmith, 1996). An individual can have a higher level of SA with the team display, yet if they are not confident in their perceptions then the benefit could be lost. The calibration statistic was used to investigate if the presence of a team-oriented display has an effect on participants' calibration. In order to interpret SA calibration, normalized confidence ratings were compared with QUASA SA probe responses according to methods outlined in Koriat and Goldsmith (1996). SA accuracy was quantified as the proportion of probes answered correctly (i.e. hits plus correct rejections) while perceived accuracy was obtained from self-ratings of confidence in individual probe responses. Typically, this information is then illustrated using a calibration plot (Keren, 1991). This graph consists of a visualization of confidence scores plotted against accuracy (proportion correct). A well-calibrated judge is one who is highly confident about those responses that are in fact correct and unconfident about those that are incorrect. Optimal

performance in a calibration graph is represented by a one to one ratio between confidence and accuracy; this is depicted by a line of optimal calibration in the graph. The results shown in Figure 10 revealed that when participants had access to the team-display they demonstrated a higher level of SA. However the display did not appear to affect participants' confidence in their own responses as perceived accuracy remained almost identical for both display conditions. This was verified using a paired sample t-test, which found no significant difference in confidence ratings between the team display ( $M = 32.58, SD = 7.13$ ) and non-team display conditions ( $M = 31.30, SD = 6.27$ ),  $t(29) = .81, ns$ .

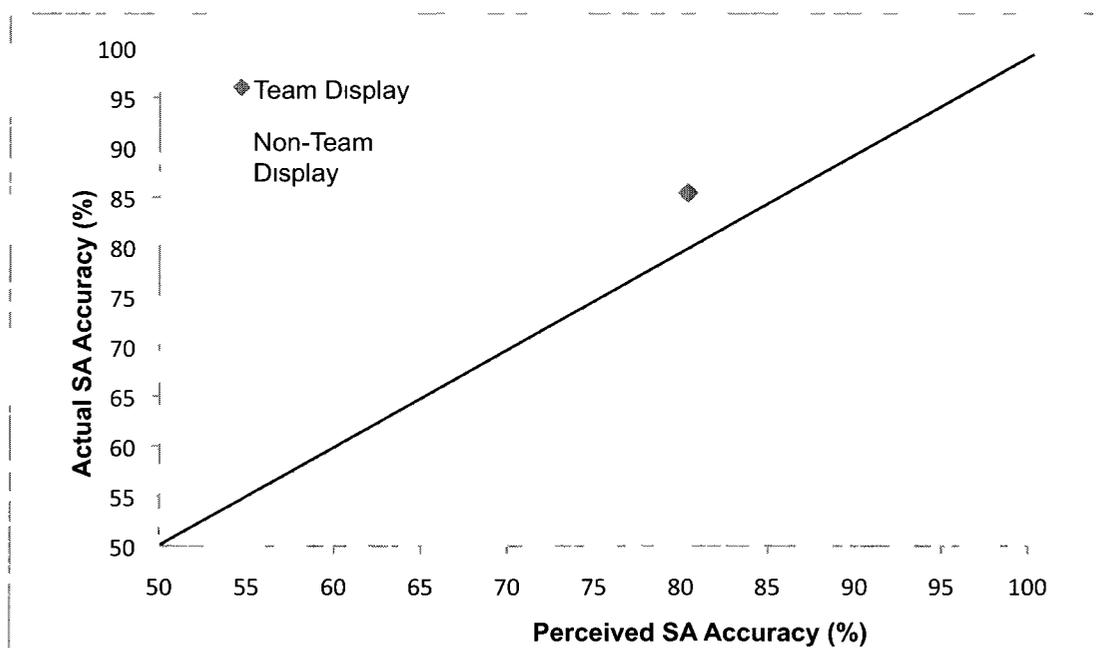


Figure 10 Calibration means of actual and perceived SA of participants with and without use of the team oriented display with best possible performance depicted by the line of optimal calibration.

## Communication Analysis

The analysis of team communication has been used by many to reflect team cognition and situation awareness (e.g., Cooke & Gorman, 2006; Hazlehurst, McMullen, & Gorman, 2007; Gorman, Cooke, Pederson, Connor, & DeJoode, 2005; Gorman, Cooke, & Winner, 2006; Parush et al., 2011; Fischer & Orasanu, 1999; Heath & Luff, 1991). Communication analysis was used here as an additional perspective on team performance and as another metric that can reflect the impact of team display on teamwork and situation awareness.

Conversation analysis was employed as the specific communication analysis approach and it guided the mapping and description of communication patterns between team members (Schegloff, 1987; Pomerantz & Fehr, 1997; Parush et al., 2009). The full protocols of human verbal communication during trials were segmented into utterances produced from each participant taking turns in the verbal interaction. The unit of analysis was each utterance produced by each of the two members of the firefighting team. The sequence of utterances shown below is an example of a set of three utterances between the Fire Commander (FC) and the information officer (IO).

IO to FC: "There is a fire growing on the north side of the lake."

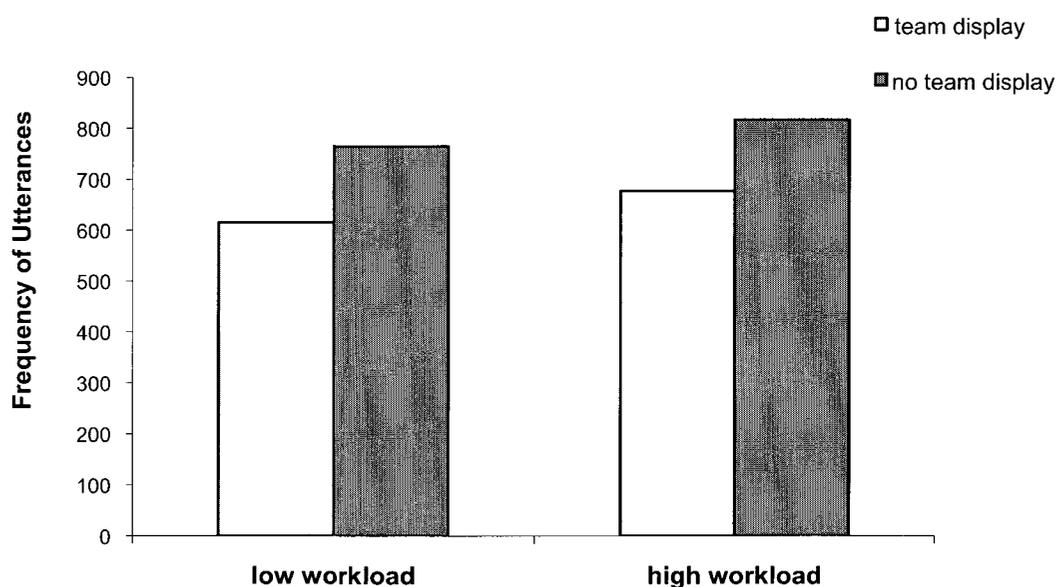
FC to IO: "Ok, I see it."

IO to FC: "...and the wind is blowing east pushing the fire towards the houses."

Utterances were chosen as the unit of analysis to reflect the volume of communication between participants. Utterances were chosen because by definition an utterance represents the basic unit of communication that can stand-alone and express something meaningful. The following analyses are primarily qualitative. Utterances are coded into categories that reveal

teamwork and situation awareness. In addition, the coded categories were also counted to provide general descriptive quantitative patterns.

In total, 2874 utterances were documented over the course of 104 simulation trials (31 teams x 4 scenarios each). Individual communication was first grouped into team communication, and then organized according to display type and workload. Figure 11 shows a comparison of the mean frequency of utterances for workload (high, low) and display type (team display, no team display).



*Figure 11.* Distribution of communication frequency as a function of display type and workload level (represented by mean frequency values)

Results show that when comparing the effects of display type, there was more communication without team display, 1582 utterances (55% of total utterances), compared to 1292 utterances (45% of total utterances) with team display. This suggests that the presence of the team display supported information gathering, which may have reduced the need for

participants to seek out information verbally from their teammate. Results also show that communication volume was higher for the high workload condition, 1494 utterances (52% of total utterances) compared to the low workload condition, 1380 utterances (48% of total utterances).

The effects of display types were further analyzed by organizing utterances according to 1) speech acts; 2) content of communication; and 3) SA based communication. The main variable of interest in this study was display factor; therefore the focus of the following analyses was communication as a function of display type. The analysis of workload will not be further discussed, however the analysis is presented in Appendix E.

*Speech acts.* Categories describing the speech act (i.e., purpose of communication) were based on conversation analysis adapted from Schegloff (1987) combined with categories that emerged through data coding. This method produced six high level communication categories: announcing, directing, coaching, seeking-information, confirmation, and planning. Such communication categories reflect team collaboration and coordination activities, and as such, can provide another perspective on the impact of team display. Table 4 summarizes each of these categories of communication types, each illustrated by an example.

Table 4

*Communication Categories and Examples of Coded Utterances*

Categories	Definition	Example
Announcing	Offering information	“there is a new fire developing”
Directing	Providing information	“go to the top left quadrant of

	pertaining to location and navigation	the landscape”
Coaching	Offering strategies and support	“You should send both helicopters to the high priority fire”
Seeking Information	One person requires information from another	“What is the closest water source to my fire truck?”
Confirmation	Giving feedback regarding specific information	“Ok I’ll deploy my all my helicopters to that location”
Planning	Sharing strategic information about the future	“Once you extinguish that fire, you might want to re-fill your water because it’s low”

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The frequency of communication categories was computed as a function of the display condition (see Figure 12). The most likely reason to communicate in both the team display and non-team display conditions was to make an announcement. Announcements accounted for 754 utterances during the non-team display condition and 583 utterances during the team display condition. The full count of communication frequency is presented in Appendix E. Another interesting finding was the frequency of Information Seeking utterances, which accounted for 137 utterances in the non-display condition, and only 57 utterances when the display was present. Announcements and Information Seeking are both speech acts that reflect the sharing of information; thus, both findings further support the expectation that a team-oriented display can support information gathering, which is a critical aspect in building and maintaining SA.

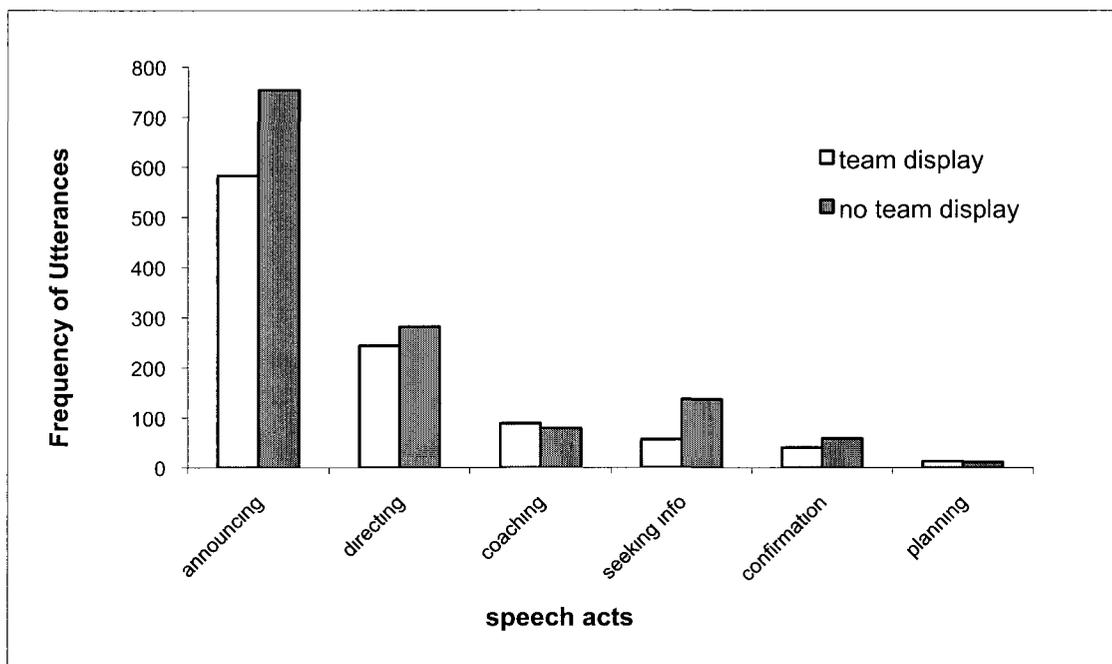


Figure 12. Distribution of high-level communication categories, with and without team display

*Content of communication.* The content of communication, the topic of each utterance, was coded into categories. Analysis of the content can provide insight to which information items are better covered by the team display and which are missing. Understanding this can help in the future in better designing such team displays. Eight content categories were identified and are summarized in Table 5.

Table 5

*Content Categories and Examples of Coded Utterances*

Content	Description	Examples
New fire	Presence of a new fire in the landscape	“I want to confirm that there is a new fire developing”
Wind	The wind is changing or will soon	“prepare for a wind change from

	change	North to West”
Location	Communicating location based information	“The fire in the North-East of the landscape is growing fast”
Firefighting Action	Current action/task being undertaken	“I’m sending my truck to the new fire”
Fire behaviour	Stating/predicting the changes in fire behaviour	“the wind is changing, the fire is going to start blowing into the human populated area”
Firefighting Strategy	Discussing techniques used to extinguish fires	“ignore the fire in the trees, and send all your fire vehicles to the high priority fire in the top right”
Fire status update	Sharing current state	“There are four separate fires burning at the moment”
False alert	Citing a false alert	“I thought it was a new fire, but it was a false alert”

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Utterance content was assessed as a function of display type in order to map patterns of teamwork and communication throughout the firefighting trials. Figure 13 presents an analysis of content categories by display condition. The two most frequent communication topics were regarding “new fires” (team display= 23%, no team display= 26% of utterances) and “location of fires” (team display= 29%, no team display= 32% of utterances). This suggests that the greatest amount of information being communicated was situation related, dealing specifically with the presence and location of fires. Again, the team display appears to have supported information gathering and sharing, thus reducing the need for verbal communication. The full count of communication frequency is available in Appendix E.

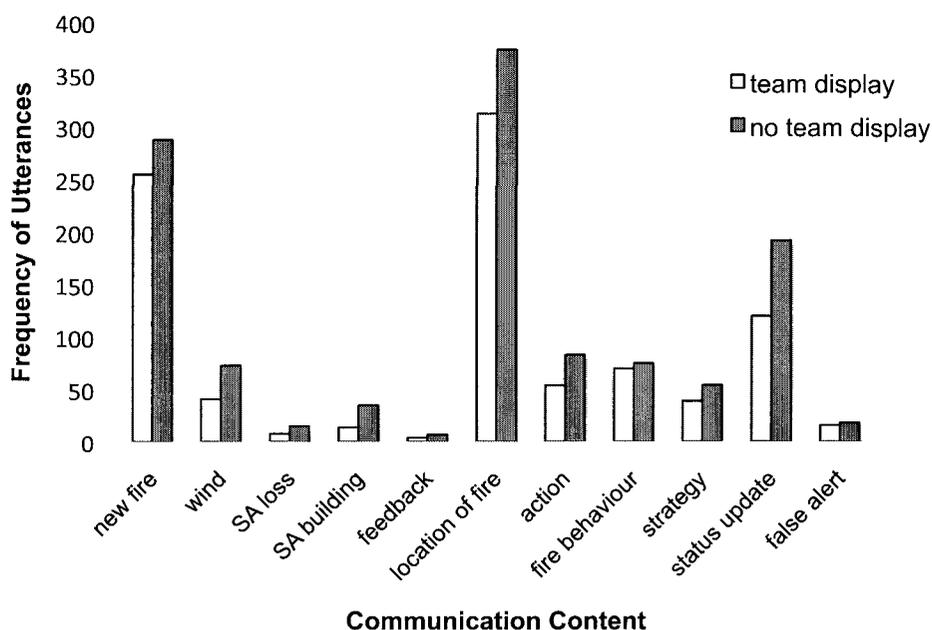


Figure 13. Distribution of content categories with and without team display

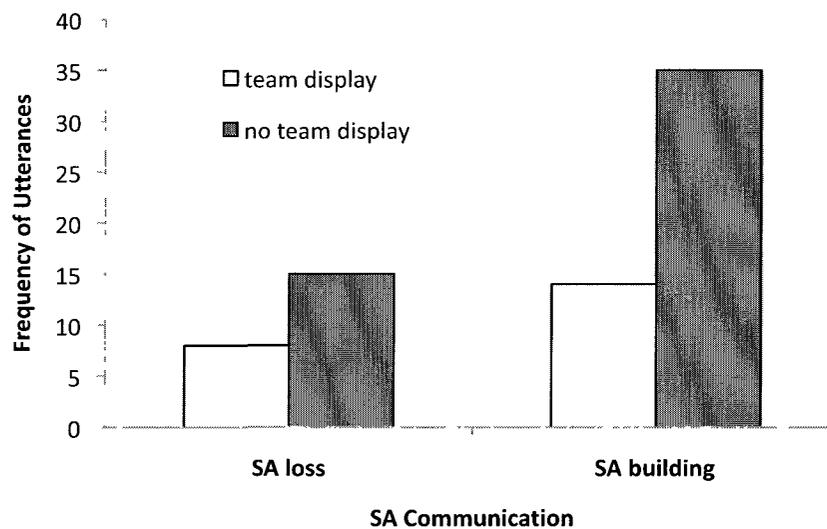
*SA-related communication.* Communication content specifically related to SA was also coded into distinct categories. The two categories were SA building and SA loss. Table 6 presents the definition along with an example for each of these two categories.

Table 6

*Situation Awareness Communication Content*

Content	Description	Examples
SA/TSA loss	Expression reflecting not knowing what is going on	“I don’t know where my fire truck went”
SA/TSA building	Sharing information to build awareness of what is going on	“I currently have four helicopters and I have situated them in each of the four quadrants”

Figure 14 presents the frequency of the two SA-related communication categories by display condition. It can be seen that there was a difference between the display and non-display groups when comparing the amount of SA building related communication, with more communication occurring in the non-team display condition than in the display condition. The figure also revealed that there were smaller differences between groups regarding SA loss. This may suggest that the team display is more effective for building SA, but is less effective in supporting the recovery of lost SA.



*Figure 14.* Distribution of situation awareness content by display and non-display conditions

### Discussion

The goal of this research was to evaluate the effectiveness of a team-oriented display intended to assist individuals in achieving a high level of situation awareness when involved in collaborative monitoring and decision making tasks. Three separate variables - situation

awareness, team performance, and team communication – were evaluated in simulated forest fire-fighting command-and-control scenarios, both with and without the presence of a team-oriented display. The results from this study indicate that the use of a team-oriented display can significantly improve situation awareness and team communication. This first portion of this section summarizes the main findings of this thesis, and presents implications of these findings for the research on team oriented displays and teamwork in high-risk organizations. This is followed by an outline of the limitations of the experiment and a description of the potential for future research in this field.

### **Situation Awareness**

Situation awareness was evaluated in this study through the triangulation of several related measurements. Accuracy of SA probe responses, sensitivity scores ( $d'$ ), and SA response bias all helped to identify that overall SA was better when team members had the support of the team-oriented display. Participants scored significantly higher in situation awareness probe accuracy with the aid of a team display compared to when the team display was absent. Participants also displayed greater SA sensitivity ( $d'$ ) in the presence of the team display, demonstrating that they were able to better discriminate the difference between actual SA signals and non-SA signals. Finally, a neutral response bias score in the presence of a team display demonstrated an ability to make SA related decisions without any type of preconception or skew, which was not the case when the team display was not available. As a whole these findings support the hypothesis that a team oriented display can in fact act as an aid in improving situation awareness in teams.

Furthermore, the aforementioned benefits of the team SA display were even more evident when participants had to deal with a higher workload environment; these results provide support

for the hypothesis that a team-display can be more effective as an aid to teams working in high stress situations, this relationship will be further discussed later.

### **Team performance**

Performance scores were directly recorded through the Networked Fire Chief simulation, and were intended as an indirect measure of SA. While performance scores did vary as a function of workload, they did not vary as a function of the presence or absence of the team oriented display. This was an unexpected yet plausible finding as previous research has provided mixed results with regards to the impact of a team-oriented display on performance scores. Several studies (e.g., Pritchett et al., 1996; Rusnica et al., 1999) have supported the hypothesis that a team display could significantly impact performance in a variety of team-based tasks, while others have given evidence to the contrary (Bolstad & Endsley, 1999; Bolstad & Endsley, 2000)

One factor that should be taken into consideration was the presence of a learning effect. More specifically, it was found that performance in the first experimental scenario was significantly lower compared to the second, third, and fourth, regardless of the experimental condition, suggesting that participants were still learning the task and had not yet achieved a baseline level of performance. Although participants spent a significant amount of time training the experimental task, anecdotal observations support the hypothesis that team coordination and communication may require additional time to develop. This is an important consideration for future research. Further investigation also revealed an interaction between the experimental order and workload condition, and between experimental order and the display condition. In both cases it was revealed that participants performed more poorly when presented with a more challenging task in their first scenario, for example a high workload scenario, or a non-team display scenario.

Again, this suggests that participants had a difficult time adjusting to the experimental task, and when faced with a steeper learning curve (such as a high workload scenario) they performed more poorly. This should also be an important consideration for future research in this field.

Another factor that could contribute to the lack of significant performance findings is that the team-oriented task in the firefighting scenario did not create an environment that resulted in a large number of errors and did not generate numerous opportunities for miscommunication. Therefore SA may not have been challenged enough to impact performance scores. This is a noteworthy finding as it could provide insight into the relationship between situation awareness and performance, which is not yet clearly understood (Endsley, 1995). The relationship between SA and performance is discussed next.

### **Situation Awareness and Performance**

Situation awareness is generally depicted as an individual's internal model of the state of an environment as defined by their perception, comprehension, and projection (Endsley, 1995). Based on this representation, individuals can make decisions about what to do within a specific situation and carry out any related or necessary actions. Situation awareness therefore is represented as the main precursor to decision making (Adams et al., 1995; Smith & Hancock, 1994). It should be noted however, that many other factors also come into play in turning good situation awareness into successful performance.

As this study has demonstrated, it is possible to attain a high level of SA with little to no direct impact on performance. For example, a Fire Commander may understand where a fire is and the characteristics of that fire, yet select a poor or inappropriate strategy to extinguish it. In this situation there are several factors that could have influenced this individual. He or she may have had inadequate strategies or tactics guiding the decision-making processes, or may have

been limited in decision choices due to organizational or technical constraints. Alternatively, he or she may have lacked the experience or training to have good, well-developed plans of action for the situation. Individual personality factors (such as impulsiveness, indecisiveness or riskiness) may also have made some individuals prone to poor decisions. A study of human error in aircraft accidents found that 26.6% involved situations where there was poor decision making even though the aircrew appeared to have adequate situation awareness for the decision (Endsley, 1995). Conversely, it is also possible to make good decisions even with poor SA, if only by luck.

One of the most important findings that can be derived from this study is the relationship between SA and performance. In the past, it has often been assumed that a positive relationship between SA and performance exists. However this study provides evidence to the contrary; the relationship between SA and performance continues to be debated (Endsley, 2000). Good SA should increase the probability of good decisions and good performance, but does not guarantee it and vice versa. Poor SA increases the probability of poor performance, but in many cases does not create a serious error. For instance, being disoriented in an aircraft is more likely to lead to an accident when flying at low altitude than when flying at high altitude. The lack of consistency of relationship between SA and performance in the literature (Bolstad & Endsley, 1999; Midkiff & Hansman, 1993; Pritchett & Hansman, 1997) indicates that performance is only an indirect measure of individual and team SA.

The probabilistic link between SA and performance raises an important question: how much SA is enough? As identified by Pew (1991), no criteria exist that establishes the level of SA required for successful performance. This is a complex issue; it can be asserted that SA is seen as a factor that increases the probability of good performance but that it does not necessarily

guarantee it, as other factors also come into effect (e.g. decision making, workload, performance execution, system capabilities, and SA of team members). The amount of SA that an individual needs, therefore, becomes a matter of how much probability of error is acceptable within a given task. Moving forward, future design would benefit from the establishment of guidelines in order to have new system design on the basis of SA.

### **SA and Workload**

Varying workload levels was aimed to facilitate understanding how workload impacts SA and performance. Overall, performance scores were significantly lower in the high workload condition. This was an expected result as the manipulation of workload was the number of fires present in the landscape; the increased number of fires was associated with poorer performance. In addition, higher workload levels were associated with lower SA accuracy (as reflected in overall correct responses to SA probes) and in the lower sensitivity (as measure by  $d'$ ). Finally, as workload level increased, the amount of communication between team members also increased.

One of the important implications to arise from this research is the relationship between SA and workload. The nature of these two constructs is still unclear: some researchers have assumed that this relationship is a direct negative correlation, with an increase in workload resulting in reduced SA (Taylor, 1990). Others investigated whether there are circumstances in which the relationship between these two constructs varies (Bolstad, 2001). Wickens (2008) hypothesized that SA and workload diverge due to several factors such as system design, interface design, and the individual operator. For example, if an individual is exerting effort to attain SA as well as perform a task, and if the demands exceed their limited capacity, only then will a decrement in SA be expected. Endsley (1993) attempts to articulate this relationship by demonstrating

independence between these two constructs across a range of values, predicting that the following four circumstances may exist:

- 1) “Low SA with Low Workload: The operator may have little idea of what is going on and is not actively working to find out because of inattentiveness, vigilance problems, or low motivation.
- 2) Low SA with High Workload: If the volume of information and number of tasks are too great, SA may suffer because the operator can attend to only a subset of information or may be actively working to achieve SA, yet has erroneous or incomplete perception and integration of information
- 3) High SA with Low Workload: The required information can be presented in a manner that is easy to process (an ideal state).
- 4) High SA with High Workload: The operator is working hard but is successful in achieving an accurate and complete picture of the situation” (p. 906).

The nature of these two constructs remains an empirical question, and Endsley (1993) appears to have been the first to systematically address this issue. This research experiment created scenarios similar to the four aforementioned settings, as participants faced both high and low workload scenarios and demonstrated varying levels of SA as mediated by the presence or absence of the team-oriented display. Findings supported the hypothesis by Wickens (2008) that SA and workload are divergent constructs and, more importantly, they demonstrated that interface elements such as a team-oriented display can play an important role in moderating the negative impact of high workload on SA.

A reasonable expectation is that team members would be forced to focus more on their individual tasks and thus would decrease their communication. However, it was found that as

workload level increased, the amount of communication between team members also increased. This finding indicates that team members communicated at an increased rate and the act of communicating with their teammate during this more highly cognitively demanding task may have competed for the limited mental resource of the individuals, leading to less attention to, and less accurate knowledge of the firefighting task. This finding was reflected in SA scores, as participants displayed significantly lower situation awareness when dealing with the high workload scenarios. It was also found that although SA was consistently lower during high workload scenarios, the difference between SA during high workload and low workload was diminished with the presence of a team display. This indicates that the display reduced the negative impact of high workload on TSA.

### **Communication patterns**

The evaluation of communication between team members provided additional insights into the role of a team-oriented display. In general, there were different communication patterns in the presence of the team display as compared with its absence. Overall, team members communicated less when a team-oriented display was present while still maintaining a high level of performance and TSA. This finding implies that the presence of a team display may have induced a shift from direct verbal communications to more implicit coordination. This is an important finding as it suggests that team members were able to extract vital information through the use of the team display, as an alternative to verbally communicating with their partner.

Furthermore, the absence of a team display revealed a difference in the type of communication exchanged: team members spent more time sharing information by making announcements and requesting specific information from their team member (seeking information). These types of communication represent Level 1 situation awareness (perception,

getting the information). The decrease of these types of communication in the presence of a team display suggests that the display enabled team members to extract needed information from the display. It is reasonable to speculate that this could leave the lines of communication open to discuss the meaning and implications of the information (reflecting higher levels of situation awareness, comprehension and projection). This speculation still needs to be studied as such a higher level of communication related to comprehension and projection was not observed directly during the presence of the team display. Lines of communication that are not completely devoted to only information sharing would be important in instances of errors, breakdowns, or unexpected events, where more urgent communication would be required and the need to discuss implications and collaborative thinking ahead becomes critical. These findings have considerable real world repercussions, which will be further discussed in the next *practical implications* section.

### **Practical Implications**

This study yielded two important practical implications. The first is the impact that a team-oriented display can have on teamwork and SA, particularly in high-risk organizations. The second is the replicable methodology identified as an effective method of testing and measuring SA.

The finding that both communication and situation awareness can be significantly enhanced through the introduction of a team display in command-and-control environments highlights the benefits of team displays in high reliability organizations such as fire fighting command centers, nuclear power plants, and hospital operating rooms. These important findings imply that methods of helping team members build and maintain high levels of situation awareness can potentially reduce error and alleviate challenges faced by high reliability

organizations. These methods may include technological aids such as team displays, or alternatively, means such as the development of communication protocols.

A team-oriented display is not necessarily meant to replace human communication; rather it is meant to function as support and backup for potential communication breakdowns. Many concepts and technologies are currently being developed to enhance SA (Endlsey, 2001; Zhang et al., 2002; Kaber et al., 2000), and these new technologies have the potential to facilitate communication and coordination across distributed organizations. However, if not carefully designed, they may disrupt existing strategies for building and maintaining the common ground that is critical to coordinating work and ensuring effective teamwork.

It is also imperative that research targets the evaluation of and effectiveness of collaborative technology such as team displays. Without this it will be impossible to tell if a proposed concept actually helps SA, does not affect it, or inadvertently compromises it in some way. To this point research in this area has generally been very context specific and difficult to replicate. This study has provided a replicable evaluation framework using freely available software to assess the situational awareness of multidisciplinary teams.

An important implication of this study is the multi-faceted approach implemented to assess SA: the triangulation of several SA measurements, performance scores, and communication analysis provided a far more rich depiction of teamwork and coordination than any single measure of SA could have. This is critical, as one of the factors that continue to limit situation awareness research is the inability to effectively measure it with consistency. The ability to objectively measure SA is critical for future progress in this field. It provides a means of evaluating the efficacy of design concepts and technologies, provides diagnostic data for design iteration, and supports the evaluation and development of training concepts. It also

provides a means of researching the SA construct, investigating the impact of various factors in SA, and explicitly testing hypotheses concerning SA. Without this capability, no real progress in the area of SA design or theory can be made.

While the microworld task created for this study was simplified in nature, as with previous research (e.g., Berggren et al., 2008; Artman, 1997, Valentine et al., 2007), it has proven to be a beneficial tool in evaluating teamwork in a controlled setting. The use of the NFC microworld helped demonstrate that when members of a team are dependent on each other for successful performance, a team-oriented display can play a significant role in supporting team communication and in building situation awareness.

The relationship between high workload levels and low SA creates a unique design challenge. Although past research has identified an apparent relationship between these constructs (Hendy, 1995; Parasuraman et al., 2008), it has also become clear that other underlying factors also play a role, for example: stress (Fracker, 1987), teamwork (Cooke & Gorman, 2006), and decision making (Endsley, 1997). This distinct relationship should encourage designers to carefully consider the potential impact of SA augmenting aids on both workload and SA. Future experiments should always employ techniques for measuring both workload and situation awareness to identify the intricacies of this connection. In some cases, as observed here, workload and situation awareness may trade off. This is particularly important as, if new information is presented with the intention of increasing situation awareness, it may require additional processing and therefore increase workload. If a tradeoff relationship exists, this increased workload may counterproductively decrease situation awareness.

### **Limitations of study**

Due to the overall scope of this study, certain limitations were foreseeable. One limitation was that, in order to maintain consistency, all participants were paired with team members who they had not previously met. Although this practice ensured a consistent baseline across the sample, it does not necessarily reflect a real-world scenario in which team members typically have a previously established relationship with each other. Unfamiliarity with team members appears to have also affected the measurement of performance. A significant learning effect was found, indicating that participants continued to improve across trials regardless of which condition they were in. Anecdotal observations revealed the improvement to be linked with the building of rapport and strategy between team members. Therefore, this finding may simply be a consequence of strangers working together as a team for the first time.

Another limitation was the fact that teams consisted of only two individuals. This limits the generalizability of findings to only pairs of teammates, and thus may have restricted the scope of findings; however, given the limited practicality of testing larger groups from the undergraduate participant pool, this was a necessary constraint. Finally, it should also be taken into consideration that participants consisted of undergraduate students drawn from the Carleton participant pool; thus their knowledge and skills may differ significantly from those of professional forest fire fighters, again limiting the generalizability of findings.

## **Future work**

The promising results of this study suggest that more elaborate and expansive research in this field is warranted. Based on findings from this study there are several elements that should be further investigated.

One of the most important findings in this study is the apparent lack of relationship between SA and performance. Future work could prove fundamental in identifying the role of situation awareness in HRO's by investigating how unexpected events and interruptions impact performance and by testing if improved SA can help support team performance during potentially error inducing events.

It is also recommended that future work incorporate more complex scenarios that require more detailed team-based strategies to achieve higher performance levels. However, it is cautioned that when incorporating such complex scenarios, teams are given time to not only learn how to complete their task, but are also given time to coordinate team-strategies and communication.

Overall, it is hoped that this study will stimulate new conceptual development in this field. More research is required on how and when to assess SA and new training strategies for both SA and TSA should be designed, developed, and evaluated. Collectively, these efforts will enhance our understanding of situation awareness and team performance in general.

Furthermore, the prototyping and simulation of new technologies, new displays and new SA concepts is extremely important for evaluating the actual effects of proposed concepts; if SA is to be a design objective, then it is important that it be critically evaluated throughout the design process.

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**Appendix A**

**Task Analysis – Information Breakdown**

Task/event	Info required	Info displayed		Info via comm./team display		SA Prob (abbreviated)	
		Info officer	Fire command	Info Officer	Fire Command	Info officer	Fire command
Appearance of new fire	<ul style="list-style-type: none"> <li>• Fire location</li> <li>• Number of fires</li> <li>• Size of fires</li> <li>• Which appliances are where</li> <li>• Wind conditions</li> <li>• Access to fire location</li> </ul>	<ul style="list-style-type: none"> <li>• Loc of search planes</li> <li>• Wind conditions</li> <li>• Forecasted wind</li> </ul>	<ul style="list-style-type: none"> <li>• Loc of fire fighting vehicles</li> <li>• Wind conditions</li> <li>• Forecasted wind</li> <li>• Water in tanks</li> <li>• Fire warnings</li> </ul>	<ul style="list-style-type: none"> <li>• Heli loc</li> <li>• Heli status</li> <li>• Truck loc</li> <li>• Truck status</li> </ul>	<ul style="list-style-type: none"> <li>• Fire loc</li> <li>• Type of landscape burnt</li> <li>• Priority of fire</li> </ul>	<ul style="list-style-type: none"> <li>• Does the fire warning represent a real fire?</li> <li>• Where are the helis?</li> <li>• Where are the trucks?</li> <li>• Are helis/ trucks occupied?</li> <li>• Are helis/ trucks planned to arrive at the new fire loc?</li> <li>• Do helis/trucks have sufficient water?</li> </ul>	<ul style="list-style-type: none"> <li>• Where is the fire?</li> <li>• What type of landscape is being burnt?</li> <li>• Is the fire accessible to trucks?</li> <li>• Is the new fire high priority?</li> <li>• Which route to take to the fire?</li> </ul>
Navigate vehicle	<ul style="list-style-type: none"> <li>• Status of vehicle</li> <li>• Location of vehicle</li> <li>• Future location</li> </ul>	<ul style="list-style-type: none"> <li>• Loc of fires</li> <li>• Loc of search planes</li> <li>• Wind conditions</li> <li>• Forecasted wind</li> </ul>	<ul style="list-style-type: none"> <li>• Truck loc</li> <li>• Heli loc</li> <li>• Wind conditions</li> <li>• Forecasted wind</li> </ul>	<ul style="list-style-type: none"> <li>• Heli loc</li> <li>• Heli status</li> <li>• Truck loc</li> <li>• Truck status</li> <li>• Future location of fire crew</li> </ul>	<ul style="list-style-type: none"> <li>• Search plane loc</li> </ul>	<ul style="list-style-type: none"> <li>• Where is the heli/ truck?</li> <li>• What is the heli/ truck current action?</li> </ul>	<ul style="list-style-type: none"> <li>• Where is the search plane?</li> <li>• What is the plane's current action?</li> </ul>

Prioritization of fires	<ul style="list-style-type: none"> <li>• Location of fires</li> <li>• Number of fires</li> <li>• Proximity of fires to high priority land</li> <li>• Status/ availability of fire crew</li> </ul>	<ul style="list-style-type: none"> <li>• Loc of fires</li> <li>• Number of fires</li> <li>• Fire proximity to priority land</li> <li>• Fire warnings</li> </ul>	<ul style="list-style-type: none"> <li>• Status/ availability of fire crew</li> </ul>	<ul style="list-style-type: none"> <li>• Status/ location of fire crew</li> </ul>	<ul style="list-style-type: none"> <li>• Location of fires</li> <li>• Number of fires</li> <li>• Fire proximity to priority land</li> </ul>	<ul style="list-style-type: none"> <li>• Where are the trucks /helis?</li> <li>• What are their current actions?</li> <li>• Are any fires high priority?</li> <li>• Are they being attended?</li> <li>• Is the wind likely to change the priority of fires?</li> </ul>	<ul style="list-style-type: none"> <li>• How many fires?</li> <li>• Where are the fires?</li> <li>• Are any fires high priority?</li> <li>• Is the wind likely to change fire priority?</li> </ul>
Wind condition change	<ul style="list-style-type: none"> <li>• Current wind conditions</li> <li>• Forecasted wind conditions</li> </ul>	<ul style="list-style-type: none"> <li>• Current wind</li> <li>• Forecasted wind</li> </ul>	<ul style="list-style-type: none"> <li>• Current wind</li> <li>• Forecasted wind</li> </ul>			<ul style="list-style-type: none"> <li>• What is the current wind direction?</li> <li>• Forecasted wind condition?</li> <li>• How will wind change affect fire?</li> </ul>	<ul style="list-style-type: none"> <li>• Current wind condition?</li> <li>• Forecasted wind condition?</li> <li>• How will wind change affect fire?</li> </ul>
Fire climbs to high elevation	<ul style="list-style-type: none"> <li>• Size/location of fire</li> <li>• Current and forecasted wind</li> <li>• Location of helicopters</li> </ul>	<ul style="list-style-type: none"> <li>• Location/ size of fire</li> <li>• Current and forecasted wind</li> </ul>	<ul style="list-style-type: none"> <li>• Current and forecasted wind</li> </ul>	<ul style="list-style-type: none"> <li>• Location of heli</li> <li>• Status of heli</li> </ul>	<ul style="list-style-type: none"> <li>• Location of fire</li> <li>• Size of fire</li> <li>• Directions to efficiently navigate to fire</li> </ul>	<ul style="list-style-type: none"> <li>• Location of heli?</li> <li>• What is the status of heli?</li> </ul>	<ul style="list-style-type: none"> <li>• Location of high elevation fire?</li> </ul>
Appearance of high intensity fire	<ul style="list-style-type: none"> <li>• Size/location of fire</li> <li>• Availability of fire trucks</li> <li>• Priority of fire</li> </ul>	<ul style="list-style-type: none"> <li>• Loc of fire</li> <li>• Fire proximity to priority land</li> </ul>	<ul style="list-style-type: none"> <li>• Status/ availability of fire-fighting trucks (only vehicles that can extinguish high intensity fire)</li> </ul>	<ul style="list-style-type: none"> <li>• Location of fire trucks</li> <li>• Status + availability of fire truck</li> </ul>	<ul style="list-style-type: none"> <li>• Location of fire</li> <li>• Prioritization of fire fighting based on location</li> </ul>	<ul style="list-style-type: none"> <li>• Are there fire trucks available to fight high intensity fire?</li> <li>• Is this a priority fire?</li> <li>• Location of fire?</li> <li>• Is team member</li> </ul>	<ul style="list-style-type: none"> <li>• Location of high intensity fire?</li> <li>• Is a fire truck available?</li> <li>• Is this a priority fire?</li> <li>• Where is the</li> </ul>

						aware of fire?	nearest fire truck?
Obstruction present in landscape	<ul style="list-style-type: none"> <li>• Location of obstruction</li> <li>• Size of obstruction</li> <li>• Routes to avoid obstruction</li> </ul>	<ul style="list-style-type: none"> <li>• Location + size of obstruction</li> <li>• Routes to avoid obstruction</li> </ul>	<ul style="list-style-type: none"> <li>• Limited view of obstruction</li> </ul>	<ul style="list-style-type: none"> <li>• Location of firefighting vehicles in relation to obstruction</li> </ul>	<ul style="list-style-type: none"> <li>• Full view of location and size of obstruction</li> <li>• Navigational routes around obstruction</li> </ul>	<ul style="list-style-type: none"> <li>• Location of obstruction?</li> <li>• If fire is at ____ location, will you need to inform teammate about an obstruction?</li> </ul>	<ul style="list-style-type: none"> <li>• Location of obstruction?</li> <li>• If a fire is located in ____ location, will your route be blocked?</li> <li>• To get to ____ fire what route will you take?</li> </ul>
Re-fill fuel tanks (search planes only)	<ul style="list-style-type: none"> <li>• Fuel levels of each of your vehicles</li> <li>• Actions of each vehicle</li> <li>• Availability of fuel station</li> </ul>	<ul style="list-style-type: none"> <li>• Fuel levels of search planes</li> <li>• Availability of fuel station</li> </ul>			<ul style="list-style-type: none"> <li>• Current actions of search planes</li> </ul>	<ul style="list-style-type: none"> <li>• Is your vehicle currently in need of re-filling? (less than 20% fuel)</li> <li>• Is there an unoccupied fuel station?</li> </ul>	<ul style="list-style-type: none"> <li>• Is teammate occupied re-filling fuel?</li> </ul>
Re-fill water tanks (fire crew only)	<ul style="list-style-type: none"> <li>• Water levels of each of your vehicles</li> <li>• Actions of each vehicle</li> <li>• Availability of water source</li> </ul>		<ul style="list-style-type: none"> <li>• Water levels of fire crew vehicles</li> <li>• Availability of water source</li> </ul>	<ul style="list-style-type: none"> <li>• Current actions of fire crew vehicles</li> </ul>		<ul style="list-style-type: none"> <li>• Is teammate occupied re-filling fuel?</li> </ul>	<ul style="list-style-type: none"> <li>• Is your vehicle currently in need of re-filling? (less than 20% water)</li> <li>• Is there an unoccupied water source?</li> </ul>

<p>Team member actions</p>	<ul style="list-style-type: none"> <li>• Status of teammate</li> <li>• Current actions of teammate</li> <li>• Prioritization of teammates goals/actions</li> </ul>	<ul style="list-style-type: none"> <li>•</li> </ul>	<ul style="list-style-type: none"> <li>•</li> </ul>	<ul style="list-style-type: none"> <li>• Current actions of fire crew commander</li> <li>• Location of fire vehicles</li> <li>• Current task drawing teammates attention</li> </ul>	<ul style="list-style-type: none"> <li>• Current actions of Info officer</li> <li>• Location of search planes</li> <li>• Current task drawing teammates attention</li> </ul>	<ul style="list-style-type: none"> <li>• What is your teammate currently doing?</li> <li>• Is your teammate occupied?</li> <li>• Is there attention needed for a higher priority?</li> </ul>	<ul style="list-style-type: none"> <li>• What is your teammate currently doing?</li> <li>• Is your teammate occupied?</li> <li>• Is there attention needed for a higher priority?</li> </ul>
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## Appendix B

### DEMOGRAPHIC QUESTIONNAIRE

#### Background Information

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What is your age? \_\_\_\_\_

What is your sex?

- Male
- Female

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 them?

- I have never met them before
- I have met them before, but we are not well acquainted
- I am well acquainted with my teammate

### Experience with Technology

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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?

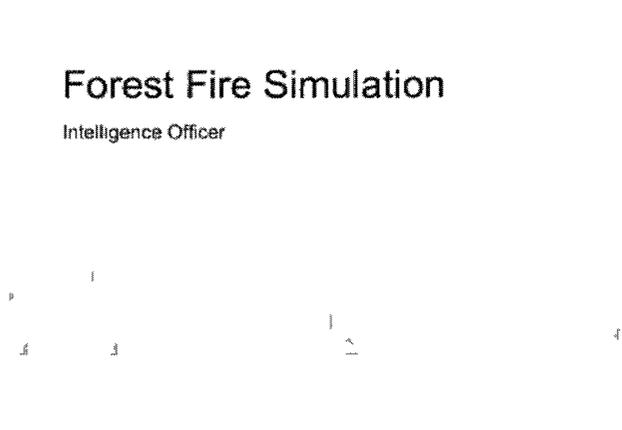
- Several times a day
- Once a day
- Several times a week
- Once a week
- Once/twice a month
- Every few months
- Once/twice a year
- Never

How often do you play video games on a video game console (i.e. 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

## Appendix C

### Power Point training slides



#### Scenario:

The town of Kelowna, British Columbia has been dealing with a series of forest fires over the past few weeks. These fires occur quite frequently and have the capability to spread uncontrollably.

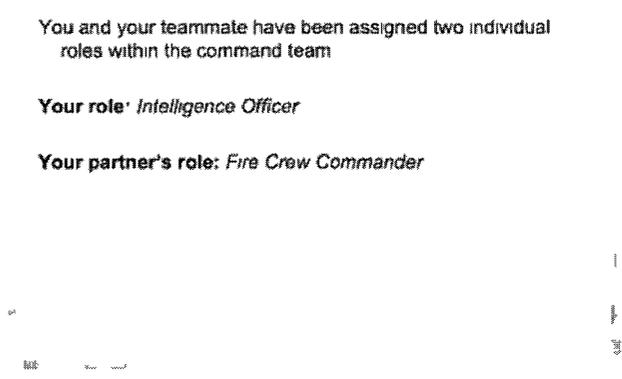
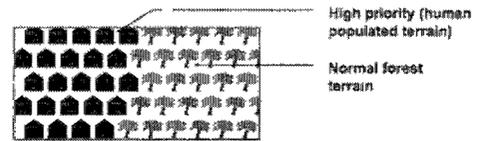
#### Your role:

Several forest firefighting units from surrounding areas have been called in to help fight wildfires. In an effort to enhance team coordination, you and your colleague have been brought in as team leaders.

Your job, along with your partner, will be to orchestrate the firefighting efforts by overseeing all operations from this command and control center, and by controlling firefighting equipment (search-planes, trucks & helicopters).

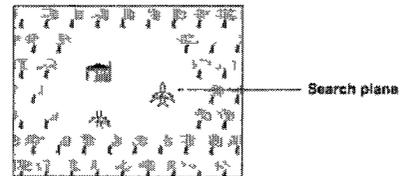
#### Your goal:

To extinguish all fires while leaving the least amount of damage to the terrain. You must also pay specific attention to protect areas with human populations (indicated by houses on the simulation map).



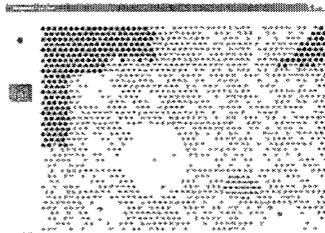
#### Intelligence Officer

It is your job as an Intelligence Officer to fly search planes across the landscape in search of new fires.



### Intelligence Officer

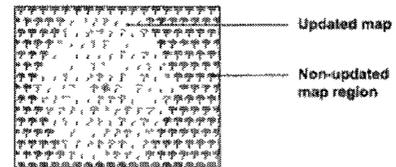
Your workstation will look like this:



\* Note that you can not see your partners firefighting vehicles on your workstation display

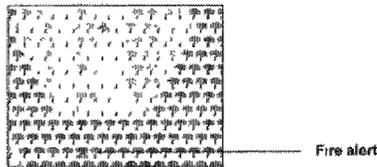
### Workstation Map

The information available about the size, location, and severity of fires is not constantly updated on the simulator map. Therefore only a limited area on the map (within a small radius of your search plane) will show up-to-date information.



### Intelligence Officer

You will be alerted to the possible location of new fires through visual fire alerts. These will pop up and flash on the map. These alerts may or may not indicate the location of a new fire, but should always be investigated.



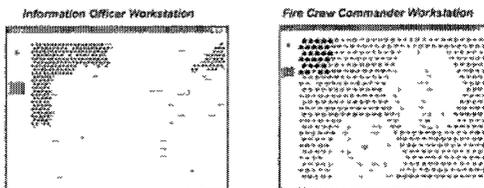
### Fire Crew Commander

Your partner (Fire Crew Commander) will be responsible for taking the information you give him/her and deploying the fire crew to extinguish these fires.



### Fire Crew Commander

Keep in mind that your partner does not see the same information as you and will have a much more limited idea of what is going on across the entire landscape. Thus it is your responsibility to keep them informed



### Coordination

You and your teammate will need to communicate throughout the simulation about:

- the location of fires
- changes in fires due to wind change

*\*It is recommended that you practice a communication strategy with your teammate during the training session.*

# Forest Fire Simulation

Fire Crew Commander

## Scenario

The town of Kelowna, British Columbia has been dealing with a series of forest fires over the past few weeks. These fires occur quite frequently and have the capability to spread uncontrollably.

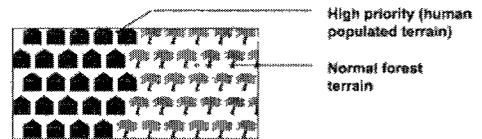
### Your role:

Several forest firefighting units from surrounding areas have been called in to help fight wildfires. In an effort to enhance team coordination, you and your colleague have been brought in as team leaders.

Your job, along with your partner, will be to orchestrate the firefighting efforts by overseeing all operations from this command and control center, and by controlling firefighting equipment (search-planes, trucks & helicopters).

### Your goal:

Your goal is to extinguish all fires while leaving the least amount of damage to the terrain. You must also pay special attention to protect areas with human populations (indicated by houses on the simulation map).



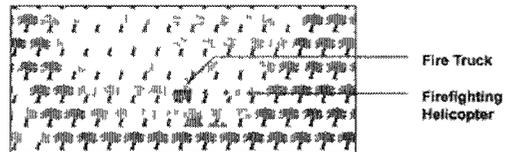
You and your teammate have been assigned two individual roles within the command team.

**Your role:** *Fire Crew Commander*

**Your partner's role:** *Intelligence Officer*

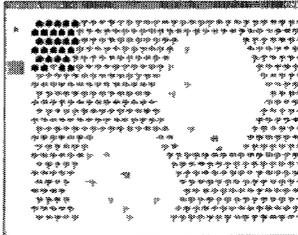
## Fire Crew Commander

As Fire Crew Commander you are in charge of the navigation and command of firefighting trucks and helicopters.



### Fire Crew Commander

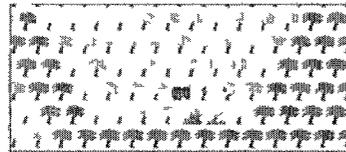
Your workstation will look like this



\* Note that you can not see your partners search planes on your workstation display

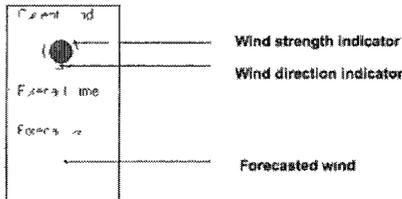
### Fire Crew Commander

It will be your job to receive information about the location of fires from your teammate and act to suppress these fires by deploying firefighting vehicles



### Wind

It will be critical to monitor wind conditions to predict how the fires will change Both current, and forecasted wind conditions will be displayed at your workstation



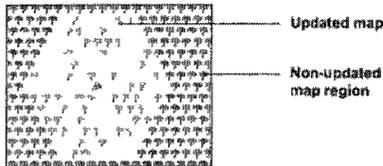
### Water

You will also be responsible for monitoring the water levels in the tanks of your vehicles When they are running low you will need to direct vehicles to a water source to re-fill

### Workstation Map

Only a limited area on the map (a small radius around your vehicles) will show updated information (such as new fires)

Your partner (Intelligence Officer) will control search planes which have a much larger updated area surrounding their vehicles which will help him/her search for fires



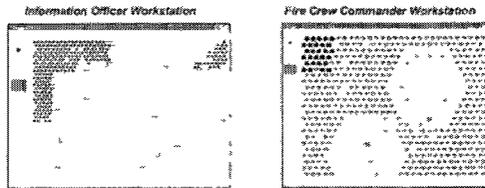
### Intelligence Officer

Your partner (Intelligence Officer) will receive alerts on their map indicating the locations of new fires

He/she will be responsible for keeping you informed about new fires and will also support you in deciding which fires to fight (choosing the ones of highest priority) when there are too many for you to fight at once

## Intelligence Officer

Keep in mind that your partner does not see the same information as you and will have a broader view of what is going on across the entire landscape. Thus you will depend on them for information.



## Coordination

You and your teammate will need to communicate throughout the simulation about:

- the location of fires
- changes in fires due to wind change

*\*It is recommended that you practice a communication strategy with your teammate during the training session*

## Coordination - Team Display

During half of the simulations you will have access to a large team display which will provide a more overall view of the landscape and situation

-See team display mounted on wall in front of you-

**\*On this display ALL vehicles are viewable**

## You're ready to start training!

Remember, as **Fire Crew Commander**, your responsibilities are:

- Receive information from the Intelligence Officer about the location of fires and direct vehicles to these locations to fight the fires
- Monitor changes in wind conditions
- Tell vehicles where and when to refill water
- **Overall goal:** Protect the landscape, with EXTRA attention to protecting human populated areas

## Appendix D

QUASA probes

### SA Level 1—Perception of firefighting situation

*Info Commander*

- . What is the current water level for the \_\_\_\_\_ (identifying colour) search plane?
- . Is there a fire burning in the indicated location?
- . How many of your vehicles are currently occupied (flying/searching)?
- . Is there a firefighting vehicle in the indicated location?
- . Are there currently \_\_\_\_\_# of fires burning in the landscape?
- . What is the current direction of the wind?
- . What is the forecasted (future) wind direction?
- . Are all firefighting vehicles currently occupied (moving/firefighting)?
- . Is a human populated area currently on fire?
- . What is the current action of the \_\_\_\_\_ (identifying colour) search plane?
- . What is the current action of the \_\_\_\_\_ (identifying colour) firefighting vehicle?

*Fire Commander*

- . How many of your vehicles are currently occupied (moving/firefighting)?
- . Is there a search plane in the indicated location?
- . Are there currently \_\_\_\_\_# of fires burning in the landscape?
- . What is the current direction of the wind?
- . What is the forecasting (future) wind direction?
- . Are all search planes currently occupied (flying/searching)?

- . Is a human populated area currently on fire?
- . What is the current action of the \_\_\_\_\_ (identifying colour) firefighting vehicle?
- . What is the current action of the \_\_\_\_\_ (identifying colour) search plane?

### **SA Level 2/3—Comprehension and projection of firefighting situation**

#### *Info Commander*

- . Which fire is currently highest priority?
- . What direction are the fires spreading?
- . Which fire will threaten a human populated area if they stay on their current (wind directed) course?
- . Which fire will threaten a human populated area if the wind changes, and starts blowing \_\_\_\_\_ (direction)?
- . Which fire will be highest priority once the wind changes to the forecasted direction?
- . What is the planned destination of the \_\_\_\_\_ (identifying colour) search plane?
- . What is the planned destination of the \_\_\_\_\_ (identifying colour) firefighting vehicle?
- . What percentage of fire alerts are false alarms?

#### *Fire Commander*

- . Which of your fire fighting vehicles will run out of water soonest?
- . What direction are the fires spreading?
- . Which fire is currently highest priority?
- . Which fire will threaten a human populated area if they stay on their current (wind directed) course?

. Which fire will threaten a human populated area if the wind changes, and starts blowing \_\_\_\_\_ (direction)?

. Which fire will be highest priority once the wind changes to the forecasted direction?

. What is the planned destination of the \_\_\_\_\_ (identifying colour) firefighting vehicle?

. What is the planned destination of the \_\_\_\_\_ (identifying colour) search plane?

## Appendix E

### Communication Frequencies

*The Frequencies of Each of the Speech Act Categories as a Function of the Display Condition*

---

Types of Communication	Display	
	No team display	Team display
Announcement	754	583
Directing	282	263
Coaching	89	69
Seeking info	127	77
Confirmation	59	41
Planning	11	13

---

*The Frequencies of Each of the Speech Act Categories as a Function of the Workload  
Condition*

---

Types of Communication	Workload	
	High	Low
Announcement	682	655

Directing	290	236
Coaching	78	80
Seeking info	107	97
Confirmation	63	37
Planning	8	16

---

*The Frequencies of Each of the Communication Content Categories as a Function of the Display Condition*

---

Types of Communication	Display	
	No team display	Team display
New fire	288	255 (1)
Wind	73	41 (1)
Location	374	313
Firefighting	83	54
Action		
Fire behaviour	75	70
Firefighting	54	39
Strategy		

Fire status	192	120
update		
False alert	18	16

---

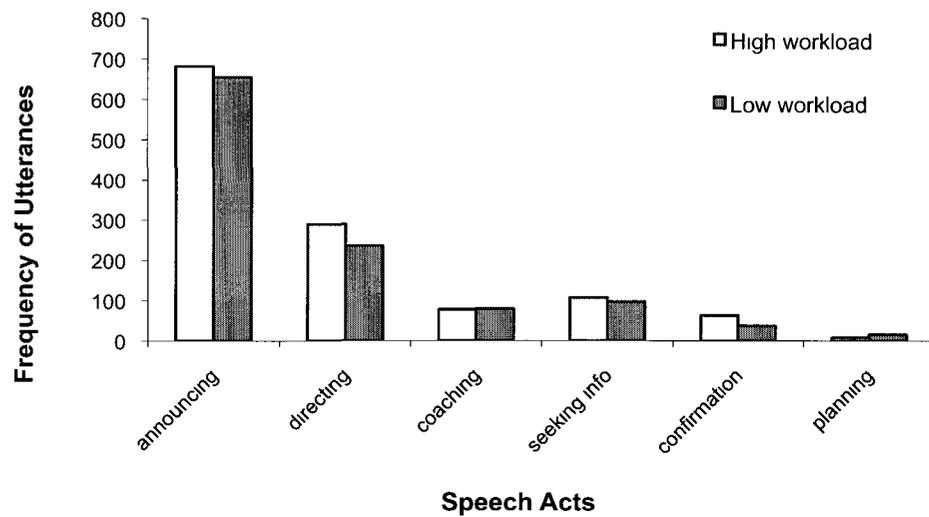
*The Frequencies of Each of the Communication Content Categories as a Function of the Workload Condition*

---

Types of	Workload	
	High	Low
Communication		
New fire	307	236
Wind	51	63
Firefighting	392	295
Action		
Fire behaviour	70.0	67
Firefighting	69	76
Strategy		
Fire status update	46	47
False alert	138	174
New fire	15	19

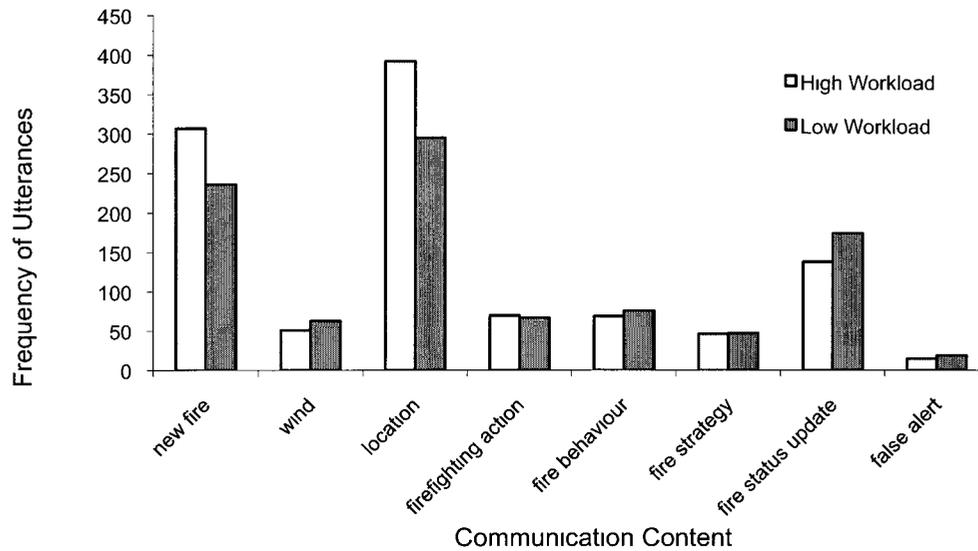
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*Distribution of high-level communication categories across high and low workload conditions*



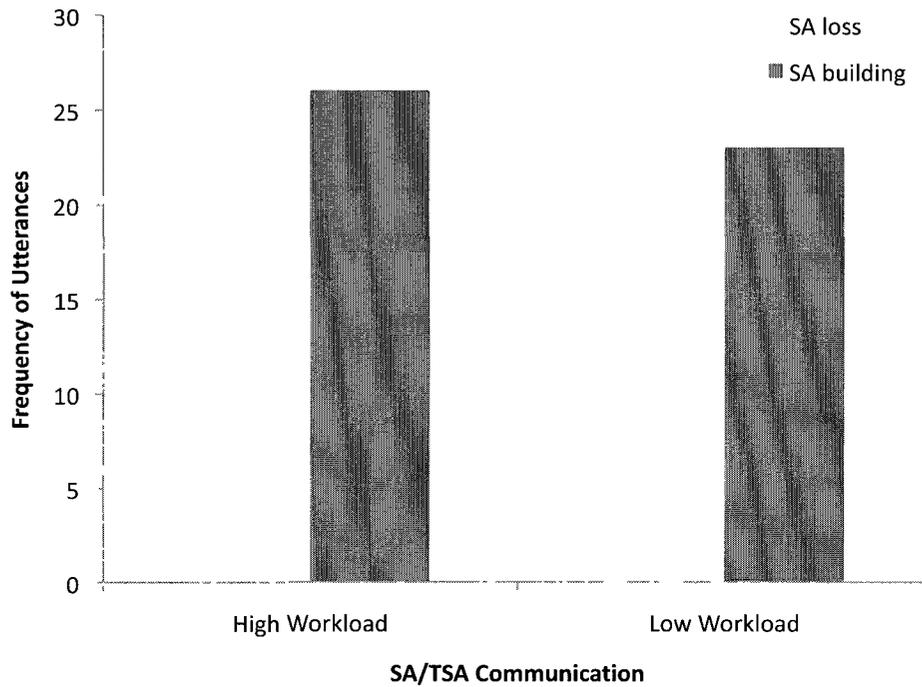
The most likely reason to communicate in both the high workload and low workload conditions was to make an announcement, which accounted for approximately 55% of all utterances during high workload trials and 52% during low workload trials.

*Distribution of content categories across high and low workload conditions*



The two most frequent communication topics were regarding new fires (high workload= 26%, low workload= 22% of total utterances) and location of fires (high= 33%, low= 28% of total utterances).

*Distribution of situation awareness content across high and low workload conditions*



The preceding graph presents an analysis of SA and TSA communication content by workload condition. The revealing minimal difference between the high and low workload groups for either SA building related communication, and only small differences for communication regarding SA loss.