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Information Distribution in Complex Systems to Improve Team Performance

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13. ABSTRACT *(Maximum 200 words)*
This study investigates the distribution of information sources within a team's environment. Specifically, this study hypothesizes that providing task specific information to individual team members will improve coordination and decision-making, and therefore team performance, at time-critical tasks. Major themes addressed in this research include teams and team processes, mental models, team mental models, work domain analysis, and hierarchical task analysis. Furthermore, the theory behind the development of complementary models is introduced.

The findings are presented of two experiments examining the effects of imposing different information distribution strategies that range from no complementariness to full complementariness of information. Team communication, team and individual task performance, workload, and timeliness and effectiveness of team decision making were assessed in nominal and off-nominal conditions. The first experiment used a fixed base automobile-driving simulator, while the second experiment used a UH-60 Black Hawk full motion helicopter flight simulator.

The results of these experiments provide empirical evidence that providing task relevant information to individual team members in a time-critical environment, while limiting their access to non-relevant information, improves individual and team performance. The findings of this research provide new insights into how the distribution of information among team members effects the development of mental models and information requirements, team and individual performance, and communications, and highlight several directions for future research.

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Introduction

Although complementary mental models may be a distinction novel to this thesis, the proposal that shared mental models exist is not. Extensive research has been conducted in this area. There also has been significant related work outlining cognitive constructs at the team level such as distributed cognition (Hutchins, 1991), team decision making, shared mental models, and team situation awareness (Cannon-Bowers, Salas, and Converse, 1993; Cooke et al., in press; Orasanu, 1990; Stout, Cannon-Bowers, and Salas, 1996). While this literature review focuses on the development of team mental models, some of the concepts discussed overlap with the theoretical constructs listed above.

Military significance

Crew coordination and team performance are extremely important to military small teams and their missions. Obtaining measurements of these constructs within participant samples is essential for better understanding of the components of both crew coordination and team performance, yet to date measures have mostly been of a subjective nature. Enhanced study of the roles of team members during team tasks and emergency procedures will add greatly to our knowledge about team performance and its relationship to information-sharing strategies.

Background and literature review

What are teams?

"Teams are more than just a gathering of persons pursuing their own goals, and teamwork is more than just the aggregate of individual team member's behaviors" (Paris, Salas, and Cannon-Bowers, 2000).

Even a cursory review of the literature available on teams reveals that no single definition of a team has been universally accepted (LaJoie and Sterling, 1999). Then what is a team? Salas gives a generally accepted definition of a team as a collection of (two or more) individuals working together interdependently to achieve a common goal (Salas et al., 1992). For the purpose of clarity, in this research a team is further defined as a small number of cognitive agents, each with defined roles and responsibilities, task relevant knowledge and common goals. Their task requires more than one information source and interdependence and coordination among members (Orasanu and Salas, 1993; Paris, Salas, and Cannon-Bowers, 2000). Although this research effort focuses on the interactions between two team members in close proximity conducting a task that requires continuous coordination, it is important to note that the structure of a team may vary from highly structured interdependent teams to teams whose members interact little and perform tasks in the same location (Salas et al., 1992).

One of the most important characteristics of a team that is identified in nearly all definitions is the existence of common goals. Common goals are crucial to successful teamwork; they help bind a team together, instill a vested interest in each other's performance, and reduce self-centered actions. Furthermore, realizing team goals contributes to a team's mutual awareness of not only the goals, but also other information requirements such as team member roles, team structure and task structure (what information is required for each task). Along with other characteristics of "good" team performance, teams must maintain an on-going dialogue to continuously exchange these information requirements. This mutual awareness is described as a team "shared mental model" (Rouse, Cannon-Bowers, and Salas, 1992; Cannon-Bowers, Salas, and Converse, 1993). Consequently, the development of shared mental models among team members is a common goal of training programs in order to increase performance (Volpe et al., 1996; Cannon-Bowers et al., 1998), but has not been a focus of system design. For example, Volpe et al. (1996) looked at the effect of cross training on team process and performance. They found that cross training improved team member's inter-positional knowledge and team performance. This increase in performance was theorized to be related to an improved team shared mental model (Volpe et al., 1996).

Small groups are also considered in this review. Groups differ from teams in that they may not have specific roles and can be loosely assembled without a common goal or shared history (McIntyre and Salas, 1995). Klimoski and Mohammed identified another distinction between teams and groups: "groups are collections of individuals whose tenure together and division or responsibilities can vary considerably …a team consists of differentiated and interdependent members. All teams are groups, but the converse is not necessarily so." (Klimoski and Mohammed, 1994). There is a gray area between groups and teams in which the military commonly operates. During many military operations, and likewise, a condition present during experimentation in this thesis, although roles are specified and the crew shares common goals, crew composition may be improvised for a specific mission; this ad hoc collection of people may sometimes operate as a team and sometimes as a small group.

Mental models

An aspect of groups and teams that directly affects group processes is the compatibility of teams' mental models. Therefore, it is important to discuss what mental models are, how they are developed, and finally what is shared in a shared mental model that individuals hold about their team, task, etc. This section focuses on the topic of mental models in terms of individual members and shared representations within a team.

"Mental models are the mechanisms whereby humans are able to generate descriptions of system purpose and form explanations of system functioning and observed system states, and predictions (or expectations) of future system states" (Rouse and Morris, 1986). Essentially, mental models are organized knowledge structures that allow individuals to interact with their environment. A mental model is a type of knowledge representation or structure that individuals possess concerning their interaction with the world (Norman, 1983). Specifically, mental models allow people to describe, explain and predict the behavior of the world around them (see Figure 1), to recognize and remember relationships among components of the environment, and to construct expectations for what is likely to occur next (Orasanu, 1993; Rouse, Cannon-Bowers, and Salas, 1992; Rouse and Morris, 1986). This implies that a specific mental model of a system state may be sufficient or even advanced for one function (e.g., describing) yet inadequate for another (e.g., predicting). The mental model construct also has been used as a means to evaluate the nature of an operator's knowledge of complex system performance, and as a basis to analyze effective and ineffective performance. Gentner and Stevens (1983) and

Rumelhart and Ortony (as cited in Smith-Jentsch et al., 1998) indicated that mental models also guide team members' interactions with others.

Research cited in the previous paragraph suggests that different individuals may possess different yet accurate mental models. Accurate mental models give an individual the ability to

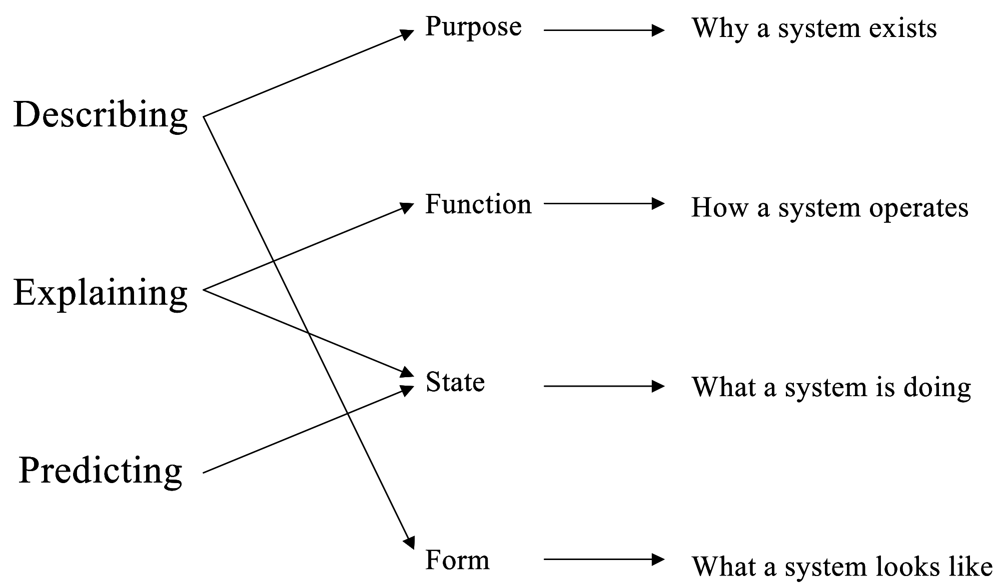


Figure 1. Nature of mental models (Rouse, Cannon-Bowers, and Salas, 1992).

retrieve information relevant to a task quicker than if they possessed an inaccurate model. More simply, individuals with an accurate mental model will be more likely to correctly interpret and respond to a situation that confronts them (Stout, Salas, and Fowlkes, 1997). Mental models may contain various types and levels of information. For instance, Jonassen and Tessmer (1996) say that mental models contain information concerning declarative knowledge, conditional knowledge, procedural skills, and functions. Rouse, Cannon-Bowers, and Salas (1992) comment on the dimension of knowledge. They assert that the level of knowledge within the mental model construct can range from detailed, specific, or concrete to global, general, or abstract (Rouse, Cannon-Bowers, and Salas, 1992).

The knowledge structure of individual mental models includes an equipment model, task model, team interaction model, and team model (Rouse, Cannon-Bowers, and Salas, 1992; Cannon-Bowers, Salas, and Converse, 1993):

- Equipment knowledge relates to equipment functioning, limitations, operating procedures, and likely failures.
- Task knowledge considers task procedures, strategies, contingencies and scenarios, and environmental constraints.
- Team knowledge includes the following dimensions of teams: (1) a team interaction model incorporating roles and responsibilities, sources of information, patterns of interaction and communication, and interdependencies among members; and (2) a team model containing the knowledge, skills, abilities, and behavioral tendencies of team members.

Part of team knowledge consists of what each team member understands about teamwork. Although team members may have teamwork knowledge within a specific domain, (e.g., teamwork on a football team or an aircraft cockpit), it is likely that they will also acquire and develop a core teamwork knowledge structure that applies to most types of teams (Gibson and Zellmer, 1998). This might include communications, relationships, and so on (Salas et al., 1988). Core teamwork knowledge provides individuals with an understanding and a structure for working together as a team.

These four types of knowledge that form mental models can be viewed as reflecting two major content domains: (1) task-related features of the situation (e.g., the technology/equipment and job/task models), and (2) team-related aspects of the situation (e.g., the team interaction and team models). This division is consistent with the idea that teams develop two tracks of behavior: a teamwork track and a task-work track (Morgan et al., 1986; McIntyre and Salas, 1995; Mathieu et al., 2000).

The study of mental models places emphasis on the organization of information as it is stored in memory, not necessarily the amount of information (Johnson-Laird, 1983; Rouse and Morris, 1986). This organization of information as stored in an individual's memory is of great import to the study of teamwork. For example, Wegner (1987) described the idea of transactive memory systems, analogizing team information sharing as an expansion of personal memory through interdependence on team members. He explained that, just like all parts of an individual's recall system do not contain the same knowledge; neither does each member of a team. Yet, effective teams are aware of *who* possesses certain information (Wegner, 1987). Therefore, if team member's access to task critical information is focused on their roles and tasks, labels identifying "who knows what information" are naturally created.

Shared mental models

This study focuses on the processes involved in the acquisition, storage, transmission, and use of information for the purposes of improving team performance. Although acquisition, storage, transmission and use of information occurs independent of team affiliation to form an individual's mental model, the process is consistent with views in small group and team literature that consider intra-personal communication as a form of information processing (Gibson and Zellmer, 1998). This processing has been referred to as transactive memory, as described above (Wegner, 1987), team or shared mental models (Rouse, Cannon-Bowers, and Salas, 1992; Klimoski and Mohammed, 1994), distributed cognition (Hutchins and Klausen

1996), collective cognition (Gibson, 1996), and teamwork knowledge schemas (Rentsch, Heffner, and Duffy, 1994; Gibson and Zellmer, 1998). Upon examination, each of these terms fundamentally refers to the level of congruence of individual knowledge structures between members of a small group or team. This review will use the term "shared mental model" as the primary reference to this relationship between knowledge structures of team members.

Klimoske and Mohammed (1994) contended "there can be (and probably would be) multiple mental models co-existing among team members at a given point in time." As discussed in the previous section, these would include models of task (e.g., navigation), equipment (e.g., technology), teamwork, and interactions (e.g., communications). Teams with members that share similar knowledge structures regarding the task, the environment, equipment, member capabilities, and member interactions communicate more effectively and perform better than teams whose members do not share such knowledge (Klimoske and Mohammed 1994). According to Cannon-Bowers, Salas, and Converse (1993), complex tasks probably require that multiple mental models be shared among members. The concept of closely related mental models among team members has been offered as a means to explain coordinated performance in teams, especially in conditions of high workload (Cannon-Bowers, Salas, and Converse, 1993; Rouse, Cannon-Bowers, and Salas, 1992). The benefits of shared mental models are unmistakably evident when a team is conducting a complex task and/or operating in a complex environment. Shared mental models help team members form accurate expectations of the task and each other (Cannon-Bowers, Salas, and Converse, 1993; Espinosa et al., 2001; Klimoski and Mohamed, 1994; Rouse and Morris, 1986). Recent studies show that team performance at tasks requiring anticipation of team member's actions and information requirements is improved with enhanced shared mental models (Espinosa et al., 2001).

The notion of shared mental models in teams has received a considerable amount of attention in the literature in recent years. Shared mental models are thought to provide team members with a common understanding of who is responsible for what task and what the information requirements are and to allow team members to anticipate one another's needs so that they can work in sync and adjust their behavior accordingly (Smith-Jentsch, Johnston, and Payne, 1998). The shared-mental-model construct suggests that it is not only the overlap of knowledge among team members that is predictive of team outcomes but also the synergy of the knowledge organizations (Mathieu et al., 2000).

Forming a shared mental model of the team, the task, and the informational requirements of team members, serves as an important mechanism for achieving efficient communications and overall improved team performance (Stout et al., 1999). When team members share accurate mental models of the teamwork processes that influence their performance, they should be better able to uncover performance trends and diagnose deficiencies, focus their practice appropriately on specific goals, and generalize the lessons they learn to new situations. The link between shared mental models and team performance is evident in the literature. Numerous studies in the past decade have recently highlighted the positive relationship between congruent shared mental models and successful team performance (e.g., Smith-Jentsch, Johnston, and Payne, 1998; Blickensderfer, Cannon-Bowers, and Salas, 1994; Heffner, Mathieu, and Goodwin, 1995; Cannon-Bowers et al., 1995; Minionis, 1994; Volpe et al., 1996; Duffy, 1992; Converse, Cannon-Bowers, and Salas, 1991).

Shared mental models and communication

"Put simply, if team members know what to expect and can explain what they observe, team performance is likely to be enhanced" (Rouse, Cannon-Bowers, and Salas, 1992).

The importance of communication to team performance and the development of shared mental models cannot be overstated. Communication is more than an exchange of information, it is a means by which teams coordinate resources and activities (Entin and Serfaty, 1999), construct and maintain shared mental models (Orasanu, 1990), and establish and maintain situational awareness (Prince and Salas, 1993). There are three basic types of communication between team members; (1) verbal communication between crewmembers; (2) non-verbal communication between crewmembers (this could be hand signals, facial expressions, head movements etc.); and (3) written communication (this can occur on kneeboard spot reports, graphics on maps etc.) (Orlady and Orlady, 2002).

These types of communication are rarely mutually exclusive and commonly used together during operations in a complex environment and, when necessary, crews will find ways to communicate. For example, in an instance of "lost communications" between the front and back seat pilot of a tandem seated helicopter during a mission in Operation Desert Storm" (all radios were inoperative along with the internal communication system in an AH-1 Cobra attack helicopter), the gunner was reduced to writing messages with a grease pen on the canopy to the back seat pilot; to get the attention of the gunner the back seat pilot used a pointer to hit him on the head.

Explicit communication is easily observed. Through the use of voice data recorders, an analyst can review the dialogue of a crew while watching a computer-generated video of the aircraft and its critical flight data. Similarly, pilots can be video taped and audio taped in the cockpit of a simulator. There are various methods available to capture explicit communication. The difficulty arises in determining a taxonomy to determine what is "good or bad" communication and what is "improved or degraded" communication. Entin and Entin (2001) have had success in accurately capturing what communications occur among team members; through the use of a verbal communication matrix, they have developed a taxonomy by which improvement in communication might be measured in a crew environment (Figure 2).

Measure	Description
Overall Rate	
Total Communications	Total number of communications per minute
Communication Types	
Information Requests	Number of requests for information per minute
Information Transfers	Number of Information Transfers per minute
Action Requests	Number of Action Requests per minute
Action Transfers	Number of Action Transfers per minute
Coordination Requests	Number of Coordination Requests per minute
Coordination Transfers	Number of Coordination Transfers per minute
Acknowledgements	Number of non-substantive acknowledgements of receipt of communication per minute (e.g. "OK")
Communication Ratios	
Overall anticipation	All communication transfers divided by all communication requests
Information anticipation	Information transfers divided by information requests
Action anticipation	Action transfers divided by action requests

Figure 2. Communication taxonomy (Entin and Entin, 2001).

The level of team knowledge required to have shared mental models can be gained through familiarity with team members and the task at hand (Endsley, 1995; Wegner, 1987), but many situations typical to operations in a complex environment dictate that the team members and/or the task be novel and dynamic. This is the case with many civilian and military aircraft crews; they may not have personal knowledge of team members. Consequently, this team knowledge must be acquired through other means. Teams that operate in complex environments, such as military teams and emergency teams in high hazard industries, need shared mental models, which are based on team knowledge, if they are to operate successfully. The most effective teams seem to share their mental picture (or model) of the situation with other team members (Stout et al., 1999). These shared mental models help team members to anticipate the needs of others and this permits them to either provide assistance, as it is required, or to predict and pre-empt the need for assistance (Martin and Flin, 1997).

The communication literature (e.g., Johnston and Briggs, as cited in Stout and Salas, 1993) suggests interesting implications for the development of shared mental models in the use of efficient communication strategies. Providing information in advance appears to be particularly beneficial in situations characterized by increased workload. Considering that Johnston and Briggs (1968) theorized that communications are restricted in high-workload conditions, it appears that, in such cases, effective teams contain at least one member who continues to provide information so that others do not need to explicitly request it (as cited in Stout and Salas, 1993). In routine situations with highly defined roles and tasks, shared mental models enable a team to function efficiently with little or no explicit communication; this might occur in a performing arts crew or a baseball team (Orasanu, 1993). Adaptive team communication and coordination skills have their primary impact on the team's mutual mental models (Serfaty, Entin, and Johnston, 1998), and their effect is enhanced when a team is under stress and they are more likely to fail to consider critical information even when it is available to them (Orasanu, 1993).

Numerous studies support the concept that shared mental models may lead to more efficient and effective communication strategies (Cannon-Bowers, Salas, and Converse, 1993; Orasanu, 1990; Rouse, Cannon-Bowers, and Salas, 1992). The converse is also true, i.e., communication is important for the development and maintenance of shared mental models (Blickensderfer, Cannon-Bowers, and Salas, 1997; Gibson and Zellmer, 1998; Orasanu, 1990; Rentsch and Hall, 1994; Stout, Cannon-Bowers, and Salas, 1996). During explicit communication between team members, social cognition occurs and mental models develop. In the past, the term social cognition has referred to the content of individual cognitions regarding social behavior in interaction with other people. More recently, researchers are looking at a different type of social cognition in which the word "social" denotes how cognition is accomplished (Gibson and Zellmer, 1998). These explicit communications and interaction among team members serve a number of purposes: (1) helping bring problem-relevant information to light; (2) serving as a means of influencing the individual-level cognitive processes that take place within each group member (for example, by highlighting certain items of information group members can affect one another's perceptions, judgments, and opinions [Stasser and Davis, 1981]); and (3) serving as the vehicle by which group members' perceptions, judgments and opinions are combined to arrive at a single solution to a given problem (Gibson and Zellmer, 1998).

Three basic functions of communication are to share information, direct actions and reflect thoughts (Orasanu, 1993). Through these functions, communication fulfils two important purposes concerning the development and maintenance of shared mental models. First, during task execution, communication improves team mental models with contextual cues, which may result in more precise predictions of the team task (Stout, Cannon-Bowers, and Salas, 1996). Second, communication ensures that the team mental models are kept current with regard to changes that occur during task execution (Schraagen and Rasker, 2001). Team members must communicate in dynamic or novel situations; this aids team members in determining why a previous strategy may not have worked, developing new strategies, reacting to and anticipating environmental cues and predicting future states of the system (Orasanu, 1990; Schraagen and Rasker, 2001). In short, "explicit and efficient communication assures that all crew members share an understanding of the problem, strategies for coping with it, and who will do what tasks" (Orasanu, 1993).

Complementary mental models

Throughout the review of current literature concerning mental models presented above, it is clear that, although the expression "shared mental model" is commonly used throughout the literature, the term "shared" has multiple senses (Klimoski and Mohammed, 1994). To share can mean "to have in common" (as in share the equipment or share the belief), or it can mean, "to divide" (e.g., share the workload) (Cooke et al., 2000). Likewise, shared information can refer to either information that is homogeneous with respect to team members, or information that is distributed among team members (i.e., heterogeneous) (Cooke et al., 2000). Because of this confusion, Cooke et al. (2000) have refrained from using the term "shared" when they discuss team awareness and knowledge. “Team knowledge” is their preferred term because it does not imply the aspect of sharing that refers to holding in common. Within team knowledge are team mental models (a collective knowledge base of task and team-relevant information) and situational models which make use of team mental models, but also include situational characteristics and develop while engaged in the task (Hopp, Smith, and Hayne, 2002).

Previous empirical research does not support the view that effective teams have shared knowledge or shared mental models in the sense of common or identical knowledge. Instead, team members might hold compatible or complementary knowledge in addition to common knowledge (Cannon-Bowers and Salas, 1997; Klimoski and Mohammed, 1994). That is, there might be some knowledge overlap required among team members, but, in addition, role-specific yet compatible knowledge is required (Cooke et al, 2000). Cooke explains:

> A surgical team is an example of knowledge heterogeneity. In some instances, the nurse and the surgeon might need to have some knowledge that is held in common. However, the nurse probably won't be able to understand, and probably won't need to understand, all of the surgeon's knowledge. Hence the nurse must have some knowledge that is compatible with, but not necessarily identical to, the surgeon's knowledge (Cooke et al., 2000).

Accordingly, a certain degree of overlap in team mental models is preferred, whereas "completely overlapping team mental models are viewed as dysfunctional with regard to team performance" (Klimoski and Mohammed, 1994).

This study instead proposes that, to possess appropriate team knowledge, a team needs to develop “complementary mental models” of the information available for their individual and team tasks. Figure 3 represents the relationship between a team’s information base, task relevant information, shared information and complementary information. This is similar to Cooke’s description of types of knowledge (Cooke et al., 2000) but distinctively different in that this representation refers to the information available within a team’s domain and supports the development of complementary team mental models.

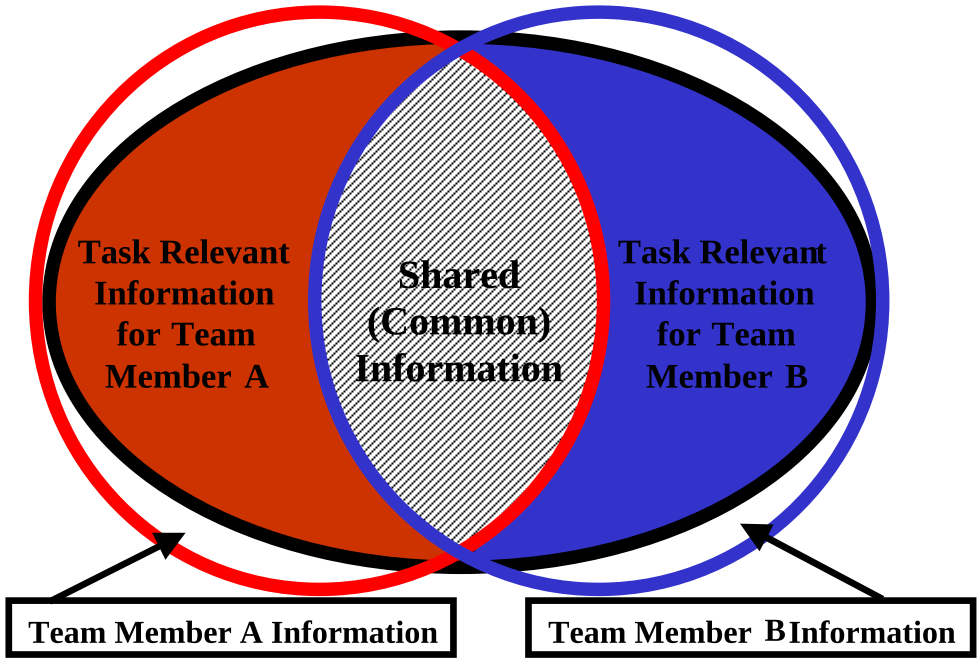


Figure 3. Information distribution for a complementary team mental model.

An aircraft crew is an example of a domain in which a complementary mental model is necessary. Assuming that pilots and copilot/navigators possess a similar knowledge base (i.e., training), in some instances, the pilot and the copilot/navigator might need to have some information that is held in common. However, the copilot/navigator probably won't need access to all of the information the pilot needs and vice-versa. Therefore the copilot/navigator must have some information that is complementary to, but not necessarily identical to, the pilot's information. Complementary team mental models are extremely beneficial in this type of domain where, although each team member fulfills an independent role on the team as well as an interdependent role as team member, these roles may switch during operations.

This study hypothesizes that providing each team member with the information relevant only to his/her tasks will assist in the establishment of complementary team mental models. A complementary team mental model is defined here as the condition in which:

- Each team member has the knowledge necessary to conduct his/her tasks.
- Each team member knows which information is available to the other team member should he/she need to seek it.
- Each team member knows which information is needed from them to other team members and when.

This study supports the concept of a "team centered" system design approach, focused on a complementary distribution of information among team members based on their tasks. This approach will naturally promote improved team coordination by aiding team members in developing a complementary team mental model. Complementary team mental models can be influenced by the distribution of knowledge between team members, the distribution of information in the environment, or a combination of the two (see Figure 4). The quadrants in Figure 4 represent the levels of knowledge and information distribution as described below:

- Quadrant I: Team member knowledge is distributed among team members. The information in the environment is common to all team members. Based on the division of knowledge, team members are more aware of their specific information requirements and can identify their required information sources in the environment more readily.
- Quadrant II: Team member knowledge is distributed among team members and the information in the environment is complementarily distributed. The distribution of information sources in the environment support the division of knowledge between team members, and performance is further enhanced.
- Quadrant III: Team knowledge and information are common to all team members. Team members must rely heavily on training, operating procedures, checklists and regulations to align information sources of the environment with individual tasks and team responsibilities.
- Quadrant IV: Team knowledge is common among members, yet the information in the environment is complementarily distributed between team members according to tasks and responsibilities.

This study proposes that complementary team mental models are enhanced in quadrants I,

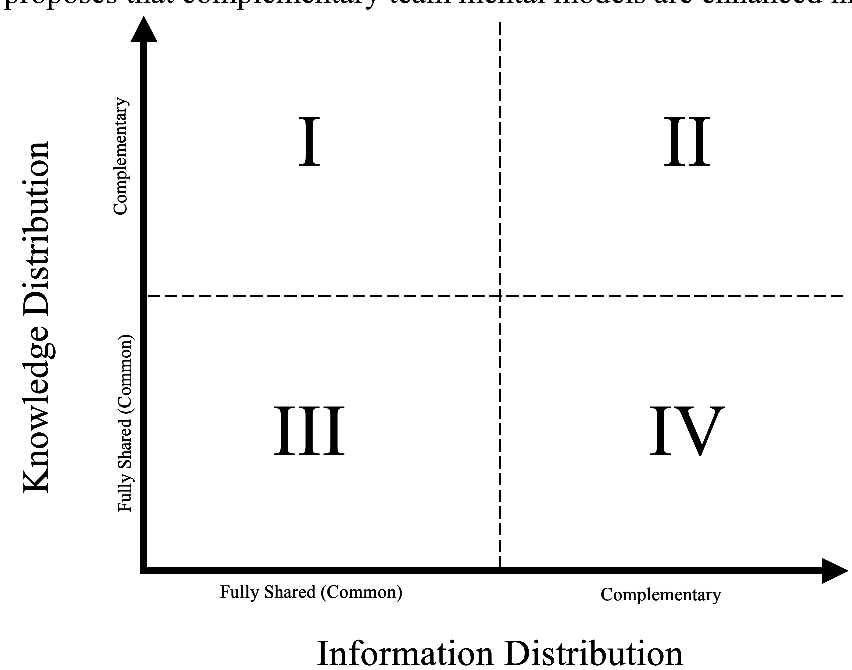


Figure 4: Knowledge distribution vs. information

II, and IV, while quadrant III is not conducive to team operations. Teams discussed in this study rarely possess fully distributed knowledge; generally there is a great amount of knowledge overlap between members.

Furthermore, the proposed method of distributing information among team members will provide individual crewmembers with a more accurate task relevant mental model of their environment. The formulation of complementary team mental models can improve team knowledge and team performance by streamlining team processes, helping to clarify roles and responsibilities, individual and team member information requirements, and improving the efficiency of explicit communications. All of the team models presented in this section result in the formulation of team knowledge; the level of this knowledge is manifested through team performance as shown in Figure 5. By efficiently designing the environment in which the team processes occur, communication, adaptiveness, and decision-making also should become more efficient.

Summary

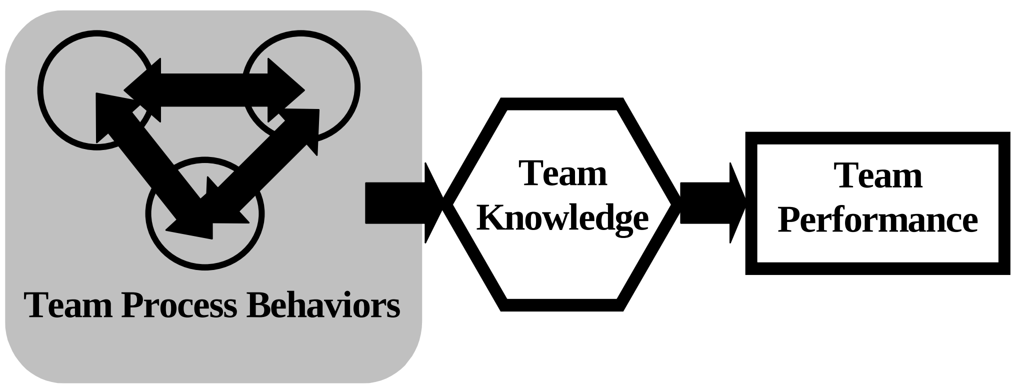


Figure 5. Team cognition framework (Cooke, 2002).

This review of literature makes clear the following:

- Shared mental models within a team improve performance.
- Traditionally, the premise has been that increasing the amount of information that is shared between team members will naturally improve the team's shared mental model.
- Previously, no empirical evidence demonstrated that providing team members compatible or complementary information, in addition to common knowledge, improves team performance.
- Explicit communication is related to the presence of shared mental models and helps to develop accurate shared mental models.
- Measurement of mental models is difficult, particularly in a complex environment; therefore multiple techniques should be used to arrive at the best possible assessment.

Some recent research has implied that, during certain situations when team members are presented with the exact same information within a problem space, other factors influence their decision-making, which may lead team members to different conclusions. This anomaly is even evident when the team members have similar training and backgrounds (e.g., pilots). Team members may perceive the same cues differently, miss information, or place greater importance on different information (Fischer, Orasanu, and Wich, 1995). Redundancy of information between team members, i.e., providing everyone with all information available in a problem space, may be beneficial in some situations or domains, but the literature suggests that there may be situations when there is greater benefit in providing complementary task relevant information (i.e., providing task specific information to individual team members while limiting their access to non-task relevant information) within the team. That is, there might be some information overlap required among team members but, in addition, role-specific complementary information is required and can establish a complementary team mental model of information requirements within the operational domain. This study explores the development of complementary team mental models and the distribution of information within a teams working environment in two separate domains while keeping the cognitive tasks relatively consistent.

Objective

The goal of this research was to further the understanding of crew coordination and team performance in small teams under different information-sharing conditions. In other words, the overarching objective of this study was to examine whether providing task relevant information to individual team members in a time critical environment, while limiting their access to non-relevant information, would foster complementary team mental models with corresponding changes to team process and performance.

Determination of task information requirements

Imagine the benefits of designing the information distribution within a team to naturally support individual and team tasks and encourage efficient communication between team members. The pursuit of such a design, regardless of domain, is underpinned by the accurate determination of information sources in the environment and by team information requirements. This chapter proposes that information sources and requirements can be systematically identified through a three phase analysis: (1) work domain analysis of the information available in the work environment, (2) analysis of the information requirements of specific tasks, and (3) mapping information sources to their corresponding tasks. This section describes a unique application of two separate analytical processes, work domain analysis and hierarchical task analysis. These processes are combined to link information sources available to the task information requirements of a team operating in the domain. The method is applicable to various situations and is recommended when the analyst requires a descriptive analysis of a specified task conducted by a small team in a complex domain. This method is discussed in general and then specifically described through the analysis of two domains. In addition, the results of these examples are used as a basis for two experiments discussed in subsequent chapters.

Method

Requirements for a method

Various methods exist for determining information requirements. Aside from cognitive work analysis, human-centered systems design (Rouse, 1991) and contextual design (Beyer and Holtzblatt, 1998) have both been adopted in numerous domains and have appeared to be successful relative to their purposes (Vicente, 1999). These methods were not designed to be exclusive analysis tools or meant to replace other analysis methods; each of them has both positive and negative aspects when applied to different domains. In system design, particularly the design of a team environment, there is no solution that applies to every problem.

The basic premise of this team centered design approach is that the system should support the team rather than vice versa. Too often, system design focuses on incorporating new technology or displays with limited consideration of how a team will actually use the system. This often results in system modifications at the end of development, or even after completion, once it becomes obvious that the team cannot function effectively. If retrofit is not possible, a team may resort to checklists, procedures, ad hoc practices, or additional training to adapt to a system that does not support their tasks; this adds complexity and the team becomes less effective. Emphasizing the team's needs based on the specified tasks that will be conducted in the environment can lead to a system that supports team operations.

Norman and Draper (1986) and Davis (1989) suggested that the structure of the presentation of information greatly influences a user's ideas about the functions of the system or an individual's mental model. Individual mental models that conform to the actual workings of the system are said to possess the quality of *cognitive compatibility* (Norman, 1983), a desired state for human-system interaction. Generally, the user's understanding of the system is diminished when the presentation is cluttered and disorganized, and when it does not directly match the functions it is trying to support. Logically, team interfaces that promote high cognitive compatibility should be more usable. Two similar principles that address the design of displays for human use are the *proximity compatibility principle* (PCP) and the *ecological compatibility principle* (ECP). Fundamentally, PCP states that the perceptual characteristics of displays should be designed to be compatible with the cognitive processes used by operators to perform a particular task (Wickens and Carswell, 1995). ECP suggests that the design process should begin by ensuring that the content and structure of the interface are compatible with the constraints that actually govern the process to be controlled (Vicente, 1997). Both of these principles can be, and should be, extended from the design of an individual's interface to the design (i.e., organization) of multiple interfaces for teams. PCP is based on an information-processing approach to human factors focusing on how the human will use this information in the display. In contrast, ECP addresses the constraints that the environment places on the processes requiring information.

Extending this to the team level supports the use of a task analysis (information-processing) method combined with a work domain analysis (WDA) (ecological approach). A hierarchical task analysis focuses on the observable aspects of operator behavior; it can describe the interactions between people and control systems, and communication requirements between team members. In comparison, analysis of the work domain identifies the affordances and constraints of the environment where the tasks are conducted. The combination of these analyses can identify team-machine interface issues that arise when a team task is conducted within the environment, and insights to efficient environmental design for team operations can be gained.

The first phase of this method is a work domain analysis to identify the structures in the environment where work takes place. The second phase conducts a separate Hierarchical Task Analyses (HTA). The last phase maps the information sources available in each domain to the individual and team tasks that they support.

The strengths and weaknesses of WDA and HTA, discussed below, make this type of analysis most appropriate for systems where:

- The domain is:
    - Supportive of team operations; i.e., generally, tasks require more than one information source and coordination among members (Orasanu and Salas, 1993; Paris, Salas, and Cannon-Bowers, 2000).
    - Complex; i.e., ill-structured problems, shifting, or competing goals, and time stresses with severe perceived consequences for poor performance (Orasanu and Connolly, 1993; Rouse, Cannon-Bowers, and Salas, 1992)

- The tasks are:
    - Clearly defined;
    - Able to be broken down into goals, tasks, and operations.

<u>Work domain analysis</u>

An understanding of how the environment affects team members can be used deliberately to create environments to suit team adaptation (Carroll, 1991, as cited in Vicente, 1999). Accordingly, a thorough description of the work domain is vital to system design. Work domain analysis is a widely accepted analysis technique that has been successfully applied to various domains, including: aviation, command and control, computer programming, engineering design, information retrieval, medicine, process control, and workplace design (Vicente, 1999). These work domains represent the system being controlled, independent of workers, automation, event, task, goal, or interface. There are various aspects of the domain that can be the focus of a WDA; therefore, the purpose of the analysis must be defined. The purpose of this general analytical method is to identify sources of information within a work domain; the end result is a broad scope of the information sources available within the environment.

The representation most appropriate for this analysis is the 'Abstraction-Decomposition Space (ADS)' (Vicente, 1999) also known as the 'Abstraction Hierarchy (AH)' (Rasmussen, 1985). To understand the work environment, and later its relationship to the task, the analyst must look at all levels of abstraction. Each level represents a different level of granularity with

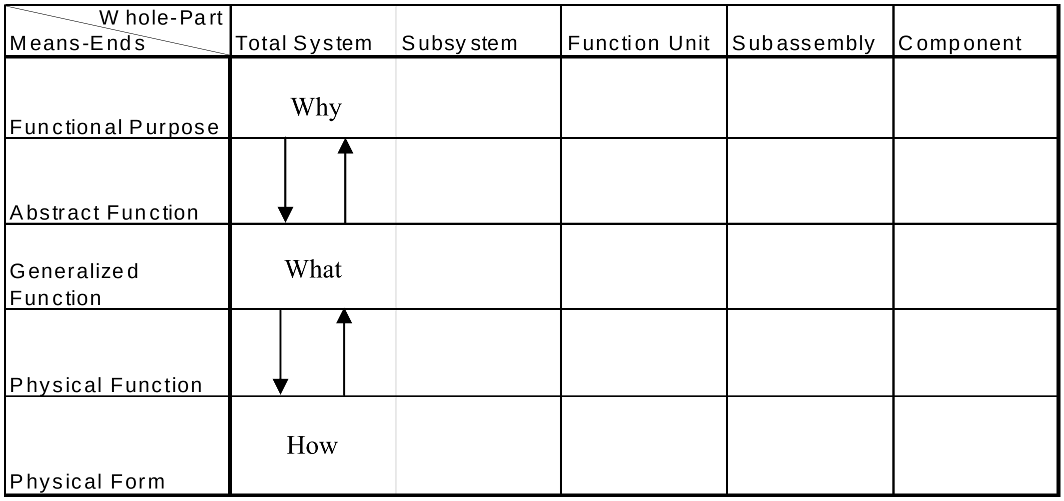


Figure 6. Abstraction hierarchy.

which the analyst can represent the work domain. By using Rasmussen's abstraction hierarchy (Rasmussen, 1985), sources of information can be organized. The analysts can identify environmental constraints and affordances and, in turn, information required for routine operations and unanticipated situations.

Work domain analysis commonly decomposes a system along two dimensions, as shown in Figure 6: parts-whole decomposition and means-ends decomposition. The parts-whole decomposition (from left to right) divides the system into a hierarchy of progressively smaller subsystems. The means-end decomposition (from top to bottom) divides the system into hierarchical levels of abstraction, making a complete representation of the system at each level. The abstraction hierarchy consists of five levels: functional purpose, abstract function, general function, physical function, and physical form (Vicente, 1999). The organization of this type of hierarchy answers three basic questions at different levels of the hierarchy: Why? What? and How? Any level answers the question "what" the element is, the level above describes "why" the element exists and the level below describes "how" that element is realized (Vicente, 1999).

WDA is designed to identify environmental constraints and affordances within the system instead of identifying the cognitive constraints internal to the system. Likewise, WDA can identify roles of agents and with what other parts of the system those agents should interact, but it will not specify their interactions. This type of analysis assumes that workers within the environment are reasonably familiar with the domain; and outside influences, such as training, regulations, or procedures, are not usually included. The primary weakness of WDA is that it does not tell the workers "what to do;" it only describes the structure of the system they will be working in. This is why a work domain analysis in itself is not sufficient and must be followed with a task analysis.

Hierarchical task analysis

The term “Task Analysis” can be applied very broadly to encompass a wide variety of human factors techniques. Nearly all task analysis techniques provide, as a minimum, a description of the observable aspects of operator behavior at various levels of detail, together with some indications of the structure of the task. These have been referred to as action oriented approaches, in contrast to cognitive approaches that focus on the mental processes that underlie observable behavior (Embrey, 2000). This research focuses on the action oriented approaches. Representations developed through task analysis serve as reference to enhance the understanding of the human-system involvement, or to identify particular requirements of the system. There are a variety of task description techniques available to the analyst, including: charting and network techniques, decomposition methods, HTA, link analysis, operational sequence diagrams, and timeline analyses (Kirwan and Ainsworth, 1992).

For the subset of tasks addressed in this study, the use of HTA is advocated. HTA focuses on the observable aspects of operator behavior; it can describe the interactions between team members, and communication requirements between team members. HTA was introduced by Annett and Duncan (1967) to evaluate an organization’s training. It is an approach to task analysis that prompts the analyst to establish the conditions when various subtasks should be carried out in order to achieve the system’s goals; these task components are then graphically represented using a structure chart. HTA provides analysts with great flexibility by allowing them to determine the level of detail to which the hierarchy is developed.

HTA is commonly used for descriptive analysis of a task; it is comprehensive and will most accurately identify information required at each level of the hierarchy (see Figure 7). The first level relates to goals; i.e., desired states of systems under control or supervision (make a cup of tea); the second to tasks, i.e., the method that is adopted to attain the goal; and the third to operations, i.e., “Any unit of behavior, no matter how long or short its duration, or how simple or complex its structure, which can be defined in terms of its objective” (Kirwan and Ainsworth, 1992). HTA recognizes the responsibility of the operator to plan the use of available resources to attain a given goal (Shepherd, 2001). The final product is a description of tasks and subtasks, identification of the team member responsible for the task, and corresponding information requirements.

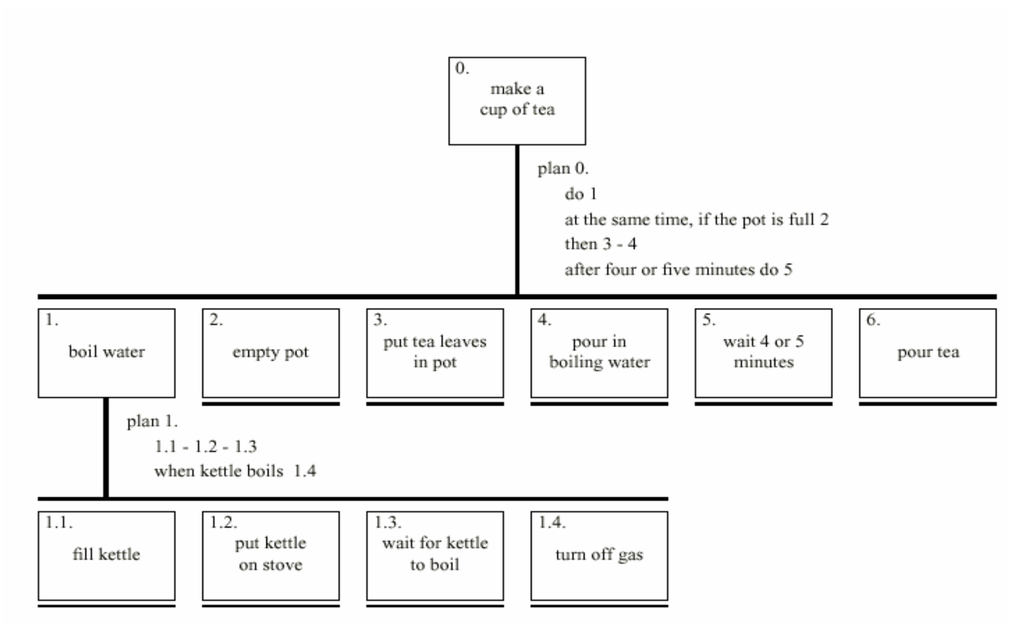


Figure 7. Example hierarchical task analysis.

The information resources required must be identified within this hierarchy as each subtask is developed. For instance, step 5 in Figure 7 states that the subtask is to "wait 4 or 5 minutes"; this requires a chronometric information source be available to the person responsible for task 5. This method of analysis is efficient and can completely describe a specified task along with the resources required, but is usually very narrow in scope and does not provide the user the ability to adapt to unforeseen contingencies or the ability to recover from error.

HTA is commonly used for analysis of tasks conducted by an individual. This method augments the HTA method by considering a team component. For instance, who is responsible for the task and their information requirements are included in the hierarchy. Taken alone, HTA would not be a sufficient analysis method. This method becomes flexible to contingencies only when combined with the WDA discussed in the previous section.

Mapping of sources to requirements

Once the sources of information have been identified through the work domain analysis and information requirements established based on the hierarchical task analysis, the sources must be mapped to their corresponding task requirements. This is accomplished by comparing the required information to the available sources. The end result is a tabulation of which information sources each team member requires access to for the specified task.

Example applications

The generalized method presented above was applied to two domains, an automobile and a military helicopter, and a specified task, team navigation. These applications both demonstrate the method and identify sources of information to distribute in a complementarily manner during two separate experiments.

Several subject matter experts were consulted during the work domain analysis and task analysis for both domains, to, include: active and retired law enforcement experts currently developing training programs for student drivers for Road Ready Inc. in Duluth, Georgia; a military helicopter instructor pilot with over 30 years experience; and aero-medical research psychologists. Five automobile teams were observed while they conducted a navigation task in a fixed base automobile simulator, completing over 20 scenarios in various conditions. For the helicopter domain, ten helicopter teams were observed during 40 flights. Military aircrew training manuals, helicopter operator's manuals, and vehicle GPS navigation training websites provided further insights into both analyses.

Work domain analysis examples

Automobile application of work domain analysis

This analysis was completed for the "total system," rather than one taken from the perspective of a driver, navigator, or any other component of the system, and the purpose of the analysis was to identify information sources for team operations. An automobile was defined as a generic midsize vehicle equipped with an electronic navigation system. The system boundaries were defined as the vehicle and the environment immediately surrounding the vehicle. A discussion of the WDA and resulting abstraction hierarchy (Figure 8) follows.

MEANS-ENDS RELATION	AUTOMOBILE: PROPERTIES REPRESENTED
Functional Purpose	Move from origin to destination. Crew survivability. Environmental impact. Provide pleasure.
Abstract Function	Conservation of energy. Conservation of resources. Flow of information. Balance of forces.
General Function	Process of distributing information. Process of moving automobile. Process of launching resources (fuel, water air, etc.). Process of coordinating forces (thrust, weight, and drag). Process of environmental control.
Physical Function	Generating signals/alerts. Navigation. Communication. Driving input. Crew protection. Speed control. Environmental protection.
Physical Form	Driving instrumentation, system health/status indicators, clock, composite body, air bags, foot pedals, steering wheel, engine, transmission, seats, side panels, windows, window washers, window wipers, tires, headlamps, horn, radio, heater, air conditioner, defroster, internal lights, global positioning system, cellular phone, paint, entertainment system, muffler, catalytic converter, maps, and procedures guide.

Figure 8. Automobile abstraction hierarchy.

The *functional purpose* level corresponds to the work domain's purpose, or why the system exists. There were four functional purposes modeled in the automobile domain: Move from origin to destination, crew survivability, environmental safety, and pleasure. This system is primarily designed to safely navigate between two designated points. Crew survivability describes the ability of the system to protect its occupants during normal and emergency conditions. Environmental impact involves those constraints that influence the vehicles impact on the environment due to various types of pollution produced (i.e., air, water, and noise pollution). Driving pleasure involves those constraints that deal with comfort of the occupants and their level of enjoyment while operating in the domain. The level to which a vehicle satisfies these constraints varies between specific makes and models, and operators; yet, the functional purposes of the system are constant.

The *abstract level* defines the causal laws and principles underlying the function of the automobile; they may need to be minimized, maximized or conserved to achieve the systems purpose (Nadimian, Griffiths, and Burns, 2002). For the automobile's purpose to be achieved, the following underlying laws and principles were identified at the abstract level: Conservation of energy, conservation of resources, balance of forces, and flow of information. Conservation of energy is a fundamental concept that states that within this domain, the amount of energy remains constant and energy is neither created nor destroyed. Energy can be converted from one form to another (potential energy can be converted to kinetic energy), but the total energy within the domain remains fixed. Conservation of resources within this domain seems quite obvious: the amount of resources remains constant as resources are neither brought into the domain nor leave the domain. Most moving things require a balance of forces, since most moving things are affected by friction. In this domain, for a car to travel at a steady speed, the engine and drive train must supply a forward force. If this forward force is stronger than the combined effects of wind resistance and friction with the road, the car speeds up; if this forward force is weaker, the car slows down. The flow of information concerns the delivery of information in various forms (analog, digital, audible, etc.) for utilization by cognitive mechanisms within the domain.

At the *generalized function* level, the processes involved in achieving the functional purposes of the automobile by influencing the constraints at the abstract level were modeled. Five processes were identified at this level: Process of distributing information, physical process of moving automobile, process of launching resources (fuel, water, air, etc.), process of coordinating forces (i.e., thrust, weight, and drag), and process of environmental control. These processes are supported by and achieved through the *physical function* level of the work domain. This level of the analysis describes the capabilities of the physical elements of the system. There were eight physical functions identified for this system: Generating signals/alerts, navigation, communication, driving input, crew protection, speed control, environmental control, environment protection. Generation of signals and alerts describes the capabilities of a number of elements at the physical form level focused on the presentation of information to operators. Navigation addresses functions used to assist the operator in navigation. Communication addresses the functions required to talk to other members within the domain and receive and send information outside the domain. Driving input and speed control address those functions that accelerate, decelerate and steer the vehicle, along with any constraints or controls on velocity limits. Environmental control deals with the comfort and conduciveness of the environment to operations being conducted, while environmental protection deals with the environment outside of the vehicle.

Lastly, the physical form level was modeled. At this level, the most concrete level, the configuration of the elements in the domain that supports the functions described above were identified. The elements in this level are self-explanatory and are displayed in Figure 8.

Military helicopter application of work domain analysis

The same method used for the automobile domain was applied to a military helicopter domain. This analysis also was completed for the "total system," rather than one taken from the perspective of a pilot, navigator, or any other component of the system. The military helicopter considered here is a modernized helicopter with an integrated electronic navigation system. The system boundaries were defined as the aircraft cockpit and the environment immediately surrounding the aircraft. A discussion of the abstraction hierarchy analysis follows; a summary of the findings is shown in Figure 9.

MEANS-ENDS RELATION	HELICOPTER: PROPERTIES REPRESENTED
Functional Purpose	Move from origin to destination. Crew survivability. Environmental impact. Provide ordnance delivery platform. Provide observation platform.
Abstract Function	Conservation of energy. Conservation of resources. Flow of information. Balance of forces.
General Function	Process of distributing information. Process of moving aircraft. Process of launching resources (fuel, water air, etc.). Process of coordinating forces (thrust, drag, lift, and weight). Process of targeting. Process of environmental control.
Physical Function	Generating signals/alerts. Navigation. Communication. Flying input. Crew protection. Speed control. Environmental control. Environmental protection. Weapons control.
Physical Form	Flight instrumentation, system health/status indicators, clock, composite body, flight controls, engine, transmission, main rotor blades, tail rotor, seats, armored side panels, wind screens, wind screen wipers, wheels, landing lights, radios, heater, air conditioner, defroster, internal lights, global positioning system, fire control computer, fire control panel, targeting sight, signature reducing paint, maps, environmental indicators, voice communication radios, (FM, VHF, UHF), navigation radios (ADF, VOR), aircraft survivability equipment (IR suppressor, AN-ALQ 136), procedures guide and checklist, and vision enhancement devices.

Figure 9. Helicopter abstraction hierarchy.

There were five *functional purposes* modeled in the helicopter domain: Move from origin to destination, crew survivability, environmental impact, provide ordnance delivery platform, and provide observation platform. Similar to the automobile domain, this system is primarily designed to safely navigate between two designated points. Crew survivability and environmental were conceptually the same as previously discussed. Two additional functional purposes of the system were to provide both an ordnance delivery and observation platform. These capabilities vary significantly between aircraft types, but are often essential functions of the total system.

For the helicopter's purpose to be achieved, the following underlying laws and principles were identified at the *abstract level*: Conservation of energy, conservation of resources, balance of forces, and flow of information. These are conceptually identical to the automobile domain. The additional force of lift was added to the balance of forces for this domain.

At the *generalized function* level, the processes involved in achieving its functional purposes were modeled. Six processes were identified at this level: Process of distributing information, physical process of moving automobile, process of launching resources (fuel, water, air, etc.), process of coordinating forces (i.e., thrust, weight, and drag), process of environmental control, and process of targeting. The only process that is different in the helicopter domain is the process of targeting which refers to the processes used by the aircraft and the team to locate and identify targets outside of their environment.

The *physical function* level of the work domain describes the capabilities of the physical elements of the system. There were nine physical functions identified for this system: Generating signals/alerts, navigation, communication, driving input, crew protection, speed control, environmental control, environment protection, and weapons control. The control of weapon systems was the only physical function particular to the helicopter domain; this concerns the human machine interfaces integral to weapon systems operations.

Summary of WDA: automobile and helicopter

The diversity within each environment at the functional purpose level reaffirms the complexity of the domains and differentiates them from other domains. Only a small number of domains must combine efficient and timely movement, survivability, and safety measures in order to meet their functional purpose. As well as providing a means to identify information sources to manipulate during experimentation, these AH analyses highlighted some similar constraints and affordances between these outwardly different complex environments; many of the levels were, in essence, uniform across the two domains. It was evident that the first four levels of abstraction were very similar between domains; the domains began to diverge at the *physical form level*. In Figure 10 cells highlighted in green (medium gray in black and white [B&W]) depict elements of the hierarchy that had a direct mapping from one domain to the other; red (dark gray in B&W) indicates that no mapping existed. The majority of the functions or purposes that did not map primarily dealt with the two functional purposes specific to the helicopter (i.e., observation platform and weapons platform) and the one functional purpose specific to the automobile (i.e., pleasure).

The abstraction provides an instrument to compare functions across domains. For example, although the navigation system supports weapons control for a helicopter, it also supports many of the same functions that appear in an automobile abstraction hierarchy: Information collection, process of moving the vehicle, and environmental control. As the abstraction hierarchy is descended, the divergence of the environments occurs the most at the physical form level, the most concrete level of the hierarchy. While the physical forms required to support the functions and purposes outlined in the AH are clearly different between these domains, their functional structures impose similar constraints and affordances to the actors operating in each of these environments, which may lead to similar behavior patterns of teams operating in these domains.

Ecological Interface Design (EID) techniques, such as the AH, are based on the concept that the constraints of the environment must be explicitly analyzed to enable the direct perception of goal relevant properties of the environment (Rasmussen and Vicente, 1989; Vicente, 2002; Vicente and Rasmussen, 1992). Using this method helped to identify sources of information available to agents operating in these environments. These sources of information identified were the basis for determining main parameter levels in the experiments conducted in this effort.

Hierarchical task analysis example

Automobile and helicopter application of task analysis

In many domains, the timing and order of tasks is important, especially when the tasks are serial in nature. The tasks and sub-tasks particular to team navigation are not serial tasks; actually, they *must* be conducted in parallel to each other. For instance, for the first sub-goal level in Figure 12 the team must maintain vehicle control while navigating; this implies general team duties must be performed while the team obeys traffic laws. All of these sub-goals are executed in parallel. Therefore, although one of the products normally developed during a hierarchical task analysis is a series of plans that state conditions that specify when each of a set of sub-goals should be carried out (Kirwan and Ainsworth, 1992), this was not done for the navigation task. The parallel nature of navigation adds to the complexity of both domains. Figures 12 and 13 represent the HTA for aircrew and automobile team navigation.

Using this method helped to identify tasks that were similar to both domains. Figure 13, using the helicopter domain as the reference domain, highlights similarities in the task between the two environments using the following color scheme:

- Green (medium gray in B&W): Those tasks/sub-tasks of the hierarchy that had a direct mapping from one domain to the other.
- Yellow (light gray in B&W): Although there was no direct mapping between domains, there was a strong similarity. For example, instead of conforming to Air Traffic Control (ATC) rules and regulations (helicopter domain), agents in the automobile domain are required to obey the rules of the road. These two sub-goals are analogous.
- Red (dark gray in B&W): No mapping existed.

Identifying similar task requirements assisted in the development of experimental task requirements.

Mapping of sources to requirements: example

The HTAs were developed using the top-level goal “move from point A to point B.” For this example, a specific sub-task was selected that could be performed in both domains during experimentation. Task selection was accomplished utilizing the similarities identified in Figure 13. Radio aided navigation could not be performed in the automobile domain and, due to limitations of the simulator used for the automobile experiment, electronically aided navigation could not be performed either. Additionally, due to the goals of this research, mission planning was not incorporated in either domain. All other sub-tasks were incorporated into experimental scenarios. The primary tasks identified for experimentation were (1) navigation by pilotage and dead reckoning (helicopter), and (2) conventional map navigation (automobile).

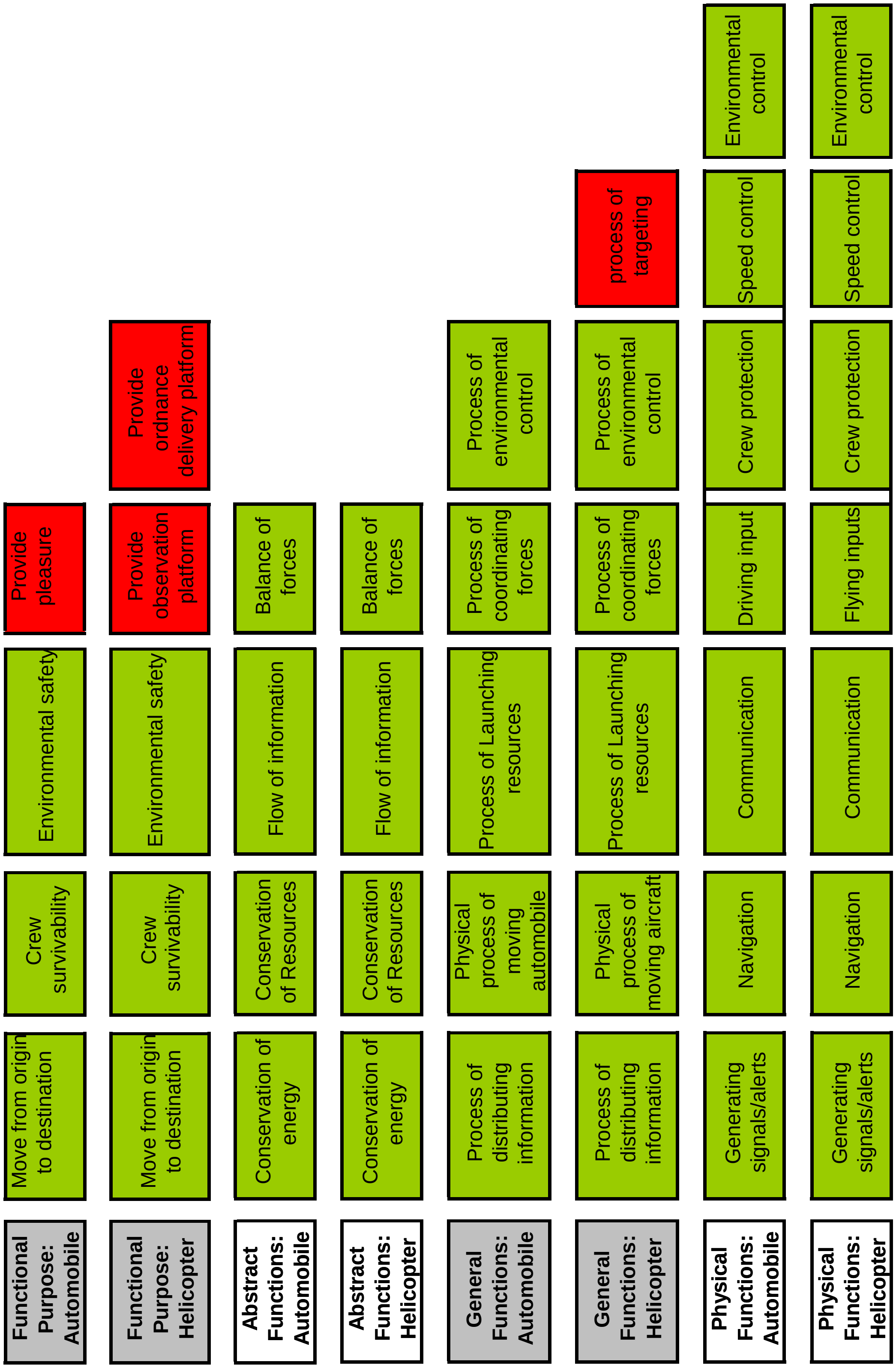


Figure 10. Similarity between work domains.

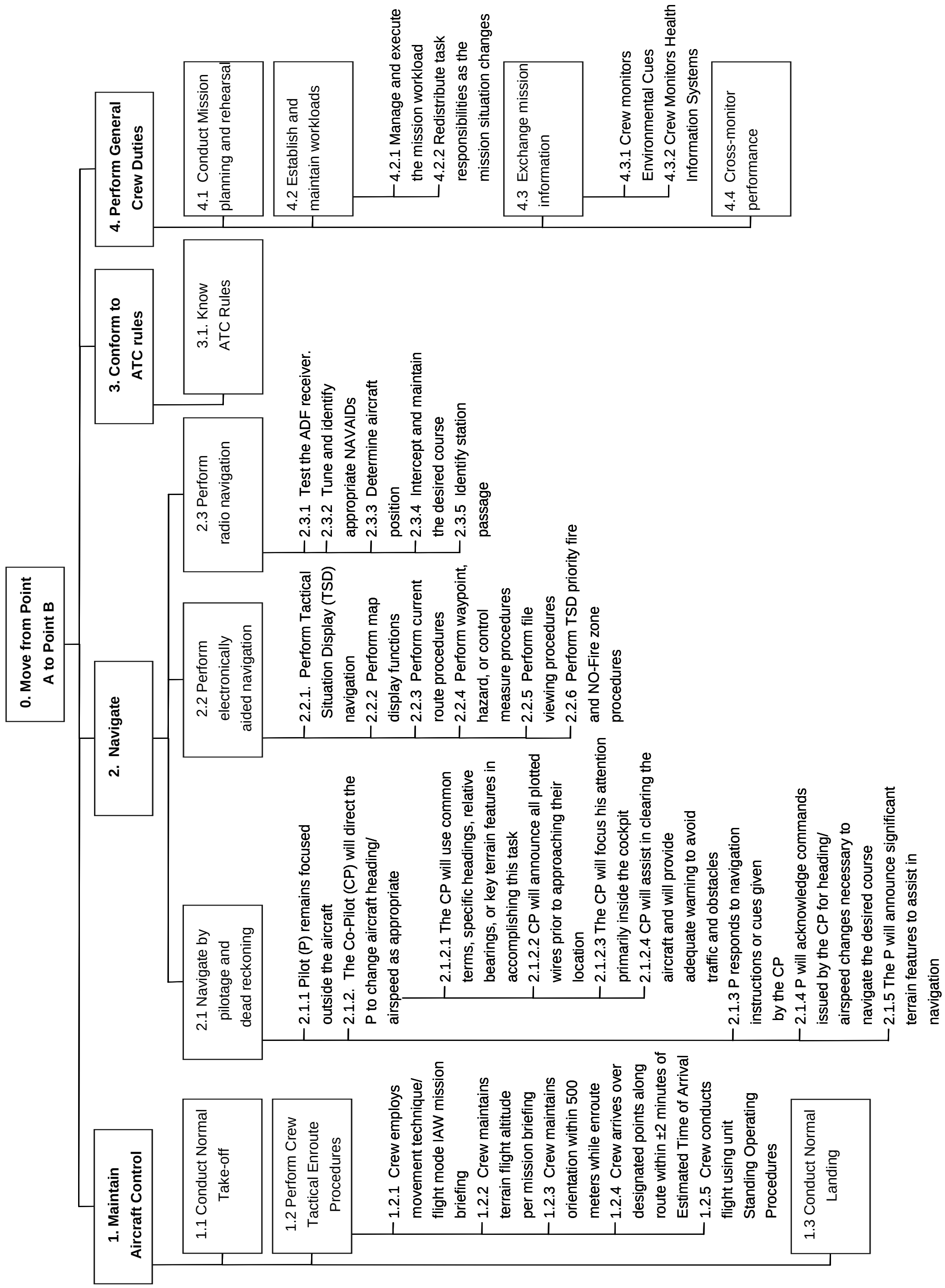


Figure 11. Helicopter team navigation HTA.

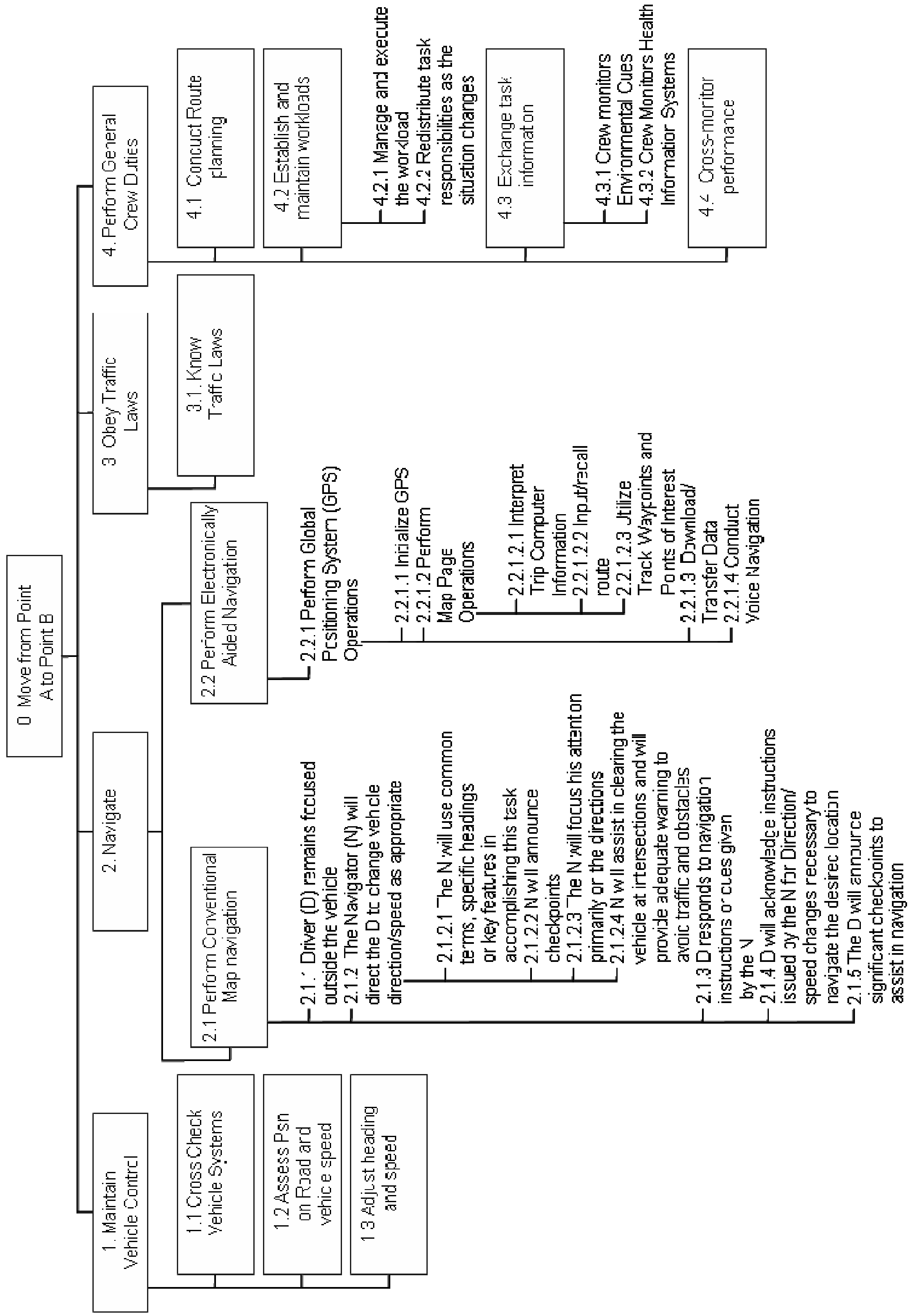


Figure 12. Automobile team navigation HTA.

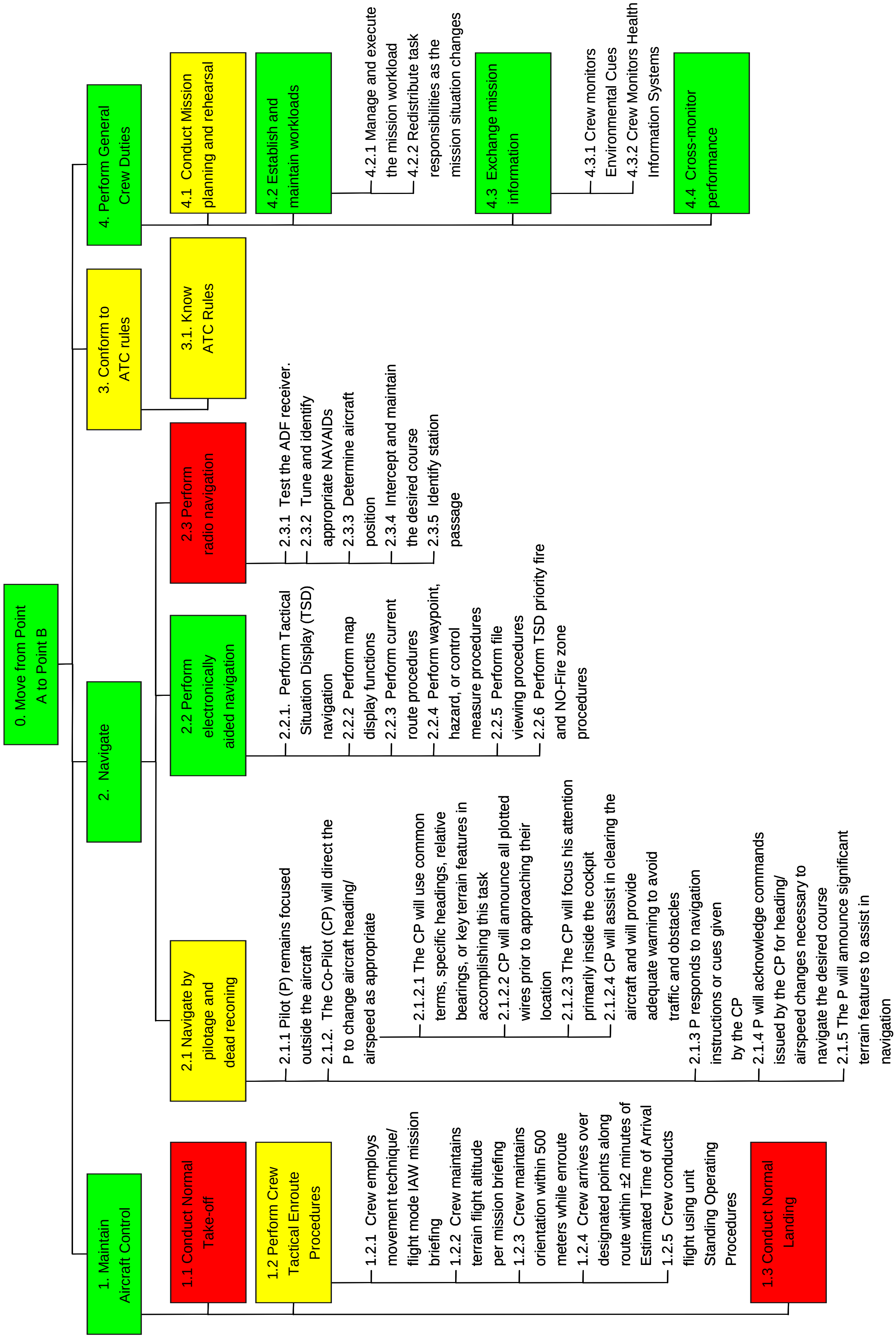


Figure 13. Domain similarities in team navigation HTA.

Once the task was selected, the physical forms that supported this task were identified. Figures 8 and 9 identify sources of information available in each domain that support these tasks; these are combined in Figure 14. Based on the task conditions established for the experimental scenarios, the requirements were reduced; e.g., all scenarios were conducted in the daylight and no scenarios incorporated rain, hail, snow, or environmental issues that could be diagnosed by the team (excluding Inadvertent Instrument Meteorological Conditions in the helicopter domain). Additionally, participants of the experiments would not switch duty positions; therefore, the driver/pilot would always have the driving/flying controls. The following physical forms were either not available for experimental purposes or not considered essential for operating in the automobile domain under the stated conditions: Window washers, window wipers, headlamps, radio, internal lights, global positioning system, and cellular phone. Likewise, the following elements were not considered in the helicopter domain: Windscreen wipers, landing light, targeting sight, environmental indicators, navigation radios (ADF, VOR), and vision enhancement devices.

Finally, using the task descriptions presented in Figures 11 and 12, the information sources identified in Figure 14 were allocated to the corresponding team member that would perform the task. Figure 15 shows the information sources for each team member for each domain.

	AUTOMOBILE	HELICOPTER
Physical Forms Supporting Navigation Tasks	Driving instrumentation, system health/status indicators, driving controls, (foot pedals, steering wheel), windows, window washers, window wipers, headlamps, radio, internal lights, global positioning system, cellular phone, and maps.	Flight instrumentation, system health/status indicators, clock, flight controls, wind screens, wind screen wipers, landing lights, radios, internal lights, global positioning system, targeting sight, maps, environmental indicators, voice communication radios, (FM, VHF, UHF), navigation radios (ADF, VOR), and vision enhancement devices.
Reduced Physical Forms Supporting Navigation Tasks	Driving instrumentation, system health/status indicators, clock, driving controls, windows, internal lights, and maps.	Flight instrumentation, system health/status indicators, clock, flight controls, wind screens, radios, internal lights, global positioning system, maps, and voice communication radios, (FM, VHF, UHF).

Figure 14. Physical forms that support navigation.

	Physical Forms Required for Navigation	
	Automobile	**Helicopter**
Driver/Pilot	Driving Instruments Window View	Flight Instruments Windscreen View
Navigator	System Health/Status Indicators Clock Maps	System Health/Status Indicators Clock Maps Global Positioning System
Crew	Internal Lights	Voice communication Radios Internal Lights

Figure 15. Physical forms required by team member.

Summary

This section has (1) established that a requirement exists for a method to identify information sources and align them with task requirements within a complex domain supporting team operations, and (2) proposed a method that identifies these sources and requirements through a unique three-phase analysis:

- Analysis of the work domain,
- Analysis of a specific task within domain, and
- A mapping of the information sources to their supported tasks.

The combination of methods described in this chapter offer a flexible method for a variety of domains and task combinations. The strengths and weaknesses of WDA and HTA make this type of analysis most appropriate for systems where the:

- The domain is:
    - Supportive of team operations; i.e., generally, tasks require more than one information source and coordination among members (Orasanu and Salas, 1993; Paris, Salas, and Cannon-Bowers, 2000).
    - Complex; i.e., ill-structured problems, shifting, or competing goals, and time stresses with severe perceived consequences for poor performance (Orasanu and Connolly, 1993; Rouse, Cannon-Bowers, and Salas, 1992).

- The tasks are:
    - Clearly defined;
    - Able to be broken down into goals, tasks, and operations.

Experiment I: fixed base automobile driving simulator

The overarching objective of this study was to examine whether providing task relevant information to individual team members in a time critical environment, while limiting their access to non-relevant information, would foster complementary team mental models with corresponding changes to team process and performance. Furthermore, this method of distributing information among team members would provide individual team members with a more accurate "task relevant" mental model of their own environment. The central proposition of this study is that providing specific task relevant information to individual team members in a time critical environment, while limiting their access to non-relevant information, will change team coordination and develop complementary team mental models. Furthermore, this method of distributing information among team members will provide individual team members with a more accurate "task relevant" mental model of their environment.

Note that this study will employ the terms nominal and off-nominal to describe experimental conditions. A condition characterized as *nominal* implies that no experimental changes/inputs were imposed on the team which altered their planned navigational runs. During off-nominal conditions, teams were forced to alter their planned runs due to unexpected events imposed by the researchers.

Specific hypotheses that investigate this central proposition are:

- *Hypothesis 1*: Team performance, during nominal conditions, will, generally, remain constant when information is complementary when compared to performance in a normal automobile cockpit configuration.
- *Hypothesis 2*: Team performance during off-nominal conditions will improve when information is complementary when compared to performance in a normal automobile cockpit configuration.
- *Hypothesis 3*: Explicit, task relevant, verbal communications will increase when information is complementary when compared to communications in a normal automobile cockpit configuration.
- *Hypothesis 4*: The team's task relevant anticipation ratio will increase when information distribution is complementary when compared to operations in a normal automobile cockpit configuration.
- *Hypothesis 5*: Individual workload ratings will remain constant between information levels regardless of cockpit configuration.

Method

This experiment was conducted at Safe Drive Technologies, Inc., located in Duluth, Georgia, using students from the Georgia Institute of Technology as participants. The main parameter was the complementariness of task specific information available to team members.

During the experiment data were collected concerning team communications, team workload, decision-making, and performance while the participants conducted a navigation task in a time critical situation. Each team member assumed a different role in the team, either the driver or the navigator; they maintained their assigned role throughout the entire experiment (i.e., there was no role switching).

Participants

Participants were 24 students from the Georgia Institute of Technology tested in pairs with the following characteristics:

- All possessed a current U.S. driver's license.
- Total driving experience ranged from 3.5 to 21 years; average experience was 7.8 years.
- Participants' ages ranged from 19-37; average age was 24 years.

Experiment apparatus

- The GE Capital I-Sim's PatrolSim™ compact, fixed base driving simulator was used for this study (Figures 16 and 17) and is further described in Appendix A). This provided an interactive environment in which team performance could be observed while certain parameters were controlled.
- Foggles are manufactured glasses that are used as a tool during instrument training to limit the pilot's field of vision. This assists the learning process by encouraging the pilot to fly with only the help of the flight instruments. In this case, the open area in the glasses was just large enough to allow the navigator to have a full view of the driving instructions without a view out of the windows of the automobile. Foggles are light, comfortable, and easy to wear; they are designed like regular glasses.
- A video camera, which also recorded audio, was temporarily mounted to record team interaction throughout the experiment. All data collection runs had video and sound of the participants recorded.
- Maps of the simulated city used for the experiment were provided to the team. Driving directions from the starting point to the team's destination were also provided. A sample map is shown in Figure 18. The complete set of maps used for the experiment is in Appendix A.

Figure 16. GE Capital I-Sim's PatrolSim™, View I.

Figure 17. GE Capital I-Sim's PatrolSim™, View II.

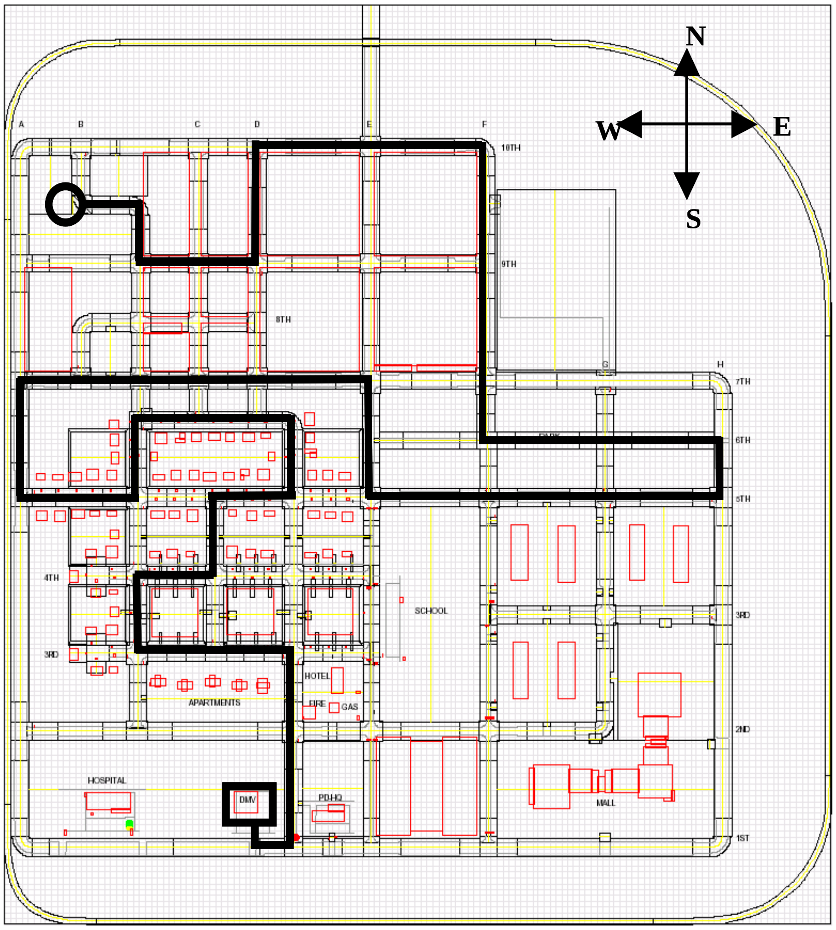


Figure 18. Sample map.

<u>Experiment procedure</u>

Introductory briefing

- Sought informed consent from participants: A copy of the consent form is contained in Appendix A.
- Explained the experiment.
- Detailed the schedule of events.
- Oriented participants with the facilities.
- Collected demographical data from participants.

Training run

The training run ensured that each participant was familiar with the feel of the simulator, the instrument displays, and the area of operation.

Data runs

Participants conducted five navigation runs during which data were collected:

- *Four nominal data runs (no diversions).* During these runs, the driver and navigator were placed in a series of scenarios that were generally the same. They started at a specified location and were asked to navigate to a destination; the information provided to team members was varied during these runs. The effects of pre-planning were not being tested; therefore, teams were not allowed time to plan out a strategy before the start of each run. The runs each took approximately 10 minutes, with a break given between them. Immediately following each of the navigation runs participants completed surveys regarding their workload, performance, etc.
- *One off-nominal data run (with diversions).* Participants were asked to partake in a fifth data run. This run was generally the same as the previous four scenarios except a planned detour was included. This detour was designed to divert the team from their given route and directions. The team was expected to formulate a plan, navigate back onto the route, and complete the run.

End of experiment survey

Following the complete experiment, individuals completed a final survey concerning overall themes of the experiment. The entire procedure lasted approximately 2.5 hours for each team; this included introduction briefing, simulator familiarization, training runs, data runs, and all surveys. Participants were free to request a break at any time.

<u>Task description</u>

This experiment was conducted in an automobile simulator provided by ROAD READY Inc. and was designed to collect data concerning team coordination, decision making and performance while conducting a navigation task under a time critical situation. Each team member assumed a different role in the team, either the vehicle driver or navigator. The team was given a map and textual directions to various locations within the simulated environment. They were asked to navigate in two specific conditions (nominal and off-nominal).

Under nominal conditions participants were asked to conduct four navigation runs. During these runs, the driver and navigator were placed in a series of scenarios that were functionally equivalent. They started at a specified location and were asked to navigate to a destination; the information provided to team members was varied during these runs. Teams were asked to maintain control of the vehicle, obey common traffic laws (e.g., speed limit, stop lights, right on red, one way streets, etc.), identify a speed zone, and navigate to the location given on their map using the route provided. Teams were expected to conduct individual tasks (i.e., maintain vehicle control), team tasks (i.e., navigation), coordinate their actions as a team, and communicate their actions, intentions and requests for information.

The off-nominal run consisted of one experimental run similar to the previous four, however, unexpectedly to the team, a roadblock required a detour from the designated route. This run thus assessed team responses to an unexpected, "off-nominal" scenario; the detour was designed to divert the team from their given route and directions. The roadblock could be overcome in a variety of ways and the optimal solution was not clear. In addition to the expectations for the nominal condition, teams were expected to formulate a plan, navigate back onto the route, and complete the navigation task.

Each run commenced when the driver turned the ignition key and started the vehicle. To avoid any pre-planning, the team members had one minute to review the directions and then were asked to start the simulation. The driver and navigator were only allowed to use verbal communication; i.e., gestures such as pointing out the window or on the map were not allowed. If teams made a mistake and deviated off the route, they were asked to get back on the route as soon as possible. The experiment ended when the team arrived at their destination and turned the vehicle off.

Experimental design

The overall study consisted of two experiments run sequentially; participants were unaware that there were two experiments. The first experiment design consisted of four runs that examined performance under nominal conditions, in which the four levels of information distribution were varied. For these first four runs, a Greco-Latin Square design was used to minimize any effects of the scenario, order, and training, and to isolate the effects of the independent factors. In these four cases, the teams were presented with 'nominal' scenarios in which they could navigate without deviation from the route to their destination. Specifically, there were no inconsistencies between the route on the map and the ability to follow the route in the simulator (e.g., there were no road blocks, detours, etc). The second experiment consisted of one additional experimental run similar to the previous four with the addition of a detour. The information distribution conditions were balanced and treated as a between-subjects variable for this run. The same scenario was used for all teams.

Independent factors

During the experiment, variations in measures were observed as the investigators presented different levels of information distribution to the participants. Two independent factors determined the distribution of information within the team. These independent factors were: (1) whether the driver has access to the map used for navigation and, (2) whether the navigator has access to the "out-of-window" view.

Figure 19 shows a matrix that was used to determine levels of information. The two by two matrix resulted in four levels of information distribution. These levels were designed by the investigator to change from non-complementary (Level I) to fully complementary (Level IV) and are described in detail below.

		Driver Had Map	
		Yes	**No**
Navigator had Out-of-Window View	**Yes**	Level I	Level II
	No	Level III	Level IV

Figure 19. Information level matrix.

Level I (Non-Complementary)

The driver and navigator were both provided with identical information, (i.e., textual directions to the destination and a map of the area with the route highlighted, and both had an unrestricted out-of-the-window view).

Level II (Partially Complementary)

Only the navigator was provided with textual directions to the destination and a map of the area with the route highlighted. The navigator was not allowed to show the map or the textual directions to the driver and instead needed to provide the driver with steering commands. Both the driver and the navigator had an unrestricted out-of-the-window view.

Level III (Partially Complementary)

The driver and navigator were both provided with the textual directions to the destination and a map of the area with the route highlighted. The navigator wore plastic eyeglasses (Foggles) that were clear only in his or her line of sight to a map held on the lap, but were opaque around that narrow field of view, thus obscuring his or her sight of the out-of-the-window view.

Level IV (Fully-Complementary)

Only the navigator was provided with textual directions to the destination and a map of the area with the route highlighted. The navigator wore Foggles.

Dependent Factors

Dependent Measures were categorized into three groups: Performance, Workload, and

Communication.
Performance

Performance under nominal conditions was assessed using five measures and two collection sources. Speed violations, lane violations, and hard decelerations were obtained through a driver's assessment report compiled by the simulator. These were recorded as the sum of individual occurrences of each violation. The experimenter observed navigation errors, and speed zone recognition. Navigation errors included both committed navigation errors and near navigation errors. Committed errors were instances in which the team navigated off of the given route; near errors were instances where the navigator gave the wrong instructions or the driver attempted to navigate off the given route. Speed zone recognition was recorded as 'yes' or 'no' depending on whether the team identified a posted reduction in speed (via speed limit sign) within the scenario; speed zone reductions were limited to one per experimental run. Performance under "off-nominal" conditions was measured by team Decision Time (DT) when faced with an unexpected detour and the Total Time (TT) it took the team to get back on the designated route, this indicated the quality of their decision.

Workload

Workload was measured through the use of the NASA Task Load Index (TLX) (Hart and Staveland, 1988). Six measures of workload were collected via the NASA TLX subjective rating sub-scales: mental demand, physical demand, temporal demand, performance, effort, and frustration. Team members scored these measures at the conclusion of each experimental run. Between each experimental run, teams completed a Raw Task Load Index (RTLX) survey. Byers, Bittner, and Hill (1989) proposed the RTLX method as a simplified but as-effective method as the full NASA-TLX. The RTLX method does not require the task-paired comparison of the full NASA-TLX (Byers, Bittner, and Hill, 1989).

Communications

Communications were categorized in three basic categories: transfers, requests, and acknowledgements (Entin and Entin, 2001). Throughout the experiment, both video and audio of the participants were recorded. These recordings were analyzed using the matrix in Figure 20. Explicit communication occurrences were aggregated to the team level. The data were normalized based on the length of each experimental run. Additionally, communication transfers were divided by communication requests to establish an "anticipation ratio." Anticipation ratios have often proved more useful than individual rate measures for understanding team communications (Entin and Entin, 2001). Larger anticipation ratios indicate increased anticipation of team member information needs. Recall that the most effective teams seem to share their mental picture of the situation with other team members (Stout et al., 1999). These shared mental models help team members to anticipate the needs of others; and this permits them to either provide assistance, as it is required, or to predict and pre-empt the need for assistance (Martin and Flin, 1997). They provide team members with a common understanding of who is responsible for what task and what the information requirements are and to allow team members to anticipate one another's needs so that they can work in sync and adjust their behavior accordingly (Smith-Jentsch, Johnston, and Payne, 1998). Hence, the presence of a high anticipation ratio, in concert with other indicators, can be an indicator of the level of similarity of a team's shared mental model.

Type & Content**		Navigator to Driver	Driver to Navigator	Total
Request	Task Relevant Information			
	Non Task Relevant Information			
	Action			
Transfers	Task Relevant Information			
	Non Task Relevant Information			
	Performing/ Will Perform Action			
Acknowledgements of Info Receipt	General (okay,roger)			
	Specific (roger, right on 1st)			

Figure 20. Communications matrix

Results

In total, 72 runs were completed: teams completed 12 familiarization, 48 nominal, and 12 off-nominal runs. The data were categorized into three main groups: Performance, Communication, and Workload. For the analyses in this section, the following statistical tests were used:

- General Linear Model (GLM) Analysis of Variance (ANOVA)
- The Mann-Whitney U Test
- Kruskal-Wallis Test

Statistical Program for the Social Sciences (SPSS) 13.0 for Windows Graduate Student Version, released September 1, 2004, was used to perform the statistical analyses. Details concerning the computational algorithms can be found at http://www.spss.com.

The GLM multivariate and univariate procedure provides regression analysis and analysis of variance for multiple or singular dependent variables by one or more factor variables or covariates. The factor variables divide the population into groups. This procedure is commonly used to test null hypotheses about the effects of factor variables on the means of various groupings of a joint distribution of dependent variables or to investigate interactions between factors, as well as the effects of individual factors (SPSS 13.0 for Windows Graduate Student Version). Although this experiment used balanced models, both balanced and unbalanced models can be tested. Post hoc Kolmogorov–Smirnov tests were used to test the assumption of normally distributed errors. Additionally, observed power was calculated with each ANOVA. In these analyses, type III sums of squares were utilized.

The Mann-Whitney U test was used as the primary non-parametric test for these analyses. It is the most commonly used of the two-independent-samples tests. It is equivalent to the Wilcoxon rank sum test and the Kruskal-Wallis test for two groups. Mann-Whitney tests that two sampled populations are equivalent in location. The observations from both groups are combined and ranked, with the average rank assigned in the case of ties. The number of times a score from group one precedes a score from group two, and the number of times a score from group two precedes a score from group one, are calculated. The Mann-Whitney U statistic is the smaller of these two numbers. The Wilcoxon rank sum W statistic, also displayed, is the rank sum of the smaller sample (SPSS 13.0 for Windows Graduate Student Version).

Performance

The measures lane violation and hard decelerations were analyzed using a GLM ANOVA. No significant differences were found (see Table 1).

The measures of speed violations, total navigation errors and the identification of speed zones were found to not fit the normality requirements for ANOVA. Therefore, each was examined using a Kruskal-Wallis test (see Table 2). They were also found to have non-significant differences across information levels. However, when levels I and II (Navigator had access to the out-of-window view) were combined, and levels III and IV (Navigator did not have access to the out-of-window view) were combined, a Mann-Whitney test was conducted and a significant effect was found. Total navigation errors significantly decreased during experimental runs when navigators did not have access to the out-of-the window view. Table 3 contains statistics associated with the Mann-Whitney Test for two independent samples.
Performance was measured for the off-nominal condition by DT from presentation of roadblock to action taken and TT to get back on the route toward final destination. Significant differences were not detected when the information levels were analyzed, however, when they were combined, as in the nominal condition, significant effects were identified. Information conditions were consolidated to reflect whether or not the navigator had access to the out-of-the window view. As predicted, the first roadblock scenario yielded non-significant results. Decision Time and Total Time for the second scenario were significant (DT; $F = 9.38$, $p = .012$ and TT; $F = 5.29$, $p = .044$) and are shown in Figure 21.

Table 1.
ANOVA: performance.

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	Hard Decelerations	85.167	3	28.389	1.050	.380
	Lane Violations	15.063	3	5.021	.531	.663
Intercept	Hard Decelerations	10443.000	1	10443.000	386.182	.000
	Lane Violations	14456.021	1	14456.021	1529.309	.000
INFO	Hard Decelerations	85.167	3	28.389	1.050	.380
	Lane Violations	15.063	3	5.021	.531	.663
Error	Hard Decelerations	1189.833	44	27.042		
	Lane Violations	415.917	44	9.453		
Total	Hard Decelerations	11718.000	48			
	Lane Violations	14887.000	48			
Corrected Total	Hard Decelerations	1275.000	47			
	Lane Violations	430.979	47			

Table 2.
Kruskal-Wallis test.

	Speed Violations	Total Navigation Errors	Speed Zone Identification
Chi-Square	4.309	5.787	.899
df	3	3	3
Asymp. Sig.	.230	.122	.826

Group Variable: Level of Information

Table 3.
Mann-Whitney test.

Navigator had Access to Out-of-Window View	Navigation Errors	Statistics	
Yes	17	Mann-Whitney U	204
No	4	Wilcoxon W	504
		Z	-2.167
		Sig.	0.030

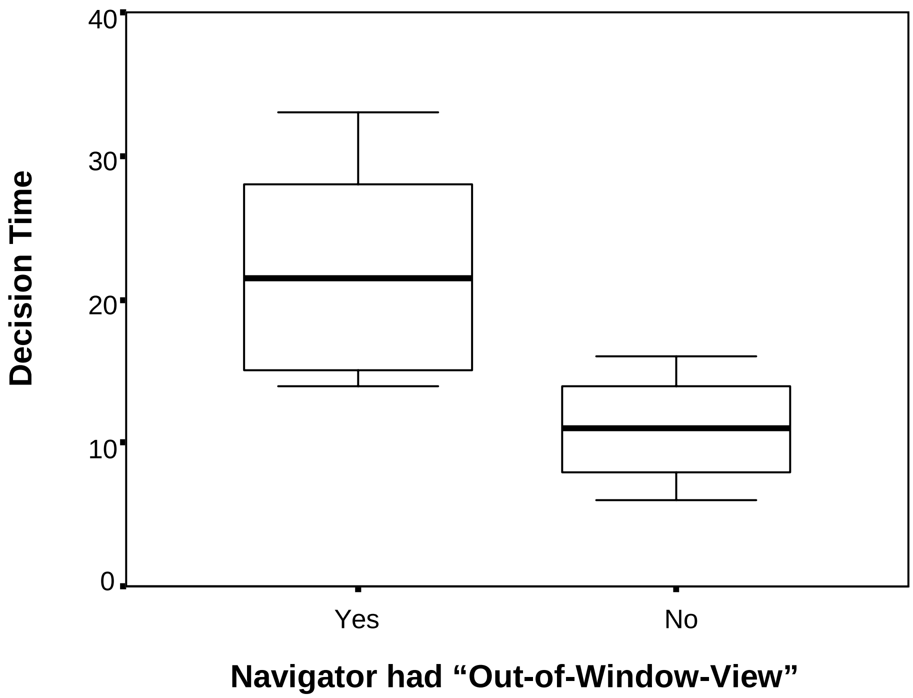


Figure 21. Decision time box plot.

Table 4.
ANOVA: effects of information level on communication.

	Variable	F	Sig.	Power
Requests	Task Info	1.159	0.336	0.290
	Non-Task Info	1.000	0.402	0.254
	Total Info	1.293	0.289	0.321
	Action	0.092	0.964	0.065
Transfers	Task Info	2.620	0.063	0.603
	Non-Task Info	**6.282**	**0.001**	**0.951**
	Action	**28.494**	**0.000**	**1.000**
	Total	**6.117**	**0.001**	**0.945**
Acknowledge	General	1.680	0.185	0.409
	Specific	**2.889**	**0.046**	**0.650**
	Total	**6.131**	**0.001**	**0.946**
Totals	**Total Commo**	**6.109**	**0.001**	**0.945**
	Anticipation Ratio	**11.083**	**0.000**	**0.998**

Communications

The communication measures were analyzed using a GLM ANOVA. The results of the ANOVA for team communication measures are summarized in Table 4 (α=. 05). Figure 22 displays the overall communication rates between information configurations. While requests for information showed no significant change across information distribution levels, there were significant differences in transfers of information, acknowledgements of receipt of information, total communications, and the anticipation ratio. The trend was a general increase in the rate of transfers of task relevant information, acknowledgements, and total communications in response to a complementary configuration of information. Additionally, the rate of transfers of non-relevant information decreased.

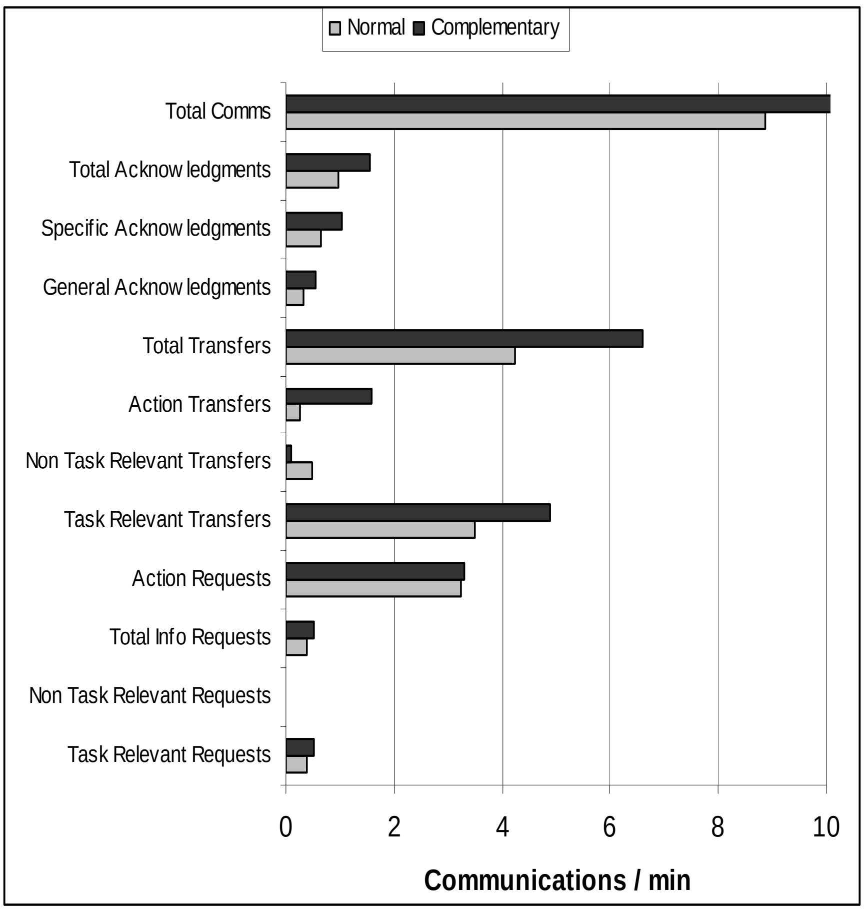


Figure 22. Nominal communications (automobile domain).

Requests were recorded when either team member explicitly asked for information or action from the other team member. Most of the requests were for information regarding the team task; specifically, the navigator requested numerous actions from the driver (e.g., turn right on E Street). There were few requests for non-relevant information. There was no significant difference in the team's requests as information levels varied.

Transfers were categorized in the same fashion as requests. Transfers of non-relevant information decreased, and task relevant information remained constant as information became more complementary. Teams became more focused on the navigation task and the transfer of relevant information to their team member. Furthermore, transfers of action increased significantly. An action transfer was recorded when one team member verbalized their actions to the other team member. The majority of transfers of action originated from the driver. During runs where information was complementary, drivers tended to verbalize their actions more frequently.

Acknowledgements of information were classified as general or specific and were recorded when a team member verbally acknowledged that they received information from the other team member. A general acknowledgement was one in which the team member verbalized that they heard the information (i.e., Roger, Okay, Got it). A specific acknowledgement not only confirmed that the information was heard, but the information was repeated (i.e., Roger…turn right on E Street). This type of acknowledgement ensured that the information that was heard was the correct information. There was a significant increase in specific and total acknowledgements as information became more complementary.

Total Communication (TC) was a combination of requests, transfers, and acknowledgements. TC significantly increased as information became more complementary. This measure indicated that the team verbalized more information, but indicated nothing concerning the quality of information. Based on the increase in action transfers and acknowledgements, TC was expected to increase.

The anticipation ratio was calculated using transfers and requests of task relevant information only. Using the communication matrix in Figure 20, the anticipation ratio was calculated by dividing all task relevant information, action, and acknowledgement transfers by all task relevant information and action requests ([Transfers of Task Relevant Information + Transfers of Action + Total Acknowledgements] / Requests for Task Relevant Information).

The anticipation ratio increased significantly during the information levels where the navigator did not have access to the out-of-window view. This indicated that during these scenarios, team members were anticipating the information required by the other team member (Figure 23).

Workload

Workload was measured using the RTLX. Only one significant difference in workload measurements was found to be caused by levels of information (Table 5); the navigators' perceived effort increased in the complementary configurations when compared to the normal configurations. Additionally, further analysis showed that teams experienced a higher level of frustration during the off-nominal runs compared to the nominal runs.

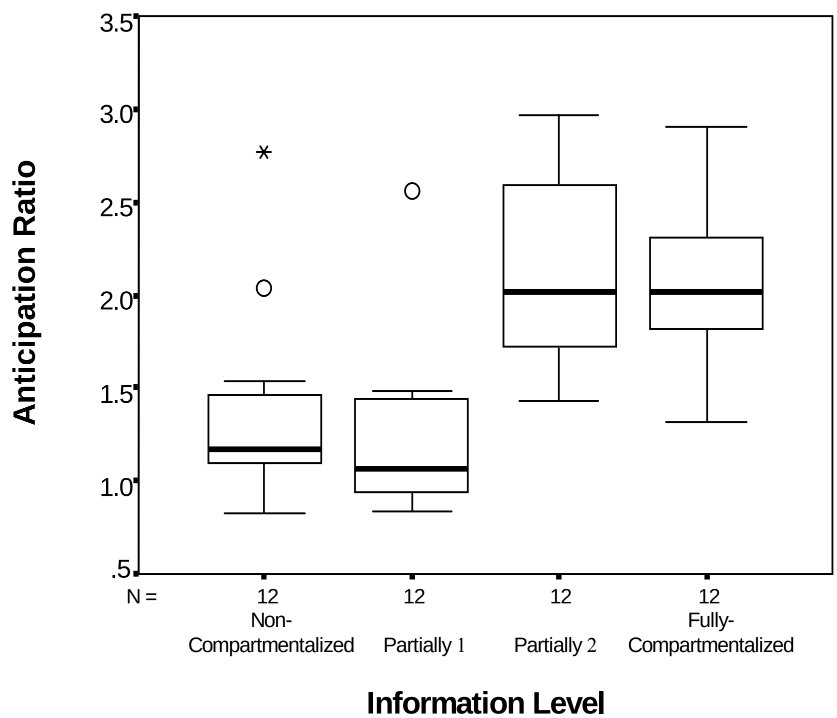


Figure 23. Anticipation ratio box

Table 5.
Individual crewmember workload significance levels.

	Nominal		Off-Nominal	
	Driver	Navigator	Driver	Navigator
Mental	0.871	0.326	0.748	0.664
Physical	0.544	0.490	0.568	0.742
Temporal	0.828	0.437	0.592	0.914
Effort	0.881	**0.042**	0.334	0.830
Performance	0.699	0.271	0.914	1.000
Frustration	0.903	0.178	0.668	0.238

Participant effects

For the first experiment, a Greco-Latin Square design was used to minimize any effects of the scenario, order, and training, and to isolate the effects of the independent factors. In the second experiment, the information distribution conditions were balanced and treated as a between-subjects variable for this run; the same scenario was used for all teams. Participant effects on communication and performance were not significant to the findings in this experiment and are detailed in Appendix A.

Conclusions

All hypotheses were supported by the data from this experiment. The results of this experiment have shown that as information is distributed in a complementary condition:

- Team performance generally remained constant under nominal conditions; when complementary levels were aggregated, team members actually navigated more accurately in the fully complementary configuration.
- Decision time decreased during off-nominal conditions.
- Task relevant communications increased.
- Non-relevant information transfers decreased.
- Anticipation ratio (of task relevant information) increased.

Designing a system such that task specific information is provided to individual team members when they need access to it, while limiting their access to non-relevant information, changes a team's communication strategy. This change occurs because teams develop complementary team mental models through explicit communication. In this experiment, the change in communications was manifested through a significant increase in explicit feedback between team members and a greater anticipation of team members' information requirements. These are both essential elements in the development of, and are indicators of congruent team shared mental models (Cannon-Bowers, Salas, and Converse, 1993; Orasanu and Salas, 1993; Stout et al., 1999).

Current literature has focused on training as an effective method for increasing the accuracy of team shared mental models (Cannon-Bowers, Salas, and Converse, 1993; Duncan et al., 1996; Minionis, Zacarro, and Perez, 1995; Orasanu and Salas, 1993). Results of this experiment indicate that it is possible to improve teams' mental models through system design by supporting the development of complementary team mental models. Investigators hypothesize that the results of this experiment are not domain specific. To investigate this hypothesis, a similar experiment was conducted in a separate domain, an aircraft cockpit. Additionally, more explicit measures of the complementariness of team mental models and individual performance were incorporated in this second experiment.

Experiment II: NUH-60 helicopter simulator

The overarching objective of this study was to test the hypothesis that providing task relevant information to individual team members in a time critical environment, while limiting their access to non-relevant information, would foster developing complementary team mental models with corresponding improvements in team process and performance. This was accomplished by imposing two different levels of complementariness of information between team members and observing the effect on team communication, team and individual task performance, team and individual workload, and timeliness and effectiveness of team decision making in nominal and off-nominal conditions. Variations in these dependent measures provide insight into the benefits of forming complementary mental models of team information requirements and, furthermore, whether the accuracy of individual mental models is improved when information is distributed in team domain based on task requirements. As in Experiment I, a condition characterized as *nominal* implies that no experimental changes/inputs were imposed on the team which altered their planned navigational flights. During off-nominal conditions, teams were forced to alter their planned flights due to unexpected events imposed by the researchers. Specific hypotheses that support this overarching objective are:

- *Hypothesis 1*: Team and individual performance, during nominal conditions, will remain constant when information is complementary when compared to performance during nominal conditions in a normal cockpit configuration.
- *Hypothesis 2*: Team and individual performance during off-nominal conditions will improve when information is complementary when compared to performance during off-nominal conditions in a normal cockpit configuration.
- *Hypothesis 3*: Explicit, task relevant, verbal communications will increase when information is complementary in both nominal and off-nominal conditions when compared to communications in a normal cockpit configuration.
- *Hypothesis 4*: The team's task relevant anticipation ratio will increase when information distribution is complementary when compared to operations in a normal cockpit configuration.
- *Hypothesis 5*: Team member information requirement rankings will be more similar when information is complementary when compared to rankings elicited while operating in a normal cockpit configuration.
- *Hypothesis 6*: Individual workload ratings will remain constant between information levels regardless of cockpit configuration.
- *Hypothesis 7*: Team member ability to estimate each other's workload rankings will improve when information is complementary when compared to rankings during operations in a normal cockpit configuration.

This is the second of two experiments designed to investigate the effects of organizing information within a complex environment to enhance the development of Complementary Team Mental Models (CMM); the first experiment was conducted in an automobile simulator. The complex environment selected for this experiment was the cockpit of a Utility Helicopter-60 (UH-60), a modern helicopter that is currently flown in both the Air Force and the Army. The levels of organization of information presented to the participants ranged from the current organization of information in the cockpit (normal) to a complementary organization of information. Some information was available to both team members (common), while other information was only made available to a certain team member, and not the other, to support their individual and team tasks. Various metrics were used to examine whether reorganizing information in this manner had a positive or negative effect on team communication, team and individual task performance, workload, and timeliness and effectiveness of team decision-making.

As noted in the previous section, analysis of the experiment conducted in an automobile simulator resulted in the identification of significant variations in some of the measures described above. The results indicated that providing task relevant information to individuals while limiting their access to non-relevant information improved the effectiveness of communications and led to better performance in both nominal and off-nominal conditions. These results indicated that designing a system's information distribution in a manner that supports the development of a CMM positively effects critical team performance metrics.

This subsequent experiment (1) investigated the design implications implied by the results from the first experiment concerning team performance through more in-depth measures of team and individual performance, (2) investigated the effects of complementary information distribution on individual performance by adding measures for individual performance, and (3) tested that the generalizability of the results found in the automobile experiment were not domain specific. Although the environment of the first experiment was clearly complex, participants were familiar with the task, but not highly trained in teamwork or navigation techniques. In contrast, the participants in the second experiment were professional military aviators, trained on team resource management tasks and, specifically, the task of aircrew navigation. Through the use of work domain analysis and task analysis techniques, the two experiments were designed to be similar in task requirements, performance measurements, and verbal/written assessments.

Method

This experiment was conducted at the U.S. Army Aeromedical Research Laboratory (USAARL), located at Fort Rucker, Alabama using military helicopter pilots as participants. The main parameter was the complementariness of task specific information available to team members. During the experiment data were collected concerning team communications, team workload, information requirements, decision-making, and performance, while the participants conducted a navigation task in a time critical situation. Each team member assumed a different role in the team, either the pilot or the navigator and maintained their assigned role throughout the entire experiment (i.e., there was no role switching).

Participants

Participants were 20 U.S. military rated aviators tested in pairs with the following characteristics:

- The military rank ranged from Chief Warrant Officer II through Lieutenant Colonel.

- Participants' ages ranged from 24-57; average age was 39 years.
- Total flight hours ranged from: 210 to 11,180; average was 3,290 hours.
- Each team was required to have at least one team member rated in a dual engine aircraft.
- 50% of the teams were qualified in the UH-60.

Participants were recruited from the pilots assigned to the 23d Flying Training Squadron; USAARL; and 1st Battalion, 14th Aviation Regiment. All units were located at Fort Rucker, Alabama. Participants received flight bags donated by "Flight Safety International" as a memento for participation.

Experiment apparatus

A qualified simulator operator operated the NUH-60 Black Hawk helicopter flight simulator used for this study; see Figures 24 and 25. This provided an interactive environment in which team performance could be observed, while certain parameters within the team were controlled. In order to force the division of information during the flight segments, the view of the instruments was blocked for the pilot and/or navigator. This was accomplished by physically obstructing the view of certain instruments in the cockpit with cardboard dividers and Velcro. Foggles are manufactured glasses that are used as a tool during instrument training to limit the pilot's field of vision. This assists the learning process by encouraging the pilot to fly with only the help of the flight instruments. In this case, they were used to restrict the navigators' field of view and, therefore, information available to him.

Figure 24. Cockpit of the NUH-60 Black Hawk simulator.

Figure 25. NUH-60 observer/operator console.

During all data collection runs, video and sound was recorded. The cameras were permanently mounted in the simulator. The recording equipment was located in a simulator monitoring room. The flight profiles in this experiment have supporting documentation such as maps, route cards, and approach plates. The route cards, the approach plates, and airfield information are included in Appendix B. Aircraft checklists were not available to pilots; checklists are designed as a back up to information that is required to be memorized and therefore, should not have a negative effect on the experimental outcome.

<u>Experiment procedure</u>

- Introductory briefing.
- Sought informed consent from participants. The consent form contained information regarding the scope of the study, the tasks that were performed by the volunteers, and the volunteers' rights as participants, as well as any risks associated with their participation. This form is contained in Appendix B.
- Explained the experiment.
- Detailed the schedule of events.
- Oriented participants with the facilities.
- Collected demographical data from participants.

Training run

A training run was conducted to ensure that each participant was familiar with the systems in the aircraft, the instrument displays, and the area of operation.

Data runs

Participants conducted three navigation runs during which data were collected, two nominal data runs (no emergency operations required), and one off-nominal data run (emergency conditions were presented). Immediately following each of the navigation runs participants completed surveys regarding their workload, performance, etc. for themselves and for their team member.

End of experiment survey

Following the complete experiment, individuals completed a final survey concerning overall themes of the experiment. The entire procedure lasted approximately 2.5 hours for each team; this included introduction briefing, simulator familiarization, training runs, data runs, and all surveys. Participants were free to request a break at any time.

Experimental tasks

The NUH-60 helicopter flight simulator was used for this experiment. The experiment was designed to collect data concerning team coordination, decision-making and performance while conducting a navigation task under a time critical situation. Each team member assumed a different role in the team, either the pilot or navigator. The team was given a map and textual directions to various locations within the simulated environment. They were asked to navigate in two specific conditions (nominal and off-nominal). Under nominal conditions, participants were asked to conduct two navigation runs. During these runs, the pilot and navigator were placed in scenarios that were functionally equivalent. They started at a specified location and were asked to navigate to a destination; the information provided to team members was varied during these runs. Teams were asked to maintain control of the aircraft, obey air traffic control, and navigate to the location given on their map using the route provided. Teams were expected to conduct individual tasks (i.e., maintain aircraft control, conduct fuel computations), team tasks (i.e., navigation), coordinate their actions as a team, and communicate their actions, intentions and requests for information.

They started at a specified location and were asked to depart via normal take-off, navigate to a destination, and land at the destination using standard route cards; the independent variable, the level of information provided to team members, varied during these runs. Teams were given a map with a route; a route card with headings, altitudes, airspeeds, and checkpoints; approach plates for local airfields; and a description of the landing area.

The off-nominal run consisted of one experimental run similar to the previous two, however, unexpectedly to the team, they were forced to enter Instrument Meteorological Conditions (IMC); subsequently the team was presented an in-flight single engine alternator failure. This run thus assessed team responses to an unexpected, 'off-nominal' scenario. In addition to the expectations for the nominal condition, teams were expected to formulate a plan upon entering IMC, continue to navigate to their final destination, and properly diagnose the in-flight emergency procedure.

Experimental design

The study consisted of two experiments run sequentially; participants were unaware that there were two experiments. The first experiment design consisted of two runs that examined performance under nominal conditions, during which the two levels of information distribution (complementary and normal) were varied. This experiment was balanced within subjects to account for order and training effects. The second experiment consisted of one experimental run similar to the previous two. However, the team was required to deviate from normal procedures (i.e., react to an in-flight emergency). This was a balanced between subjects design between the two information distribution levels.

Independent factors

There were two independent factors in this experiment: complementariness of information and operational condition.

Complementariness of information

Two levels of information distribution were presented to the participants: normal and complementary. Team member information requirements were based on the domain and task analysis described in the section on the determination of task information requirements. This analysis determined the information that each team member required access to in order to complete their individual and team tasks. The fundamental information required by each team member is shown in Figure 26. In the normal condition, the pilot and navigator were both given identical information; i.e., they both had access to all information displays in the cockpit and they were both given a map with a route posted. They also were given a route card with headings, altitudes, airspeeds, and checkpoints; approach plates for local airfields; and a description of the landing area. Under the complementary condition, individual team members were only provided access to information relevant to their individual tasks and for their defined roles in team tasks. Specifically, only the navigator was given a map with a route posted; a route card with headings, altitudes, airspeeds, and checkpoints; approach plates for local airfields; and a description of the landing area. Likewise, the navigator wore Foggles preventing out-of-windscreen viewing. The pilot had access to all flight instruments, but access to engine related performance instruments was restricted to the navigator. The navigator was not allowed to visually share the map, route card, etc. with the pilot.

Pilot	Flight Controls/Instruments Windscreen View Environmental Indicators
Navigator	Anolog/Digital Displays Clock Maps
Team	Voice communication Radios

Figure 26. Information sources.

Operational condition

Two operational conditions were presented to the participants: nominal and off-nominal. During nominal conditions teams maintained visual flight rules throughout the simulation, and they experienced no system malfunctions during the mission. During off-nominal conditions, teams experienced inadvertent instrument metrological conditions (IIMC) and a single engine alternator failure during the flight.

The flight profile incorporated various phases of flight during visual meteorological conditions (VMC) and instrument meteorological conditions (IMC). The profile has three sections to be flown in order, each lasting approximately 15 minutes. Flight phases of interest during VMC flight include take-off, VMC flight in cruise (above 200 ft AGL), and landing.

Flight phases of interest during IMC flight include take-off, straight and level flight, climbs, descents, standard rate turns, and landing. All flight maneuvers were flown in accordance with Army standards. A plan view of the profile is included in Appendix B and the profile segments are described in Table 6.

Table 6.
Flight profiles.

TASK	TASK DESCRIPTION	HDG/TRACK (DEGREES)	ALTITUDE (FEET)	AIRSPEED (KIAS)	TIME (MIN+SEC)
1	VMC Takeoff (500fpm)	230	0 AGL - 900 MSL	0 - 100	~2+00
2	Straight and Level – Cruise To Waypoint 1	226	900 MSL	100	~6+18
3	Straight and Level - Cruise To Waypoint 2	239	1300 MSL	110	~3+51
4	Straight and Level - Cruise To Waypoint 3	240	1100 MSL	90	~3+30
5	VMC Approach	240	1100 MSL - 0 AGL	90 - 0	~2+00
6	VMC Takeoff (500fpm)	240 - 332	0 AGL - 1000 MSL	0 - 80	~2+00
7	Straight and Level – Cruise To Waypoint 4	332	1000 MSL	80	~3+20
8	Straight and Level – Cruise To Waypoint 5	322	1400 MSL	90	~5+30
9	Straight and Level – Cruise To Waypoint 6	348	1100 MSL - 0 AGL	80	~4+12
10	VMC Approach	348	1100 MSL - 0 AGL	80 - 0	~2+00
11	VMC Takeoff (500fpm)	348 - 085	0 AGL - 1000 MSL	0 - 120	~2+00
12	Straight and Level – Cruise To Waypoint 7	085	1000 MSL	120	2+00
13	IIMC (Climb @ 500 fpm)	085 - 070	1000 MSL – 2000 MSL	120	2+00
14	Straight and Level (Vectors)	070	2000 MSL	120	1+00
15	Straight Climb	070	2000 MSL – 4000 MSL	120	2+00
14	Straight and Level/Emergency Procedure (Alternator Failure)	070	4000 MSL	120	2+00
15	Straight Descent	070	4000 MSL – 2100 MSL	120	4+00
16	Straight and Level	070	2100 MSL	120	1+00
17	Right Standard Rate Turn	070 - 140	2100 MSL	120	0+30
18	ILS Rwy 23 (Campbell AAF)	225	2100 MSL - 773 MSL	120	3+00

Dependent factors

During the experiment, data were collected through several means. The simulator compiled performance data (root mean square error [RMSE] for altitude, airspeed, rate of climb, rate of descent, heading, and rate of turn). The screen of the out-the-window view was synchronized with video of the pilot and navigator via split screen video, and an observer was present behind the cockpit, in an observation area, to record any anomalies. Furthermore, immediately following each of the scenarios, participants were asked to complete surveys regarding their workload, performance, information requirements, etc. Following the complete experiment, individuals were asked to complete a final survey concerning overall themes of the experiment. The data were categorized into three main groups: Performance, Communication, and Survey (RTLX, information requirements, and demographics).

Performance

During nominal conditions, performance was gauged by flight performance measures recorded by the simulator: RMSE of airspeed, altitude, and heading, and rate of climb. Additional task performance measures were evaluated:

- *Completion of required radio calls*: Teams were given a list of radio calls required in each flight leg. This metric is represented by a percentage of those calls that were actually completed.
- *Calculation of estimated time enroute*: During each run, navigators were required to calculate the estimated time enroute for two legs of the route.
- *Initiation of a fuel consumption check*: Teams were required to initiate a fuel consumption check during each run; this metric indicates whether or not this was completed.
- *Navigation and process errors*: Navigation errors concerned time, heading, distance, altitude, etc. Process errors include using the wrong frequencies and using the wrong procedures.

During the off-nominal condition, in addition to the measures used in the nominal condition, the following task performance measures were assessed:

- *IIMC call time to Campbell Army Airfield (CAAF)*: This was the time recorded from when the team entered IMC until they notified CAAF.
- *Proper IIMC procedures*: An indicator of whether the team performed the proper IIMC procedures in accordance with the aircrew-training manual.
- *Diagnosis time of emergency*: Time was recorded from the presentation of the emergency until the team verbalized the problem or the corrective action needed.
- *Diagnosis of the proper emergency procedure*: This metric indicated whether the proper emergency procedure was executed.
- *Emergency call time to CAAF*: This was the time recorded from when the team was presented with the emergency until they notified CAAF.

Communication

Communication measures were determined using the matrix in Figure 27. Verbal communications were categorized in three basic categories: transfers, requests, and acknowledgements (Entin and Entin, 2001). Throughout the experiment, both video and audio of the participants were recorded. Following the experiment, an analyst reviewed the videos of each team and recorded the data in this format. The communication data were normalized based on the length of each experimental run. Additionally, communication transfers were divided by communication requests to establish an "anticipation ratio." Anticipation ratios have often proved more useful than individual rate measures for understanding team communications (Entin and Entin, 2001). The first study conducted in this research corroborated the finding in literature that larger anticipation ratios indicate increased anticipation of team member information needs. Variations in team communication measures provide insight into the complementariness of the teams' mental models of team interaction and the accuracy of individual mental models of the environment.

Type & Content		Navigator to Pilot	Pilot to Navigator	Total
Request	Task Relevant Information			
	Non Task Relevant Information			
	Action			
Transfers	Task Relevant Information			
	Non Task Relevant Information			
	Performing/Will Perform Action			
Acknowledgements of Info Receipt	General (okay,roger)			
	Specific (roger...right on turn to 180 degrees)			

Figure 27. Communications matrix (NUH-60).

Workload

Workload was measured through the use of the NASA TLX. Between each experimental run teams completed a RTLX survey. Six subscales of workload were collected: mental demand, physical demand, temporal demand, performance, effort, and frustration. Byers, Bittner, and Hill (1989) proposed the RTLX method as a simplified but as effective method as the full NASA TLX. The RTLX method does not require task-paired comparison as the full NASA TLX does (Byers, Bittner, and Hill, 1989). These measures were collected for self assessment and assessment of team members' workload. Appendix B contains the questions and rating scale for this instrument.

Information requirements

After each scenario, participants were asked to rank the importance of their information sources during each phase of flight (Figure 28); participants ranked the importance of the types of information during different phases of flight. They rated how important each type of information was to them and how important they thought it was for their team member. This was done for each phase of flight: take-off, enroute navigation, and landing during nominal conditions and upon entering IMC and dealing with the emergency procedure in off-nominal conditions. This survey is included in Appendix B.

Scenario design

Phase of Flight						
Take-off	En-route	During IIMC procedure	During Emergency procedure	Landing	**Information Type**	**Description**
					Current Flight Information	The current airspeed, altitude, heading, climb rate etc. of the aircraft
					Future Flight Information	The future airspeed, altitude, heading, climb rate etc. that you will be required to fly
					Current Environmental Information	Description of the environment, terrain, checkpoints, etc. that you are currently flying in/over
					Future Environmental Information	Description of the environment, terrain, checkpoints, etc. that you will be flying in/over in the near future
					Aircraft Instrumentation Status	Status of the aircraft instrumentation (fuel, engine instruments, etc)

Figure 28. Information requirements

A total of four scenarios were developed: one training scenario, two nominal scenarios, and one off-nominal scenario. Following the introduction, individuals were taken through the training session. The training was designed to familiarize the pilot with the feel of the simulator controls, the simulated area of operation, and the type of scenarios that they would be expected to complete. No data collection was done at this time. The simulator operator/instructor pilot described the instrumentation in the cockpit; then the team conducted a normal take-off from CAAF and normal landing to a forward arming and refueling point (FARP). All teams generally used the same training scenario. Pilots that were qualified in the UH-60 required less familiarization of the cockpit instruments than pilots that were not qualified in the UH-60.

Two nominal scenarios were next presented to the participants. The nominal runs were always during the first two legs of the route structure (Figure 29). During these runs, the teams faced similar scenarios for each leg. These scenarios created time pressure and emphasized the importance of mission success. During each scenario, teams started at a specified location and were asked to depart via normal take-off, navigate to a destination, and land at the destination using standard route cards. The independent variable, complementariness of information provided to team members, was varied during these runs. This investigation was not intended to test the effects of pre-planning; therefore, teams were not given a dedicated time to plan a teamwork strategy. They were given a map with a route posted; they were also given a route card with headings, altitudes, airspeeds, and checkpoints, approach plates for local airfields, and a description of the landing area. The runs were each approximately 15 minutes long and a break was given between them.

The one off-nominal scenario was always presented during the third leg of the route structure. This run, unexpectedly to the team, caused them to enter IIMC; subsequently the team

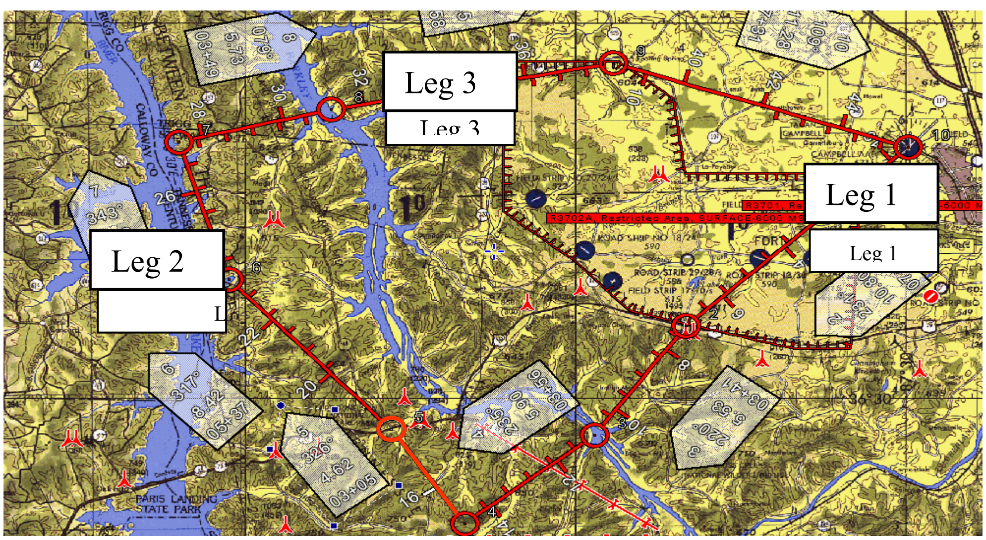


Figure 29. Route structure.

was presented an in-flight aircraft emergency, a single engine alternator failure, along their designated route. This run was designed to assess team responses to an unexpected, ‘off-nominal' scenario. The two levels of information distribution were treated as a between-subjects variable; the same scenario was used for all teams.

The nominal scenarios were functionally equivalent; off-nominal scenarios were identical. A plan view of the three data collection runs, a description of scenarios and route cards, and a description of the airfield and approaches available at the airfield are included in Appendix B. Examples of a scenario and route card (Figure 30), for nominal conditions, are provided below. Example nominal condition scenario

This was given and read to the pilot and navigator:

Waypoint	WPT Description/ Coordinates	Course / Distance (nm/km)	ETE	Maneuver Description
				VMC takeoff 230° from Campbell Army Airfield
1	Road Intersection N36°32.91' W087°39.93'	226° / 10.5/19.3	TBD	Cruise Flight 900' MSL, 100 KIAS
2	Mouth of Inlet (Bridge) N36°28.52' W087°44.11'	239° / 7.1/13.2	TBD	Cruise Flight 1300' MSL, 110 KIAS
3	FARP 1 N36°25.00' W087°49.99'	240° / 5.8/10.8	TBD	Cruise Flight 1100' MSL, 90 KIAS

Figure 30. Sample route card.

You are assigned the mission of transporting two passengers (captured Al Qaeda operatives) from Campbell Army Airfield to FARP 1. The mission is critical and must be completed to avoid an international incident. The only reason to abort or modify the mission will be in the event of an emergency situation requiring a landing as soon as possible. Due to security concerns, a special VMC flight corridor to the FARP has been established. The GPS is inoperative and you must navigate by pilotage and dead reckoning. You <u>must</u> follow altitude, airspeed and ground track restrictions in accordance with the waypoint card in order to comply with the corridor requirements. Navigator is required to calculate estimated time enroute for each checkpoint. In addition to standard ATC radio calls, the pilot is required to contact ATC no more that one minute prior to crossing each checkpoint final destination. Maintain visual flight rules (VFR). Weather for the mission is winds calm, 1500 feet overcast; 3 statute miles visibility (ETA through 1 hour). Use ATC frequencies per the DOD FLIP. FARP 1 frequency is 34.15.

Results

In total, 40 runs were flown: 10 teams completed 10 familiarization, 20 nominal, and 10 off-nominal runs. The data were categorized into three main groups: Performance, Communication, and Survey (NASA RTLX, information requirements, and demographics).

The following statistical tests were used:

- GLM ANOVA
- The Mann-Whitney U test
- Kruskal-Wallis test
- Spearman Rank Order Correlation Coefficient
- Binomial test

SPSS 13.0 for Windows Graduate Student Version, released September 1, 2004, was used to perform the statistical analyses. Details concerning the computational algorithms can be found at http://www.spss.com.

Performance

Measures of flight performance were analyzed using a GLM ANOVA. Tasks 1-10 (Table 6) were completed during nominal conditions. The first five tasks were completed during the first run; the second five tasks were completed during the second. During nominal conditions, no significant differences were found to exist due to changes in the distribution of information within the cockpit.

The measures of task performance did not fit the normality requirements for ANOVA. Therefore, each was examined using a Mann-Whitney test to identify the main effects of the independent variable (Table 7). Total errors ($p = .015$) were significant; both process errors and navigation errors were on the borderline significance at the 5% level. Table 8 indicates the *total count of errors* committed by category. Fewer errors were committed in the nominal condition when the information available was distributed in a complementary manner.

Table 7.
Mann-Whitney non-par test: subjective performance measures (nominal).

	Fuel	ETE	Calls percent	Navigation errors	Process Errors	Total errors
Mann-Whitney U	30.000	45.000	34.500	26.000	35.000	20.000
Wilcoxon W	85.000	100.000	89.500	81.000	90.000	75.000
Z	-1.744	-.457	-1.329	-1.934	-1.831	-2.437
Asymp. Sig.	.081	.648	.184	.053	.067	.015

Table 8.
Errors committed (nominal).

Complementary Information	Navigation Errors	Process Errors	Total Errors
No	12	3	15
Yes	5	0	5

Tasks 11-20 from the flight profile table (Table 6) were performed during the off-nominal run. Once again, the flight performance measures were analyzed using a GLM ANOVA. The results are shown in Table 9. During task 11, entry into IIMC, the *RMSE for airspeed* was found to be significantly different as the independent variable changed (p= .020). The box plot of the root mean square error of airspeed shows that the median and mean RMSE improved in the complementary condition from 23.5 to 19.5 and 22.25 to 19.08, respectively (Figure 31). Furthermore, the box plot indicates that the interquartile range of error in the complementary condition is less than the normal condition.

A number of the measures of task performance could be analyzed using the GLM ANOVA; however, others were found not to fit the normality requirements for ANOVA. The non-parametric measures were examined using a Mann-Whitney test to identify the main effects of the independent variable. Significant results were identified when examining the percent of radio calls completed and emergency procedure diagnosis time. These are discussed below.

Table 9.
ANOVA: objective performance measures: airspeed (off nominal).

Dependent Variable: Asp_rmse

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Noncent. Parameter	Observed Power[a]
Corrected Model	25.091	1	25.091	8.352	.020	8.352	.717
Intercept	4270.836	1	4270.836	1421.581	.000	1421.581	1.000
Compart	25.091	1	25.091	8.352	.020	8.352	.717
Error	24.034	8	3.004				
Total	4319.960	10					
Corrected Total	49.125	9					

a. Computed using alpha = .05

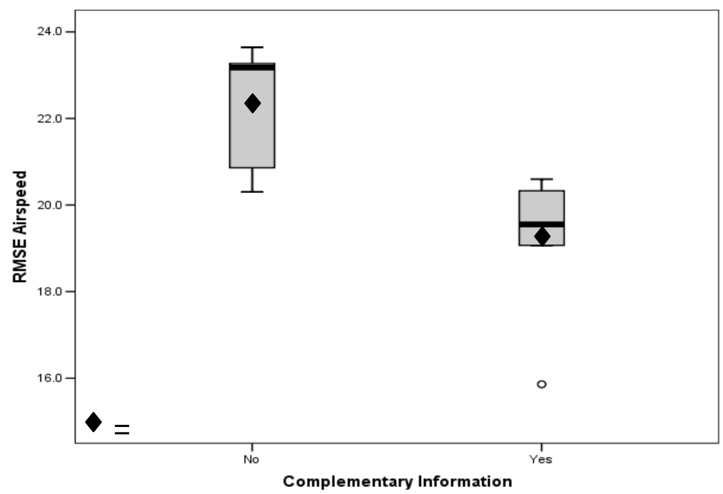


Figure 31. Box plot RMSE airspeed.

Across the complete flight profile for off nominal conditions the *completion of required radio calls* increased when the team was provided with complementary information. Table 10 tabulates the results of the Mann-Whitney test for the percent of radio calls completed. The p-value is .053, slightly above the alpha level used for this analysis (.05), but there is merit in presenting the findings. Figure 32 shows the direction of the difference and indicates the difference in completed radio calls under the normal condition; the navigators completed one hundred percent of the radio calls required during the complementary condition. Both the median and mean percent of completed calls increased across conditions, and performance was more consistent during the complementary condition.

Table 10.
Mann-Whitney test for percent of radio calls completed.

	calls percent
Mann-Whitney U	5.000
Wilcoxon W	20.000
Z	-1.936
Asymp. Sig. (2-tailed)	.053

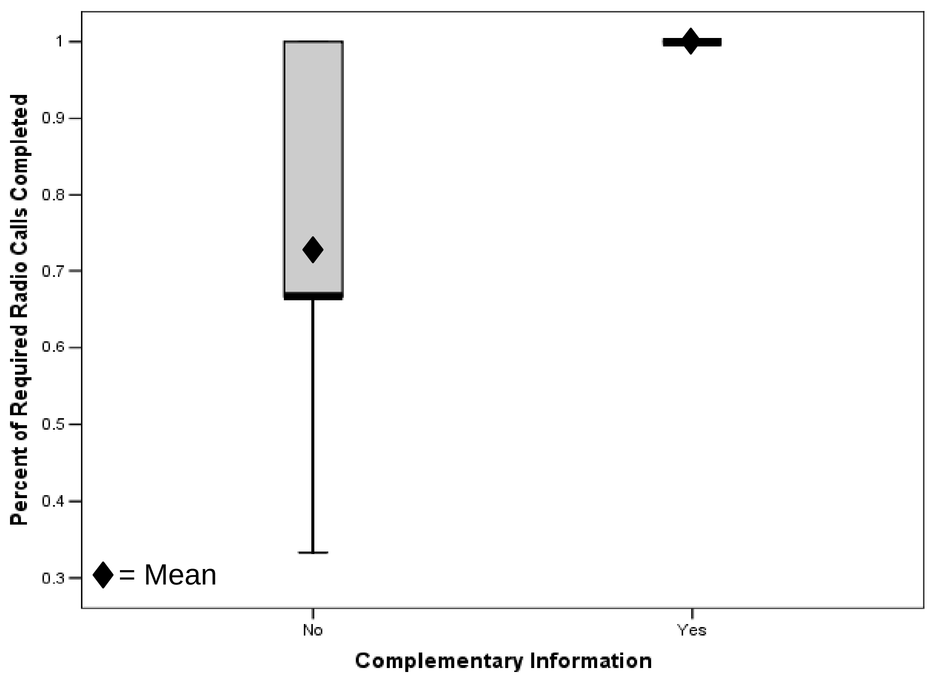


Figure 32. Box plot for percent of required radio calls completed.

Additionally, the *diagnosis time of aircraft emergency*, measured in seconds, was analyzed using a GLM ANOVA and was found to have significant differences between the levels of information complementariness; the p-value was .007 with an observed power of .912. Complete results of the ANOVA are shown in Table 11. Figure 33 illustrates the direction of the difference and highlights the significant decrease in diagnosis time. Both the median and mean diagnosis time decreased across conditions from 130 to 49 and 115.3 to 39.4 seconds, respectively. Furthermore, the standard deviation decreased from approximately 34 to 20 seconds.

<u>Table 11.</u>
Diagnosis time of aircraft emergency ANOVA.

Dependent Variable: diagnosis

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Noncent. Parameter	Observed Power
Corrected Model	10811.008	1	10811.008	16.041	.007	16.041	.912
Intercept	44892.008	1	44892.008	66.608	.000	66.608	1.000
Compart	10811.008	1	10811.008	16.041	.007	16.041	.912
Error	4043.867	6	673.978				
Total	51711.000	8					
Corrected Total	14854.875	7					

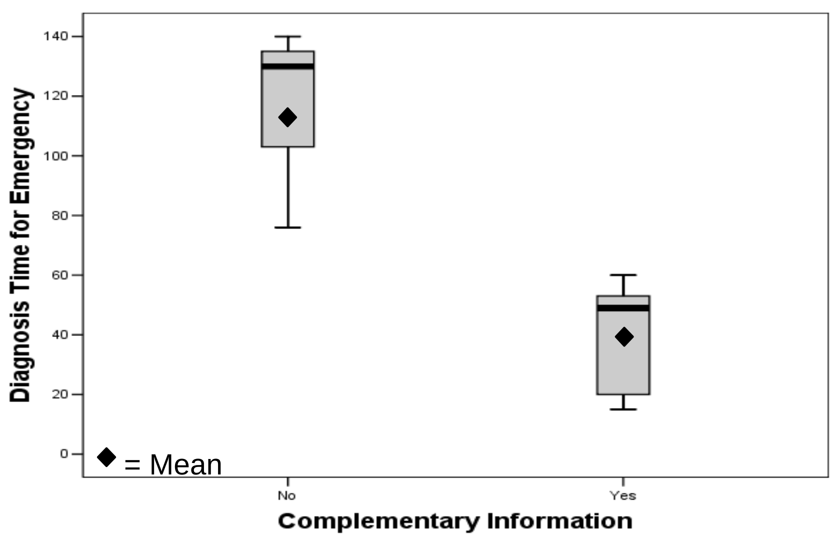


Figure 33. Box plot for diagnosis time of aircraft emergency.

Communications

For each run, communications were aggregated and analyzed at the team level. Therefore, each team contributed two sets of data (runs one and two) under nominal flight conditions and one set of data (run three) when exposed to off-nominal flight conditions.

A GLM ANOVA was used to evaluate all communication rates in the nominal condition. The results are presented in Table 12 and the significant dependent variable means are displayed in Figure 34. The following intermediate categories of team communication rates increased significantly when the team was exposed to a complementary information distribution: Team Transfers of Action (RTRA), Team Transfers of Task Relevant Information (RTTTRI), Team Total Transfers (RTTT), and Team Total Communications (RTTC).

Table 12.
Nominal communications ANOVA.

Source	Dependent Variable	Type III Sum of Squares	df	MSE	F	Sig.	Observed Power[a]
Compart	RTRTRI	.034	1	.034	1.053	.318	.163
	RTRIT	.034	1	.034	1.053	.318	.163
	RTRA	7.718	1	7.718	19.623	.000	.987
	RTTTRI	15.671	1	15.671	12.702	.002	.920
	RTTNTRI	.159	1	.159	10.377	.005	.861
	RTTA	.171	1	.171	1.364	.258	.198
	RTTT	15.785	1	15.785	14.840	.001	.953
	RTAG	.011	1	.011	.057	.814	.056
	RTAS	.544	1	.544	3.810	.067	.455
	RTAT	.707	1	.707	1.744	.203	.240
	RTTC	60.470	1	60.470	24.508	.000	.997
	RTAR	106.320	1	106.320	9.818	.006	.842

a. Computed using alpha = .05

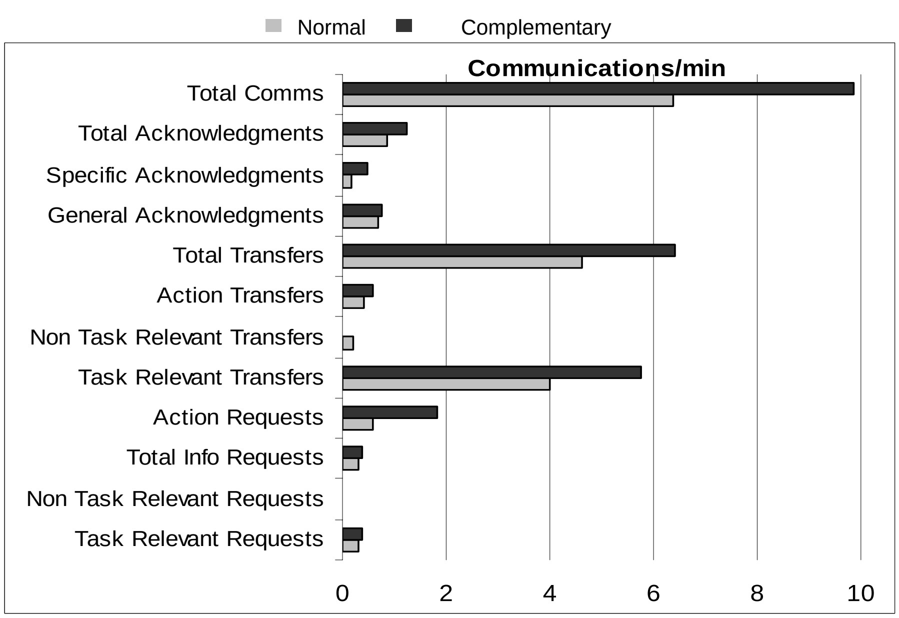


Figure 34. Communication means bar graph (nominal).

Furthermore, the rate of Transfer of Non-Task Relevant Information (RTTNTRI) decreased in the complementary configuration, as did the Team Anticipation Ratio (RTAR). Each detected change was accompanied by a strong observed power calculation; the lowest observed power was .842.

A GLM ANOVA was also used to evaluate all communication rates in the off-nominal condition. The results are presented in Table 13 and the significant dependent variable means are displayed in Figure 35. The results in the off-nominal condition were very similar to the nominal condition. The following team communication rates increased significantly when the team was exposed to a complementary information distribution: RTRA, RTTTRI, RTTT, Team Acknowledgements Specific (RTAS), and RTTC. In addition, the RTAR decreased in the complementary configuration. Each detected change was accompanied by a strong observed power calculation; the lowest observed power was .657.

Table 13.
Off-nominal communications ANOVA.

Source	Dependent Variable	Type III Sum of Squares	df	MSE	F	Sig.	Observed Power
Compart	RTRTRI	.035	1	.035	2.317	.166	.269
	RTRNTRI	.006	1	.006	1.000	.347	.143
	RTRIT	.012	1	.012	.869	.378	.131
	RTRA	6.074	1	6.074	22.520	.001	.985
	RTTTRI	9.493	1	9.493	12.348	.008	.867
	RTTNTRI	.004	1	.004	.699	.427	.115
	RTTA	.041	1	.041	.871	.378	.131
	RTTT	10.383	1	10.383	20.508	.002	.976
	RTAG	.001	1	.001	.021	.888	.052
	RTAS	.116	1	.116	7.261	.027	.657
	RTAT	.094	1	.094	1.271	.292	.169
	RTTC	37.248	1	37.248	37.525	.000	1.000
	RTAR	15.712	1	15.712	7.903	.023	.693

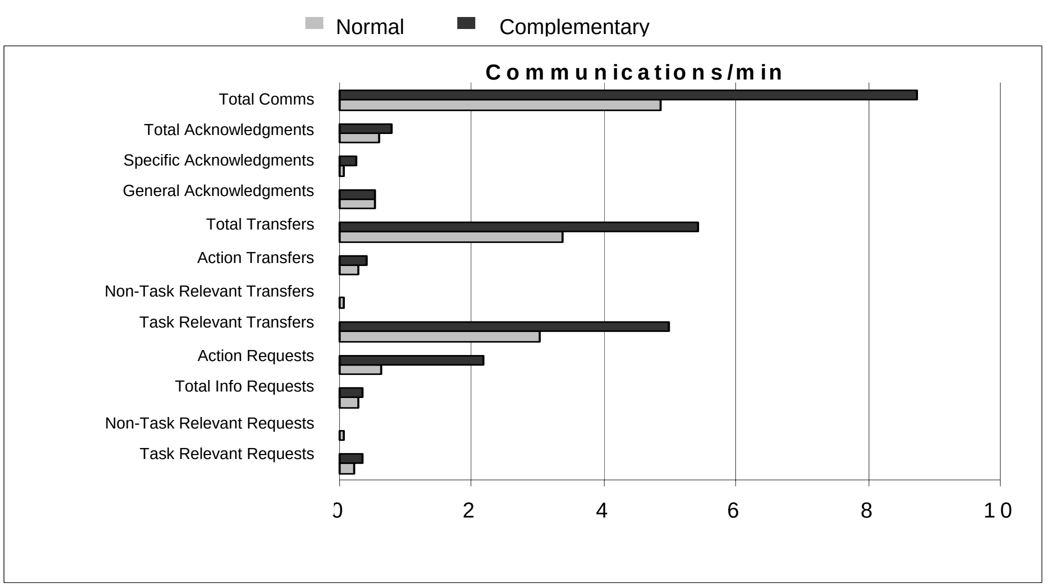
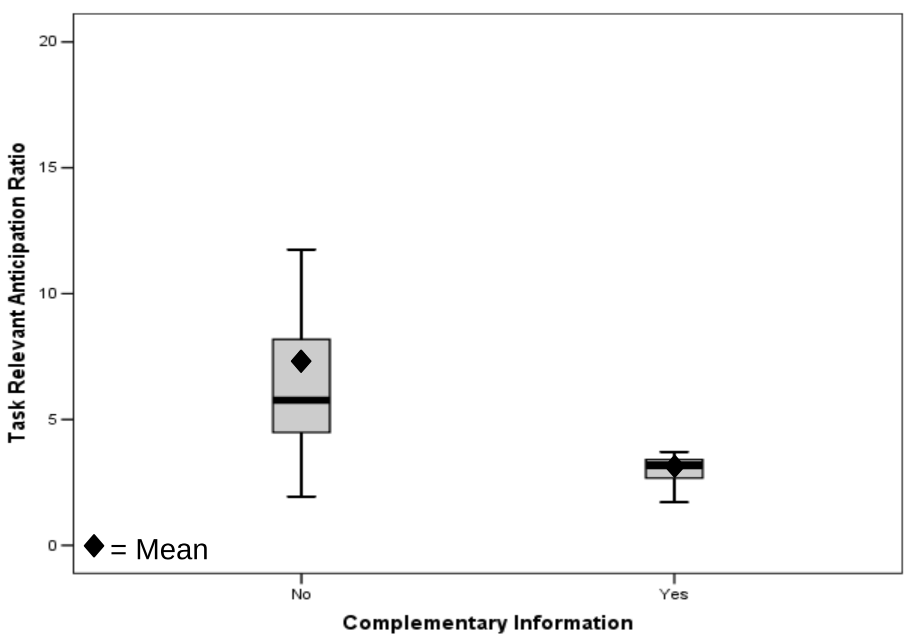


Figure 35. Communication means bar graph (off-nominal).

The disparity of results concerning the task relevant anticipation ratio between experiment one and two was radical. ANOVA of the communication metrics for this experiment indicate a significant p-value for both the nominal and off-nominal conditions; p = .006 and p = .023, respectively; across these conditions, the anticipation ratio decreased in the complementary configuration. The significant decrease in the median and mean between the two levels of information distribution has been tabulated in Table 14 and illustrated in Figure 36. In addition, each measure of dispersion in Table 15 shows a decrease, as well, from the normal configuration to the complementary configuration, to include interquartile range, standard deviation, variance, and range (min/max).

Table 14.
Descriptive statistics for anticipation ratio.

	Information Configuration	
	Normal	Complementary
Mean	7.02	3.11
Median	5.76	3.19
Variance	16.35	0.92
Std. Deviation	4.04	0.96
Minimum	1.94	1.71
Maximum	18.25	5.86
Range	16.31	4.15
Interquartile Range	3.75	0.96



Informat

Figure 36. Task relevant anticipation ratio box plot.

This section describes the results of analysis of a selection of survey questions concerning team member information requirements. Specifically, the following results address the ability, and difficulty, of each team member to identify and anticipate information required by the other team member in the normal and complementary cockpit configurations. Data were collected under nominal and off-nominal conditions.

The information requirements matrix (Figure 28) was used to record team member rankings. Three phases of flight were addressed in the nominal condition: takeoff, enroute, and landing. The three nominal phases, plus two additional phases, were addressed during the off-nominal condition: IIMC procedures and emergency procedures. Rankings of information requirements from the pilot and navigator were matched by phase of flight and a correlation matrix was developed using the Spearman Rank Order Correlation Coefficient. Relevant correlations were selected from the matrix and were analyzed using a GLM ANOVA for significant differences. The ANOVA performed for the nominal condition found no significant differences. On the contrary, differences in the means of correlation coefficients were significant in the off-nominal condition due to changes in the information distribution of the cockpit; the full ANOVA is displayed in Table 15. Figure 37 illustrates the increase in the median and mean from the normal distribution to a complementary distribution of cockpit information. The inner quartile range is consistent between information levels as is the standard deviation and variance.

The following questions were asked of each participant at the end of the experiment:

- In which condition were you more aware of your team member's information requirements (normal or complementary)?
- In which condition were your own information needs more clearly (normal or complementary)?

The results to these questions are displayed in Table 16. Over 80 percent of the participants that answered the survey question indicated that the complementary distribution of information within the cockpit provided more clarity to their own information requirements, and they felt they understood their team members' information requirements better. A binomial test was used to analyze the responses; the test proportion used for the analysis was .5 (50%), and both answers were significant at the 5% level.

<u>Workload</u>

Workload across information configurations was analyzed in three different manners: (1) Individual workload ratings were analyzed to determine whether individual team member's workload changed due to the cockpit configuration; (2) a separate survey question addressed their perceived overall workload; and (3) a correlation analysis, similar to the analysis completed for information requirements, was performed using each team member's estimations of their teammate's significant sources of workload. The findings for each of these methods are discussed below.

Table 15.
ANOVA for correlation matrix, off nominal.

Dependent Variable: Correlate

Source	df	MSE	F	Sig.	Observed Power
Corrected Model	1	.587	10.803	.0041	.874
Intercept	1	4.914	90.501	.0000	1.000
compart	1	.587	10.803	.0041	.874
Error	18	.054			
Total	20				
Corrected Total	19				

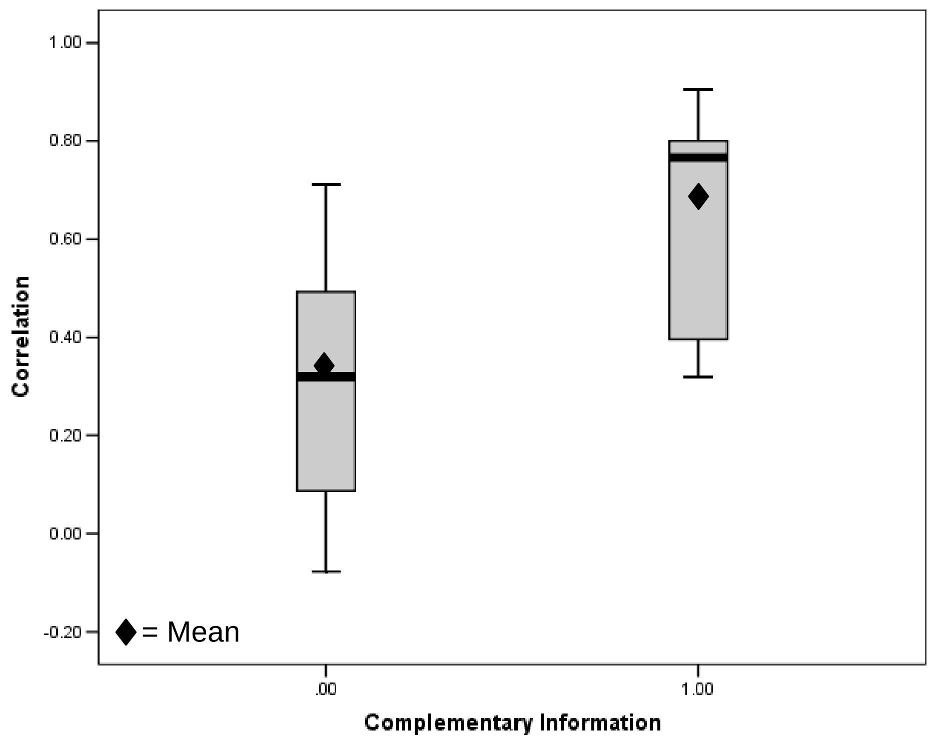


Figure 37. Box plot for Spearman Rank Correlation Coefficient.

Table 16.
Binomial test for awareness of information requirements.

		Complementary Information	N	Observed Prop.	Test Prop.	Exact Sig. (2-tailed)
Clarity of Crewmember's Requirements	Group 1	No	3	.18	.50	.013
	Group 2	Yes	14	.82		
	Total		17	1.00		
Clarity of own Requirements	Group 1	No	3	.17	.50	.008
	Group 2	Yes	15	.83		
	Total		18	1.00		

Individual workload ratings were assessed using the RTLX in Appendix B and analyzed in various groupings: aggregated to the team level, source, position, position and source, by configuration and by condition. The characteristics of the data were consistant with the assumptions necessary to analyze these data using ANOVA techniques. Therefore a GLM ANOVA was used for this analysis. Generally, there were minimal significant effects due to information complementariness on team member's workload; results of individual ratings by position and source are displayed in Table 17. The only significant change in mean ratings for individual workload due to the independent variable was detected in the navigator's mental workload in the nominal condition, which increased when operating in the complementary cockpit configuration. Additionally, the cells highlighted in yellow (italics in light gray fields) were marginally significant; these measures also increased in the complementary configuration.

Table 17.
Individual team member workload significance levels.

	Nominal		Off-Nominal	
	Helicopter		Helicopter	
	Pilot	Navigator	Pilot	Navigator
Mental	0.700	**0.015**	0.765	0.407
Physical	0.694	0.657	0.925	*0.053*
Temporal	*0.086*	0.262	0.500	0.310
Effort	0.613	*0.068*	0.535	*0.054*
Performance	0.804	0.874	0.743	0.559
Frustration	0.165	0.432	0.266	0.380

Teams were asked how difficult it was to coordinate actions with their teammate. Due to the non-parametric nature of these data, they were analyzed using a Mann-Whitney test. The results are shown in Table 18 and Table 19. The p-value of .06 was nearly significant (alpha = .05). The mean rank of the complementary configuration was lower than the normal condition, which, based on the scale above, indicated that team members felt that it was slightly more difficult to coordinate their actions when operating in the complementary configuration. The team member RTLX (Appendix B) was used to record team member rankings following each run. Team members were asked to estimate the sources of workload for their teammate using the modified NASA TLX scale. Based on their scores, the sources of workload (mental, effort, temporal, etc.) were rank ordered (1-6). Rankings from the pilot and navigator were matched, and a correlation matrix was developed using the Spearman Rank Order Correlation Coefficient. Relevant correlations were selected from the matrix and were analyzed using a GLM ANOVA for significant differences in correlation between information configurations. For instance, the pilot's ranking of the navigator's workload was matched with the navigator's ranking of the navigator's workload.

The ANOVA performed with the navigator as the estimator identified no significant results. On the contrary, differences in the mean correlation coefficients were marginally significant (p = .069) when the pilot estimated the navigator's workload. The complete ANOVA is displayed in Table 20. Figure 38 illustrates the increase in the median and mean from the normal configuration to a complementary distribution of cockpit information. The inner quartile range was decreased when the team operated in the complementary configuration (Figure 39).

Table 18.
Mann-Whitney Test for difficulty level.

	Difficulty
Mann-Whitney U	137.000
Wilcoxon W	347.000
Z	-1.880
Asymp. Sig.	.060

Table 19.
Mann-Whitney Ranks for difficulty level.

	Complementary	N	Mean Rank	Sum of Ranks
Difficulty	No	20	23.65	473.00
	Yes	20	17.35	347.00

	Difficulty Level			
Information Distribution	1=Very Difficult	2=Difficult	3=Easy	4=Very Easy
A: Normal	1	2	3	4
B: Complementary	1	2	3	4

Figure 38. Difficulty level survey question.

Table 20.
ANOVA Pilot Estimated Workload of Team Member Correlation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Observed Power
Corrected Model	.422	1	.422	3.582	.069	.447
Intercept	5.581	1	5.581	47.328	.000	1.000
complementary	.422	1	.422	3.582	.069	.447
Error	3.302	28	.118			
Total	9.306	30				
Corrected Total	3.725	29				

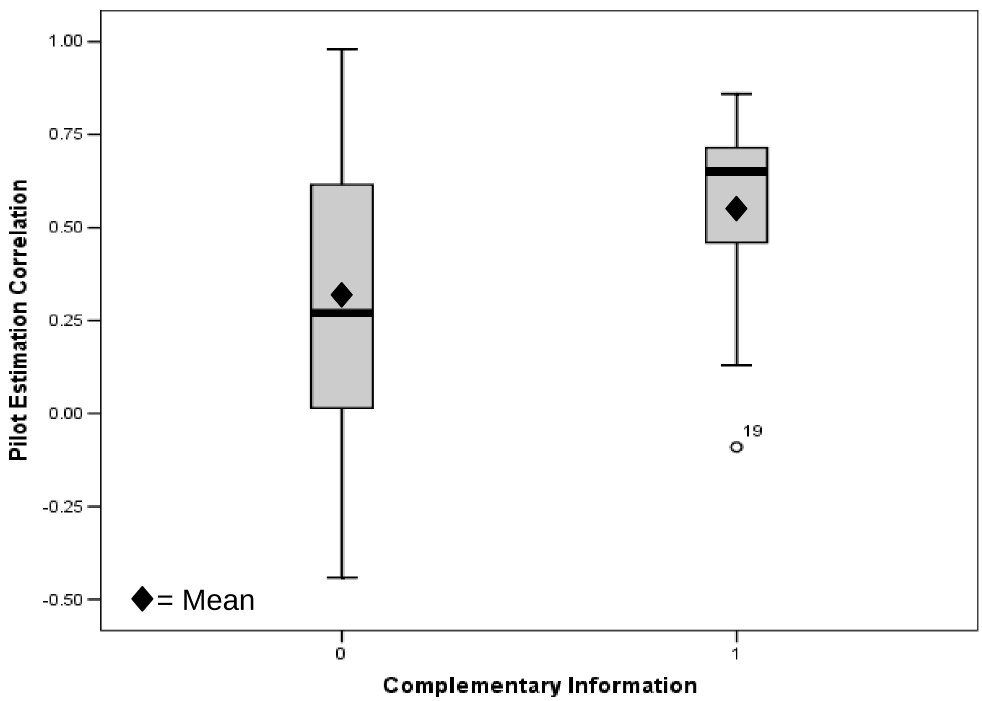


Figure 39. Box plot for pilot estimation correlation.

Participant effects

The first experiment was balanced within subjects to account for order and training effects. The second experiment consisted of one experimental run similar to the previous two; this was a balanced between subjects design between the two information distribution levels. Participant effects on communication and performance were not significant to the findings in this experiment and are detailed in Appendix B.

Discussion

As stated in the introduction, the overarching objective of this study was to provide empirical evidence that providing task relevant information to individual team members in a time critical environment, while limiting their access to non-relevant information, would improve team performance and change team interactions by developing complementary team mental models. Furthermore, this method of distributing information among team members would provide individual team members with a more accurate "task relevant" mental model of their own environment. Seven hypotheses were offered to test this theory and are discussed below.

Confirmation of experimental hypotheses

Hypothesis 1: Team and individual performance, during nominal conditions, will remain constant when information is complementary when compared to performance during nominal conditions in a normal cockpit configuration.

The set of performance measures for team and individual performance was a combination of both objective and subjective metrics. Individual performance measures showed no significant changes in their means, and total errors was the only team metric that showed a significant difference. Total errors *decreased* when teams operated in a cockpit that was configured with complementary information versus the normal configuration. Fifteen errors were committed in the normal condition versus five in the complementary configuration. This indicates that team members, under nominal conditions, performed better when the information in their environment was distributed in such a manner that individual tasks and responsibilities were supported more specifically. In terms of the hypothesis, generally team and individual performance remained constant, but total errors (process errors + navigation errors) decreased.

Nominal conditions are conditions that are:

- Highly proceduralized,
- Expected by aircrews,
- Practiced routinely,
- Operated in regularly, and
- Trained and cross-trained for by aircrews.

The fact that performance, other than errors, remained constant is a significant finding. This suggests that, in the current, normal configuration, there is information presented to team members that is not needed, nor used, to perform their individual tasks and team responsibilities; and when taken away, performance remained constant. In this experiment, team performance actually improved. This finding supports the proposition that while teams may need to have access to an abundance of relevant information, access to additional information may increase cognitive workload, add confusion and stress, and degrade performance.

Hypothesis 2: Team performance during off-nominal conditions will improve when information is complementary when compared to performance during off-nominal conditions in a normal cockpit configuration.

To test this hypothesis, metrics from the nominal condition were augmented by six metrics specific only to the off-nominal condition. Most of these additional metrics addressed the team's handling of entry into IMC and the conduct of dealing with an in-flight emergency; both of these were unforeseen events. In testing this hypothesis, the results revealed that individual and team performance either displayed non-significant variations or improved; no measure of performance worsened when information was distributed in a complementary fashion.

First, pilot control of the aircraft generally remained constant throughout the entire flight profile, except during entry into IMC. Task twelve of the flight profile was the segment of flight where teams were exposed to IIMC. During this segment, maintenance of airspeed significantly improved (i.e., RMSE airspeed decreased) in the complementary configuration. The median airspeed error decreased 17% and the mean decreased 14.2% when the distribution of information was complementary. During entry into IMC, the pilot's primary task is to maintain control of the aircraft. This requires the pilot to focus on flight instrumentation to coordinate a smooth transition from Visual Flight Rules (VFR) to Instrument Flight Rules (IFR). During this task, the importance of airspeed maintenance cannot be over stated. According to the UH-60 Aircrew Training Manual, immediate action steps are as follows:

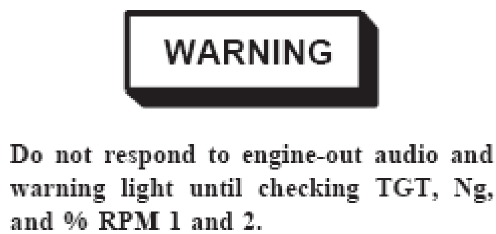
1. Announce "IMC," maintain proper aircraft control, and make the transition to instrument flight immediately.
2. Initiate correct IIMC recovery procedures.
    a. Attitude - Level the wings on the attitude indicator.
    b. Heading - Maintain heading; turn only to avoid known obstacles or as briefed for multi-ship operations.
    c. Torque - Adjust torque as necessary.
    d. Trim - Trim aircraft as necessary.
    e. Airspeed - Adjust airspeed as necessary (in this case airspeed should have been maintained as a climb was initiated).
3. Set transponder to emergency, as required.
4. Contact ATC, as required. Comply with ATC instructions, local regulations, and SOP (TC 1-237: UH-60 Aircrew Training Manual).

By providing the pilots with immediate access only to information relevant to their tasks and responsibilities, they were able to focus their attention on the flight instruments and control the aircraft better.

Second, navigators were not flying the aircraft but were responsible for a range of other tasks; complete all radio calls, calculate ETE, monitor systems, coordinate navigation with pilot, etc. Generally, performance of their specified tasks remained constant as configurations varied, except for the completion of required radio calls. Navigators were briefed that they were responsible for a list of required calls for each leg. In the complementary configuration, navigators seemed to be able to concentrate on their responsibilities better; they did not get distracted by having to divert their attention to non-relevant information. This resulted in more consistent and improved performance in this individual task.

Third, teams reacted better when they were presented with an in-flight emergency. In the complementary configuration, all teams diagnosed the proper engine malfunction and identified the proper emergency procedure; on the contrary, only three out of five were able to achieve that end in the normal condition. Additionally, the time required to diagnose the emergency was significantly reduced in the complementary configuration. The emergency presented to the team was a single engine alternator failure (#1 engine); the #2 engine was unaffected and the #1 engine was still operational. A complete loss of engine alternator power for the #1 engine results in the #1 engine increasing to maximum power with a loss of cockpit indications of engine RPM for #1 engine, torque, Gas Generator Speed (Ng) Indicator, and an engine out audio and warning light. Turbine Gas Temperature (TGT) was the only indication that the #1 Engine was still operating normally. The warning in Figure 40 is posted in the UH-60 operator's manual:

Under normal conditions teams appeared to communicate less efficiently during analysis of the engine malfunction. Both team members commented on various bits of information


WARNING

Do not respond to engine-out audio and warning light until checking TGT, Ng, and % RPM 1 and 2.

Figure 40. Engine out warning.

presented in the cockpit in a seemingly unorganized manner. Teams had been trained to immediately check TGT, Ng, and % RPM, yet this was not done. In the complementary configuration, analysis of the malfunction seemed to be more organized. The pilots were able to maintain their focus on their flight instruments while the navigators explicitly shared the engine information (TGT, Ng, etc.) with the pilots; the malfunction analysis was improved through a system design that forced explicit communication. Both team members were aware of what information each had available, and more importantly, what information the other team member did not have available to them. This resulted in a decrease in the time required to diagnose the engine malfunction of nearly 66% from the normal to the complementary condition. Teams made faster decisions (decrease in diagnosis time) and better decisions (correct analysis of emergency). Future research could include a sequential analysis of communications during the off-nominal conditions.

Hypothesis 3: Explicit, task relevant, verbal communications will increase when information is complementary in both nominal and off-nominal conditions when compared to communications in a normal cockpit configuration.

Results suggested that teams shared more task relevant information in the complementary configuration than in the normal configuration. These findings are important because they provide new insight into how teams share information. Additionally, these findings provide empirical evidence that system design can facilitate an increase in the explicit sharing of information between team members. Communications were classified as transfers and requests that were task relevant or non-relevant. Not only was there a significant increase in task relevant transfers of information, there also was a corresponding decrease in non-relevant transfers. The latter only occurred during nominal operations; non-relevant transfers were minimal in both configurations during off-nominal operations.

Furthermore, during off-nominal operations, which are typically not as proceduralized as nominal operations, specific acknowledgements of receipt of information increased significantly in the complementary condition. Team members tended to acknowledge each other's commands to ensure that they received the proper information. For instance, when the navigator instructed the pilot to "turn right to heading 150…" the pilot would respond, "roger, turn right to 150 degrees." This type of specific acknowledgement ensures that both team members know "who has what" information and increases the likelihood of catching an error before it occurs. This technique of communication is encouraged in nominal operations and trained for in other than nominal operations. For example, the following is an excerpt from the UH-60 aircrew training manual concerning team coordination procedures:

> *Procedures:* The call and response method should be used. The team member reading the checklist will read the complete checklist item. The team member performing the check will answer the appropriate response. For example, for the call "Anti-collision/position lights – As required" the response might be "Anti-collision lights, both, night; position lights, steady, bright." Responses that don't clearly communicate action of information should not be used. For example, when responding to the call, "Systems – Check" replying with, "Check" doesn't clearly indicate that the systems are within the normal operating range. A response of "All in the normal operating range" communicates more accurate information (Training Circular 1-237, Aircrew Training Manual, August 2004).

This is also the required method of communication when team members transfer the flight controls from one pilot to the other; this is referred to as a three way positive transfer of controls:

Pilot: You have the controls.
Navigator: I have the controls.
Pilot: You have the controls.

By designing the distribution of information in a complementary manner, specific acknowledgements of information were increased during critical operations in off-nominal conditions. This type of system design complements current training and procedures practiced in this and other domains.

These results indicated that when teams shared more task relevant information they performed significantly better (i.e., made fewer errors, decreased decision time, had better aircraft control, and had more effective radio communications) than when they shared less task relevant information. Thus, these results provide some empirical support that complementary team mental models may be a means of improving coordinated performance during nominal and off-nominal conditions.

Hypothesis 4: The team's task relevant anticipation ratio will increase when information distribution is complementary when compared to operations in a normal cockpit configuration.

Based on the results of Experiment 1, the task relevant anticipation ratio was expected to increase when information was complementary. However, results indicated the opposite; there was a significant decrease in this measure during nominal and off-nominal operations. Teams in this experiment provided higher rates of information, but the decreased anticipation ratio indicates that team members did not anticipate the information; information was requested at an even higher rate. The anticipation ratio is calculated as:
Investigation to the possible reasons for this unexpected behavior uncovered some interesting explanations.

Although literature has provided empirical data suggesting that teams that provide higher

(Transfers of Task Relevant Information + Transfers of Action + Total Acknowledgements) / Requests for Task Relevant Information

rates of information in advance perform better under various conditions (Entin and Entin, 2001; Stout et. al., 1999), Orasanu (1994) observed quite the opposite when dealing with some effective teams. Among two member teams analyzed by Orasanu and Fischer (1992), captains of higher performing teams talked less during the high workload phase of flight than during normal operations (Orasanu, 1994), which could account for the decrease in the off-nominal situation during the analysis of the engine malfunction.

Furthermore, care was taken to configure the cockpits in a manner that provided the information required for individual tasks to the responsible team member. This would enable team members to perform their individual tasks (i.e., control of the aircraft) without having to request information from another team member. This was attempted through a thorough task and domain analysis. However, review of the videos of team communications revealed that one of the information sources used frequently by the pilot to fly (engine torque percentage display) was not available to the pilot in the complementary configuration. This display was grouped with other engine instruments that the navigator was required to monitor. This resulted in the pilot continuously asking for information from the navigator concerning engine torque, which increased the requests for information and, therefore, decreased the anticipation ratio. This finding helped to identify a flaw in the design process. Even though a thorough task and domain analysis was completed, to include interviews with subject matter experts and personal experience of the analyst, real time observation of the environment and the task is important during development. People are innovative and will find uses for artifacts for which they were not originally designed; observation must be included as an integral step in designing or redesigning a system.

A third reason that the ratio decreased was due to the lack of structure of the environment and task. Pilots frequently request their navigator to repeat or update information concerning altitude, airspeed and heading. This is in contrast to the initial experiment that was conducted in an automobile simulator. In the automobile experiment, participants were required to drive speed limits as posted on the road so there was no need to ask their navigator for speed information. Furthermore, once the navigator gave an instruction to turn on a specific road, the driver easily maintained that "heading" by staying on the road; finally, there was no altitude concern in the automobile. In the helicopter, the pilots tended to ask for updates to these parameters to ensure that they were maintaining the proper route guidance. This also increased the denominator in the calculation of the anticipation ratio.

Finally, it was significant that all measures of the ratio's variation were decreased in the complementary configuration. Even though the ratio was lower, decreased variation indicated a more consistent communication pattern in both nominal and off-nominal operations. This suggests that the configuration of the cockpit had the same effect on all teams operating in that environment. Whereas the large variation in the ratio in the normal configuration indicates that some teams had low ratios and some high; the teams were not consistent throughout. This is significant when applied to many domains in which teams and individuals rotate. In these environments the same team members are not always present or performing the same tasks; therefore, performance is likely to improve if the system configuration supports consistency in communications among teams.

Hypothesis 5: Team member information requirement rankings will be more similar when information is complementary when compared to rankings elicited while operating in a normal cockpit configuration.

This hypothesis tested whether teams demonstrated the ability to determine the information requirements of their teammate more accurately in the complementary configuration than in the normal configuration. Using standard phases of flight (takeoff, landing, etc.) to delineate segments of each mission for assessment, team members were able to predict the information required by their teammate better while operating in the complementary configuration. This is a significant finding and suggests the complementary configuration develops a more accurate mental model of team information requirements; they were able to form accurate expectations and explanations of informational requirements. This study defines this state as complementary team mental models. Therefore, the development of this type of team mental models was supported when the information was displayed in a complementary manner among team members. Team members were able to use these expectations and explanations to provide useful information to the other team member during critical phases of their mission (i.e., during the diagnosis of an engine malfunction).

When asked explicitly which configuration supported better coordination of team activities and identification of individual and team member informational requirements, participants suggested that the complementary condition was more suitable. This result suggests that not only were the team member estimates of requirements more accurate, but so were the individuals' assessments of their own information requirements. With the abundance of information available in a helicopter cockpit, this design method is simply a filtering device that aids in both individual task performance and team coordination.

Hypothesis 6: Individual workload ratings will remain constant between information levels regardless of cockpit configuration.

Generally, individual workload remained constant across configurations except for the navigator's mental workload. The navigator's mental workload increased when exposed to the complementary cockpit configuration. Additionally, the navigator's effort was borderline significant relative to the 5% level ($p = .068$); this measure also tended to increase in the complementary configuration. It is understandable that team members might experience an increase in workload because they are operating in an unfamiliar environment for the first time. The limited increases in workload suggest that the workload would most likely decrease in subsequent exposures to this type of configuration. This effect should be studied more in-depth in future investigations.

Hypothesis 7: Team member source of workload rankings will be more similar when information is complementary when compared to rankings during operations in a normal cockpit configuration.

Teams were not found to estimate the ranks of their teammates' sources of workload better in the complementary condition. The analysis showed that the pilot's ability to estimate the navigator's workload increased slightly but the results were not significant ($p = .069$). Both the inner quartile range and variance showed a slight decrease that indicates that pilots might be more consistent in their accuracy. The analyst, using the participants' score for each source of workload, determined the rankings that were used for this analysis. This was an indirect measure of ranking workload sources. In the future, research participants could be asked to explicitly rank order the sources of workload to indicate which source is causing the most workload to the least.

Summary

The findings of this research provide new insights into how the distribution of information among team members effects the development of team mental models, team and individual performance, and communications that have not been empirically documented elsewhere. The results are applicable to a variety of domains where teams are operating in a complex environment. The results of this experiment provide empirical evidence that providing task relevant information to individual team members in a time critical environment, while limiting their access to non-relevant information, improves individual and team performance by changing team interactions and helping to develop complementary team mental models. Furthermore, this method of distributing information among team members provides individual team members with a more accurate "task relevant" mental model of their own environment.

Conclusions

This study demonstrates that a complementary information distribution among team members can promote improved team process and performance. Although not directly measurable, this improvement is likely a result of teams developing more efficient team mental models, i.e., complementary team mental models. Complementary team mental models provide a condition in which:

1. Each team member has the knowledge necessary to conduct his/her tasks, as may be measured by:
   - Individual performance and
   - Direct assessment of clarity of individual information requirements.
2. Each team member knows which information is available to the other team members should he/she need to seek it, as may be measured by:
   - Team performance,
   - Direct assessment of the clarity of team member information requirements,
   - Estimation of team member's sources of workload, and
   - Task relevant transfers of information.
3. Each team member knows which information is needed from them to other team members and when, as may be measured by:
   - Team performance,
   - Communication rates, and
   - Task anticipation ratio.

The distribution of complementary information underpinned this thesis. Hence, the precise determination of information sources available in each domain and the information required by team members to accomplish their specified task is critical. This thesis proposes that alignment of information sources with task requirements can be accomplished though a three phase method: (1) work domain analysis of the information available in the work environment, (2) analysis of the information requirements of specific tasks, and (3) a mapping of information sources to their corresponding tasks. The work domain analysis identifies the structure of the environment where work takes place; this phase produces an Abstraction-Decomposition Space (ADS) (Vicente, 1999), also known as the Abstraction Hierarchy (AH) (Rasmussen, 1985). Analysis of the tasks, the second phase, is most appropriately accomplished by conducting separate Hierarchical Task Analyses (HTA), thereby providing an efficient method of describing the task by developing only the parts of the hierarchy that are needed for the scope of the design (Kirwan and Ainsworth, 1992). The last phase maps the information sources available in each domain to the individual and team tasks that they support.

The method described above was then applied to two separate domains: driving and flying. The results identified the physical forms of information sources required to conduct the task of navigation in both domains; these sources are tabulated in Figure 41. The availability of these information sources to each of the team members determined the level of complementariness of information, the main independent variable for experimental purposes. The method of determining the information requirements is a unique application of two separate analytical processes, work domain analysis and hierarchical task analysis, and is recommended when the analyst requires a descriptive analysis of a specified task conducted by a small team in a complex domain.

	Automobile	Helicopter
Driver/Pilot	Driving Instruments Window View	Flight Instruments Windscreen View
Navigator	System Health/Status Indicators Clock Maps	System Health/Status Indicators Clock Maps Global Positioning System
Crew	Internal Lights	Voice communication Radios Internal Lights

Figure 41. Information sources required for both domains.

Over the course of two experiments, the complementariness of team mental models and its benefits was measured through a variety of dependent variables. The data were categorized into four groups: performance, communications, workload, and information requirements. Although complementary team mental models cannot be measured directly, their existence can be inferred through a combination of these metrics (Cooke et al., in press; Entin and Entin, 2001; Langan-Fox, Code, and Langfield-Smith, 2000; Rouse, Cannon-Bowers, and Salas, 1992). The process and outcome measures corroborate that complementary team mental models may help clarify decision-making roles and responsibilities, individual and team member information requirements, increase the efficiency of explicit communications, and improve performance.

The conditions that teams operated in during this research were separated in two categories: nominal conditions and off-nominal. During nominal conditions, there were no inconsistencies between instructions given and participant's ability to follow the route in the simulator. During off-nominal conditions in the automobile simulator, teams encountered a roadblock that had to be bypassed; in the helicopter domain, teams experienced IIMC and a single engine alternator failure during the flight. The results of these experiments are summarized below.

Performance

Individual and team performance was assessed through objective and subjective metrics during nominal and off-nominal conditions. Figure 42 displays dependent variables that showed significant effects due to changes in the distribution of information sources. The original hypothesis proposed that during nominal conditions, individual and team performance would remain constant; performance was hypothesized to only improve in the off-nominal condition. Results indicated that team performance also improved in the nominal condition in the presence of complementary information. Increases in team performance were shown through decreased decision making time and improved the quality of decisions. Furthermore, individual performance of helicopter pilots also improved during off-nominal conditions.

Communications

	Automobile		Helicopter	
	Individual	Team	Individual	Team
Nominal	Non-Significant	Navigation Errors Decreased	Non-Significant	Total Errors Decreased
Off-Nominal	Non-Significant	1. Decision Time Decreased 2. Total Time Decreased	1. RMSE Airspeed Decreased 2. Percent Radio Calls Increased	Diagnosis Time Decreased

Figure 42. Summary of performance effects due to a complementary distribution of information sources.

In both domains, a complementary information distribution resulted in an increase in the rate of transfers of task relevant information, acknowledgements and total communications. Additionally, the rate of transfers of non-relevant information decreased in all conditions. Although not the focus of this study, it should be noted that communication rates decreased overall in the off-nominal condition when compared to the nominal condition in both distribution configurations.

Requests were recorded when either team member explicitly asked for information or action from the other team member. Generally requests were for information regarding the team task (i.e., current or future state of vehicle); there were relatively few requests for non-relevant information. There was no significant difference in team requests between a normal and complementary configuration within the automobile domain, but a significant increase in team requests for action did occur in the helicopter domain.

In both nominal and off-nominal conditions in both domains, transfers of task relevant information increased in the complementary configuration when compared to the normal configuration (Table 21). It also is important to note that transfers of non-relevant information decreased in the nominal condition in both domains; in the off-nominal condition in the helicopter domain, there were minimal transfers in either condition. Furthermore, total team transfers increased in both domains under all conditions in the complementary configuration.

Table 21.
Summary of communication effects due to complementary distribution of information sources.

		Significant Diference Between Configurations		
		Automobile	**Helicopter**	
		Nominal	Nominal	Off-Nominal
Requests	Task Info	NO	NO	NO
	Non-Task Info	NO	N/A	NO
	Total Info	NO	NO	NO
	Action	NO	**YES**	**YES**
Transfers	Task Info	**MARGINALLY**	**YES**	**YES**
	Non-Task Info	**YES**	**YES**	NO
	Action	**YES**	NO	NO
	Total	**YES**	**YES**	**YES**
Acknowledge	General	NO	NO	NO
	Specific	**YES**	**MARGINALLY**	**YES**
	Total	**YES**	NO	NO
Totals	Total Commo	**YES**	**YES**	**YES**
	Anticipation Ratio	**YES**	**YES**	**YES**

There was a significant increase in specific acknowledgements as information became more complementary in both domains, across conditions (Note: the effect of complementary information in the nominal condition in the helicopter domain was marginally significant.) Total communication was a combination of requests, transfers, and acknowledgements. Total communications significantly increased as information became more complementary. This measure indicated that the team verbalized more information. When combined with the significant increase in task relevant information and decrease in non-relevant information, this increase was largely based on task relevant transfers.

The task relevant anticipation ratio, which describes the ratio of total task relevant communications to information requests, resulted in mixed effects across domains. In the automobile domain, the ratio increased significantly in the complementary configuration, while in the helicopter domain, the ratio decreased. There are three probable causes for this dramatic difference in results. (1) Among some high performing two member teams analyzed by Orasanu and Fischer (1992), captains of higher performing teams talked less during the high workload phase of flight than during normal operations (Orasanu, 1994). This phenomenon did occur with pilots during off-nominal conditions when compared to nominal conditions. (2) In the experiment in the helicopter, one of the pilot's gauges used for flight maintenance was erroneously grouped with the navigator's engine instruments causing some of the pilots to continuously request information from that instrument during normal operations. (3) Differences in the structure of the domains (e.g., road structure vs. air route) may have encouraged pilots to ask for repeated instructions more than the automobile teams. For example, shortly after changing heading, airspeed, and altitude, aircrews tended to ask the navigator to verify these parameters to ensure that they were maintaining the proper route guidance; this is not necessary on a road structure.

Workload

Individual workload ratings were assessed using the RTLX. The p-values for the significant and marginally significant sources of workload due to changes in information distribution are highlighted in Table 22. Generally, there were few significant changes in team members' workload.

Table 22.
Individual team member workload *p*-values due to complementary information distribution.

	Nominal				Off-Nominal			
	Automobile		Helicopter		Automobile		Helicopter	
	Driver	Navigator	Pilot	Navigator	Driver	Navigator	Pilot	Navigator
Mental	0.871	0.326	0.700	**0.015**	0.748	0.664	0.765	0.407
Physical	0.544	0.490	0.694	0.657	0.568	0.742	0.925	*0.053*
Temporal	0.828	0.437	*0.086*	0.262	0.592	0.914	0.500	0.310
Effort	0.881	**0.042**	0.613	*0.068*	0.334	0.830	0.535	*0.054*
Performance	0.699	0.271	0.804	0.874	0.914	1.000	0.743	0.559
Frustration	0.903	0.178	0.165	0.432	0.668	0.238	0.266	0.380

- Red (dark gray) cells = significant effect
- Yellow (light gray) cells and *Italicized Text* = marginally significant effect

At the end of each experimental run, participants were given an opportunity to rate their workload, specifically the difficulty in coordinating with their teammate. Within the automobile domain, participants rated the complementary distribution significantly more difficult to coordinate actions; in the helicopter domain, this measure was marginally significant. Overall, participants' answers to these questions indicated that team members felt that it was slightly more difficult to coordinate their actions when operating in the complementary configuration; however, this was not corroborated by the TLX workload ratings.

A team member workload ranking correlation analysis was conducted in the helicopter experiment. At the end of each run, team members estimated the workload of their teammate using the Raw Task Load Index. Based on their scores, the sources of workload were rank ordered and a correlation matrix of the rankings from the pilot and co-pilot was developed. With the navigator as the predictor, differences due to information distribution were not significant. In contrast, when the pilot predicted the navigator's source of workload, differences in the mean correlation coefficients were marginally significant. The median and mean correlation increased with the complementary distribution of cockpit information.

<u>Information requirements</u>

Two methods were used in the helicopter experiment to explicitly determine whether team members felt they (1) had the knowledge necessary to conduct his/her tasks, (2) knew which information was available to the other team member should he/she need to seek it, and (3) knew which information was needed from them to the other team member, and when. The first method was a similarity rating of team member's information requirements during different phases of flight; the second was a survey question at the end of the experiment that specifically addressed clarity of information requirements during complementary and normal cockpit configurations.

At the end of each run, team members ranked the importance of each type of information available during different phases of flight. In the nominal condition, no significant differences were found between the two types of information distribution. In contrast, in the off-nominal condition, the correlation between pilot and navigator rankings of information improved significantly from the normal configuration to a complementary distribution of cockpit information.

The following questions were asked of each participant at the end of the helicopter experiment:

1. In which condition were you more aware of your team member's information requirements (normal or complementary)?
2. In which condition were your own information needs more clear (normal or complementary)?

Over eighty percent of the participants that answered the survey question indicated that the complementary distribution of information within the cockpit provided more clarity to their own information requirements, and they felt they understood their team member's information requirements better. A binomial test was used to analyze the responses; the test proportion used for the analysis was .5 (50%); both response rates were significantly different from chance.

Discussion

Team members *always* share information within team environments. Historically, the term "share" has meant in this context "to be common," i.e., *all* information sources in the environment available to *all* team members. This thesis views the term "to share" as "to divide;" for example, to share the workload (Cooke et al., 2000). In this case, each team member has access to and is responsible for the exchange of a portion of the information sources available to him or her, in addition to having a portion common to the team. It is through this manner of "sharing" information that this study hypothesizes that team mental models become more accurate and efficient. They will be more accurate because the information sources are designed with the task and team member roles as a primary concern: They will be more efficient because team member's information sources are distributed so that they will mutually supply each other's lack. This research proposed that a complementary information distribution leads to "complementary team mental models," a condition where (1) each team member has the knowledge necessary to conduct his/her tasks, (2) each team member knows which information is available to the other team member should he/she need to seek it, and (3) each team member knows which information is needed from them to other team members and when. The empirical evidence corroborates the following, as discussed in the next section:

1. Development of Complementary Mental Models: Team centered, complementary configurations of information sources in correspondence-driven, complex domains will improve the accuracy and efficiency of shared mental models by developing complementary team mental models.
2. Complementary Team Mental Models Effect on Performance and Communications: Complementary team mental models enhance performance and communications in both nominal and off-nominal operations.
3. Complementary Team Mental Models Effect on Team Workload: Complementary configurations will not adversely affect team workload.

<u>Development of complementary mental models</u>

Corroborating the development of complementary mental models as defined in this report requires the following conditions:

Team members have the knowledge necessary to conduct their tasks better in the complementary information configuration as compared to a normal information configuration.

The experiments provide clear supporting evidence of increased individual performance and understanding of individual information requirements with a complementary information distribution. As Figure 53 summarizes, performance either stayed consistent or improved in each domain. Improved performance was most evident when the workload was higher, i.e., during off-nominal conditions.

Team members were more aware of their team member's information requirements in the complementary information configuration as compared to the normal configuration.

Team performance improved during both nominal and off-nominal conditions due to the complementary configuration of their environment. Likewise, with the complementary configuration, individuals were more aware of their team member's information requirements, and individuals explicitly indicated that they understood their team member's information requirements better. This increased understanding is invaluable to implicit and explicit coordination and can be seen by the fact that communication transfers of task relevant information increased when teams operated in the complementary configuration.

Team members could anticipate when information was needed from them to their team member better in the complementary information configuration when compared to a normal information configuration.

As noted in the background, the most effective teams seem to share their mental picture of the situation with other team members (Stout et al., 1999). These shared mental models help team members anticipate the needs of others, which correspondingly permits them to either provide assistance, as it is required, or to predict and pre-empt the need for assistance (Martin and Flin, 1997). Shared mental models provide team members with a common understanding of who is responsible for what task, what the information requirements are, and allow team members to anticipate one another's needs so that they can work in sync and adjust their behavior accordingly (Smith-Jentsch, Johnston, and Payne, 1998).

Hence, the presence of a high anticipation ratio, in concert with other indicators, can be an indicator of the efficiency of teams' shared mental models. Analysis of the two domains examined here produced mixed results. In the automobile domain, there was a significant increase in this ratio indicating that anticipation of team member needs increased in a complementary configuration, while the aircrews produced a significant decrease. There are indications that an oversight in the experimental procedure may have affected the aircrew's ratio.

Complementary team mental models and performance

Mathieu et al. (2000) claim the definitive function of shared mental models is to allow team members to draw on their own knowledge as a basis to decide on actions that are consistent and synchronized with those of their teammates. This research suggests that the quality of complementariness in team mental models enables team members to do this more effectively. The benefits of team mental models are unmistakably evident when a team is conducting a complex task, especially in conditions of high workload (Cannon-Bowers, Salas, and Converse, 1993; Rouse, Cannon-Bowers, and Salas, 1992). Recent studies show that team performance at tasks requiring anticipation of team member's actions and information requirements is improved with shared mental models (Espinosa et al., 2001).

Performance was assessed in both domains in both nominal and off-nominal conditions. Nominal conditions are generally highly proceduralized, expected by team members, practiced routinely, operated in regularly, and trained and cross-trained for by teams. In nominal situations, individual performance generally remained constant, but procedural and navigational errors in both domains decreased in the complementary configuration. This suggests that in normal configurations there is information presented to team members that is neither needed nor used to perform their individual tasks and team responsibilities. When this superfluous information is taken away, performance remained constant or improved. While teams may need to have access to an abundance of relevant information, access to additional information may increase workload, add confusion, and degrade performance.

Off-nominal conditions occur when an unanticipated event takes place. The value of shared mental models is greater during off-nominal conditions where the importance of adaptation to change and anticipation of team member needs increases. During off-nominal operations, teams displayed a higher level of team and individual performance. The effectiveness of teams in all aspects of performance improved in the complementary configuration when compared to the normal configuration. Teams were able to concentrate on the information relevant to their role in the decision making process. For example, in the automobile domain, as teams approached a roadblock, the navigator examined the map for alternate routes while the driver concentrated on maneuvering and clearing the vehicle. Likewise, when aircrews encountered IIMC, the pilot concentrated on maintaining aircraft control while the navigator verified the minimum safe altitude and made the appropriate radio calls.

Complementary team mental models and communications

Communications and team operations are inseparable. The very definition of teams dictates that individuals exchange information (Cannon-Bowers and Salas, 1997). Communication is more than an exchange of information: it is a means by which teams coordinate resources and activities (Entin and Serfaty, 1999), construct and maintain shared mental models (Orasanu, 1990), and establish and maintain situational awareness (Prince and Salas, 1993). The literature indicates a positive relationship between communication frequency and increased performance, specifically in aircrews (e.g., Roberts and O'Riley, 1976; Foushee and Manos, 1981); the research described here provides additional empirical evidence that supports this theory. In the experiments conducted for this study, the steady increase in transfers of task relevant information across conditions (nominal and off-nominal) in the complementary configuration reflected a greater amount of task relevant information sharing between team members in both domains. This information supported individual tasks (e.g., maintenance of flight route) and team tasks (e.g., decision making). Furthermore, the exchange of information ensures that (1) the team member that needs the information has the information and (2) both team members know that the relevant information has been received. The latter is further supported by the consistent increase in acknowledgements of receipt of information across conditions in both domains examined here.

Complementary team mental models and team workload

Workload ratings were used for two purposes: (1) to indicate changes in team mental models via correlation analysis, and (2) to identify significant changes in team member workload ratings.
The similarity ratings of team member sources of workload suggest the formation of complementary mental models when information is distributed in a complementary fashion. Additionally, only the navigator experienced the higher workload changes; recall that the navigator wore foggles, an artificial constraint used only for experimental purposes in the complementary configuration. This is a dramatic change from normal operations; it was

anticipated that they would initially experience a higher workload. These results indicate that there is little increase in workload to team members under complementary conditions, and those increases will decrease over time.

Summary of Conclusions

This study has introduced a new theoretical concept of complementary team mental models and empirical evidence has been provided that supports:

1. The use of a new system design technique to enhance these models through the complementary distribution of information within a team environment tailored to the domain and task, and
2. The benefits of complementary team mental models to team process and performance.

The method of designing team-centered environments introduced in this study is not a replacement for current methods used to enhance team process and performance (e.g., cross training). On the contrary it will enhance the effects of current methods. The concepts introduced are applicable to all models of team performance but are best incorporated into the framework of the I-P-O model introduced in the background and literature review; as shown in Figure 46. In the expanded I-P-O model, characteristics of personnel (position, pre-existing knowledge), tasks (team and individual), and tools (artifacts specific to the domain) are inputs into the environment. Inputs are “filtered” through the system design of the environment. Consequently, the complementary distribution of information sources aligns information sources within the environment to be consistent with those input characteristics and team processes; e.g., roles for each team member. The information immediately available to team members supports their individual tasks and team task responsibilities, as required by their role. Consequently, during nominal operations, team members can focus on their individual tasks and are compelled to explicitly share information with their team member; during off-nominal conditions, team members know who has access to what information and what information is critical to share. The interpersonal interactions that are encouraged by a complementary information distribution lead directly to the development of complementary team mental models. As a result, team processes such as communication, role clarification, and decision-making improve. The dashed arrow (Figure 43) from the information sources indicates that there may be some direct impact on team process due to the configuration of information sources, also impacting team performance. For instance, roles can be clarified when an information distribution limits the ability of one team member to perform tasks outside of their area of responsibility, or withholds critical decision-making information from certain team members.

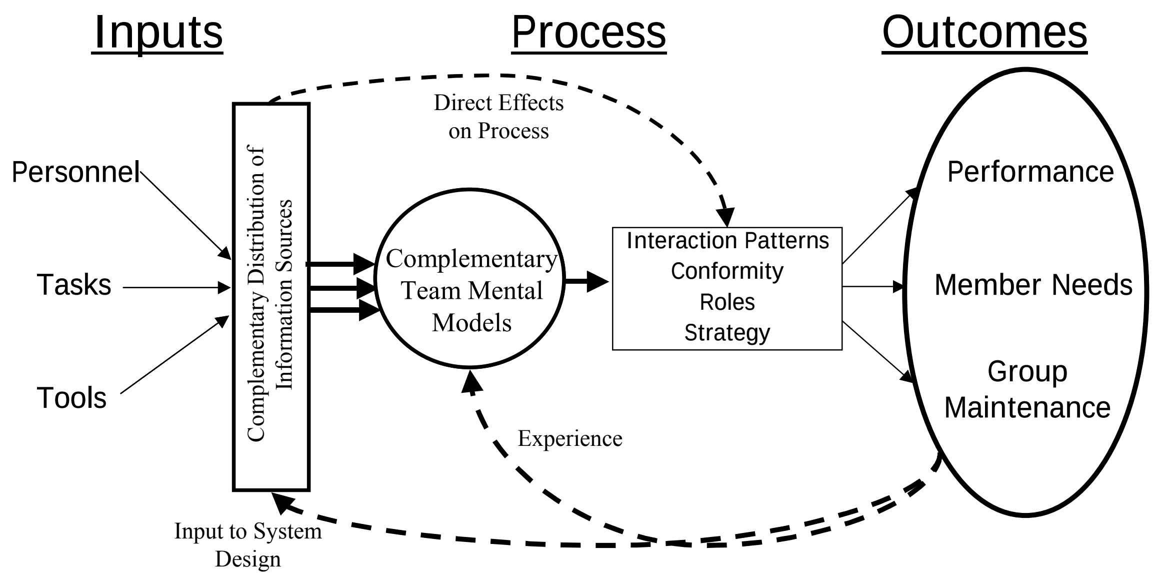


Figure 43. Expanded IPO framework with inclusion of complementary information distribution.

Domains discussed in this research frequently rotate team members. For example, aircrews in commercial and military aircraft very seldom stay together as a team and "newly formed teams" are the standard. The interchanging of team members frequently leads to uncertainty in roles and performance expectations. A complementary type of system design can clarify their roles and promote explicit communication for teams that work together infrequently.
While improved outcomes are probable, but not guaranteed, other external factors could affect the outcome in a positive or negative manner. In this research, simulator operators controlled the external factors and improved performance was generally experienced in both domains. Referring back to Figure 43, the "outcomes" feed back into the complementary team mental models and information sources. Once performance (or other outcomes such as member needs or group maintenance not examined in this research) is assessed, the information sources may need to be redesigned and/or the complementary team mental models be further developed.

Complementary team mental models are influenced by the distribution of knowledge between team members, the distribution of information in the environment, or a combination of the two. The quadrants in Figure 44 represent the levels of knowledge and information distribution as described below:

- Quadrant I: Team member knowledge is distributed among team members. The information in the environment is common to all team members. Based on the division of knowledge, team members are more aware of their specific information requirements and can identify their required information sources in the environment more readily.

- Quadrant II: Team member knowledge is distributed among team members and the information in the environment is complementarily distributed. The distribution of information sources in the environment supports the division of knowledge between team members and performance is further enhanced.
- Quadrant III: Team knowledge and information are common to all team members. Team members must rely heavily on training, operating procedures, checklists and regulations to align information sources of the environment with individual tasks and team responsibilities.
- Quadrant IV: Team knowledge is common among members, yet the information in the environment is complementarily distributed between team members according to tasks and responsibilities.

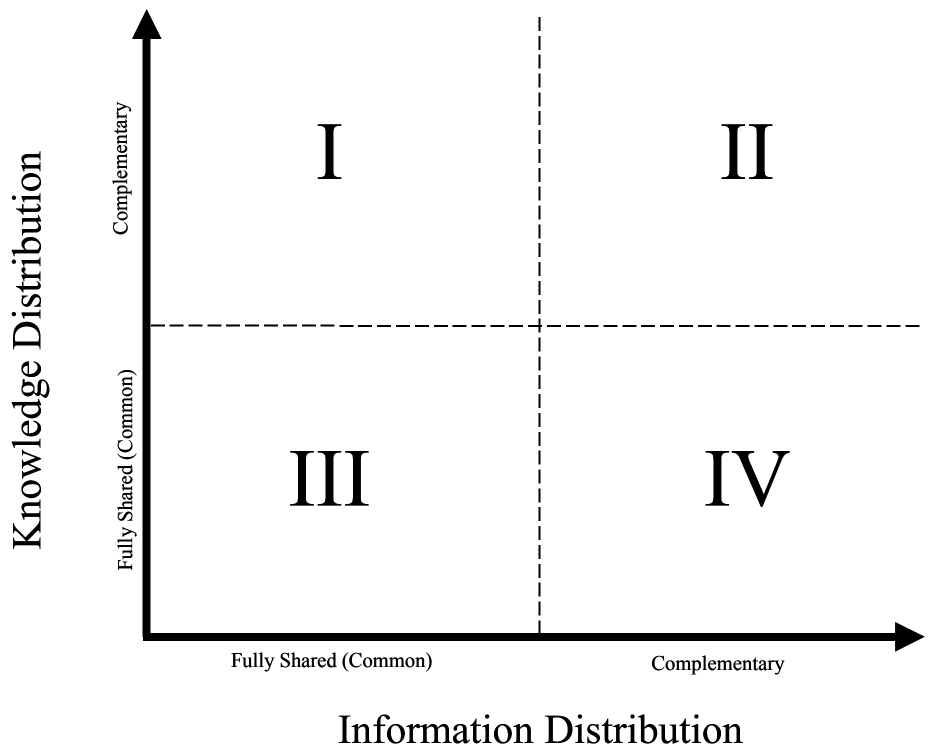


Figure 44. Knowledge distribution vs. information distribution.

While this study only examined quadrants III and IV in detail, these arguments suggest that complementary team mental models are enhanced in quadrants I, II, and IV, while quadrant III is not conducive to team operations.

Additionally, it is hypothesized that, as team members increase repetitions in the environment, their mental models will further improve based on this feedback loop. Therefore, outcomes are not only a byproduct of the team process; they are also an input to the system design and the development of complementary team mental models.

Contributions

Although this effort focused on two specific domains, teams are found in a variety of other domains; examples include sports (NASCAR pit crews, football), performing arts (jazz band, Broadway show), emergency medical teams, commercial aviation (cockpit teams, air traffic control), and numerous others. This research examined two sets of teams and conditions that spanned a wide range of possible teams within complex environments: (1) newly formed, novice teams performing a complex task in a medium fidelity simulator with little to no expectation of future interaction in a team task; and (2) newly formed, highly trained U.S. military aircrews performing a complex task in a high fidelity simulator with expectations of future interaction in a team task. Generally, results concerning the communication, workload, performance and team of mental models were consistent across domains, indicating high generalizability of these results across teams such as commercial airline crews, military aircrews, and ground vehicle teams, and numerous other small teams operating in complex domains.

A homogeneous distribution of information, where all information is available to each team member, would be acceptable if the task responsibilities were also homogeneous; in such a situation a team is most likely not warranted. Instead, the robustness of the information distribution design principles presented in this study is that they account for the heterogeneity of teams; *teams cannot be thought of as groups of identical individuals*. Each team member brings his or her own experiences, characteristics, talents and own knowledge base to the team environment. Team members will apply their knowledge to interpret information about the situation and decide how to handle it (Wigg, 1998). The sources of information within the environments consist of facts and data organized to describe a particular situation or condition. This study has demonstrated that, with newly formed teams, tailoring information distribution in accordance with team responsibilities and individual task requirements improves their team processes and performance through the development of complementary team mental models.

A unique and generalizable method to determine information sources and requirements within a domain for a given task has been introduced, demonstrated, and forms the foundation of complementary information distribution. This study re-defines the gauge of efficiency for team mental models as "complementariness" where each team member (1) has the knowledge necessary to conduct his/her tasks, (2) knows which information is available to the other team member should he/she need to seek it, (3) knows which information is needed from them to other team members and when. Furthermore, an approach to information distribution that aligns information sources with input characteristics and task has been described with empirical evidence that this method can (1) reinforce the development of complementary team mental models, and (2) improve team process and performance without significantly affecting the team's workload.

Additional research

There are improvements that could be incorporated in the experiments in this research; additionally, interesting new avenues of research are inspired by these results.

- The focus of the analysis of communications investigated the differences between complementary and normal configurations. Broader research into communication patterns between levels of complementariness should be pursued. This research could support existing research concerning communication patterns of teams exposed to off-nominal versus nominal conditions.

- Communications were analyzed at the team level for this research. A more specific analysis should focus on communications by role (e.g., pilot versus navigator).
- The method for determining information sources and requirements should be investigated for use in other system design processes.
- The effect of complementary information distribution during phased training should be investigated. Even if it is not possible or not desirable to redesign a system, this information distribution can be used in a training environment to identify important elements of team operations in a specific domain.
- The outcomes of the helicopter experiment revealed an error in the information distribution. This experiment warrants redesign and further trials, which may strengthen conclusions concerning the task relevant anticipation ratio, and continued research should be conducted to validate these results in alternate domains.
- Additional experimentation should be conducted with enhanced measures of individual mental models to measure the direct effect of complementary information design on individuals.
- Expansion of the concepts of information distribution to larger teams and distributed teams should be conducted.

References

Annett, J. and Duncan, K. D. 1967. Task analysis and training design. Journal of Occupational Psychology. 41: 211-221.

Beyer, H. and Holtzblatt, K. 1998. Contextual Design: Defining Customer-Centered Systems. Academic Press: Kaufmann Publishers.

Blickensderfer, E. L., Cannon-Bowers, J. A., and Salas, E. 1994. Training teams to self-correct: An empirical investigation. Paper presented at the 12th annual meeting of the Society for Industrial and Organizational Psychology, St. Louis, MO.

Blickensderfer, E., Cannon-Bowers, J. A., and Salas, E. 1997. Theoretical bases for team self-correction: Fostering shared mental models. In M. Beyerlein, D. Johnson, and S. Beyerlein (eds.) Advances in interdisciplinary studies in work teams series (Vol. 4), 249-279. Greenwich, CT: JAI Press.

Byers, J. C., Bittner, A. C. and Hill, S. G. 1989. Traditional and raw task load index (TLX) correlations: are paired comparisons necessary? In A. Mital (ed.), Advances in Industrial Ergonomics and Safety, I, 481-485. London: Taylor and Francis.

Cannon-Bowers, J. A., Salas, E., Blickensderfer, E., and Bowers, C. A. 1998. The impact of cross-training and workload on team functioning: A replication and extension of initial findings. Human Factors. 40: 92-101.

Cannon-Bowers, J. A., and Salas, E. 1997. Teamwork competencies: The interaction of team member knowledge, skills and attitudes. In O. F. O'Neil (ed.), Workforce readiness: Competencies and assessment, 151-174. Mahwah, NJ: Erlbaum.

Cannon-Bowers, J. A., Salas, E., and Converse, S. 1993. Shared mental models in expert team decision-making. In N.J. Castellan, Jr. (ed.), Current Issues In Individual And Group Decision Making, 221-246. Hillsdale, NJ: Erlbaum.

Cannon-Bowers, J. A., Tannenbaum, S. I., Salas, E., and Volpe, C. E. 1995. Defining team competencies and establishing training requirements. In R. Guzzo, and E. Salas, (eds.), Team effectiveness and decision making in organizations, 333-380. San Francisco, CA: Jossey-Bass.

Cooke, N. J., Salas, E., Cannon-Bowers, J. A., and Stout, R. J. 2000. Measuring team knowledge. Human Factors. 42: 151-173.

Cooke, N. J., Salas, E., Kiekel, P. A., and Bell, B. (in press). Advances in measuring team cognition. In E. Salas and S. M. Fiore (eds.), Team cognition: Process and performance at the inter- and intra-individual level. Washington, DC: American Psychological Association.

Converse, S. A., Cannon-Bowers, J. A., and Salas, E. 1991. Team member shared mental models: A theory and some methodological issues. In Proceedings of the Human Factors Society 35th Annual Meeting. 1417-1421. Santa Monica, CA: Human Factors and Ergonomics Society.

Davis, F. D. 1989. Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Quarterly. 13(3): 319-340.

Duncan, P. C., Rouse, W. B., Johnston, J. H., Cannon-Bowers, J. A., Salas, E., and Burns, J. 1996. Training Teams Working in Complex Systems: A Mental Model Based Approach. Human/ Technology Interaction in Complex Systems, 8: 173-231.

Duffy, L. 1992. Team decision making biases: An information processing perspective. In G. A. Klein, J. Orasanu, and R. Calderwood (eds.), Decision making in action: Models and methods, 234-242. Norwood, NJ:Ablex.

Embrey, D. 2000. Task Analysis Techniques. Human Reliability Associates Ltd.

Endsley, M. 1995. Toward a Theory of Situation Awareness in Dynamic Situations. Human Factors, 37: 32-64.

Entin, E. E. and Serfaty, D. 1999. Adaptive team coordination. Journal of Human Factors, 41(2): 321-325.

Entin, E. E. and Entin, E. B., 2001. Measures for Evaluation of Team Process and Performance in Experiments and Exercises. Proceedings of the 6th International Command and Control Research and Technology Symposium. Annapolis, MD.

Espinosa, J. A., Herbsleb, J. D., Mockus, A., Kraut, R. E., Lerch, F. J., and Slaughter, S. 2001. Shared Mental Models and Coordination in Large-Scale, Distributed Software Development. Proceedings of the International Conference in Information Systems, 2001. New Orleans, LA.

Fischer, U., Orasanu, J., and Wich, M. 1995. Expert pilots' perceptions of problem situations.

Foushee, H. C. and Manos, K. L. 1981. Information transfer within the cockpit: Problems in intracockpit communications. In C. E. Billings and E. S. Cheaney (eds.), Information transfer problems in the aviation system (NASA Report No. TP-1875). Moffett Field, CA: NASA-Ames Research Center. NTIS No. N81-1162.

Gibson, C. B. 1996. They do what they believe they can? Group-efficacy beliefs and group performance across tasks and cultures. Paper presented at the National Academy of Management Meetings, Cincinnati, Ohio.

Gibson C. and Zellmer, M. 1998. Intercultural Analysis Of The Meaning Of Teamwork: Evidence From Six Multinational Corporations. Paper presented at the Academy of International Business Conference, Monterrey, Mexico, 1997.

Hart., S.G., and Staveland, L.E. 1988. Development of NASA-TLX (Task Load Index): Results of experimental and theoretical research, in P.A. Hancock & N. Meshkati (eds.), Human Mental Workload (pp. 139-183). Amsterdam: North Holland.

Heffner, T. S., Mathieu, J. E., and Goodwin, G. F. 1995. An empirical examination of multiple mental models influences on team processes and performance. In J.E. Mathieu (Chair), Mental models and team effectiveness: Three empirical studies. Paper presented at the Tenth Annual Conference of the Society for Industrial and Organizational Psychology, Orlando, FL.

Hopp, P., Smith, C. A. P., and Hayne, S. C. 2002. Literature Review of Shared Cognition. Office of Naval Research, Arlington, Virginia, Grant #66001-00-1-8967.

Hutchins, E. 1991. Organizing work by adaptation. Organization Science 2: 14-38.

Hutchins, E. and Klausen, T. 1996. Distributed Cognition in an Airline Cockpit, in Engestrom, Y. and Middleton, D. (eds.): Cognition and Communication at Work, Cambridge University Press.

Johnson-Laird, P. N. 1983. Mental models: Towards a cognitive science of language, conference, and consciousness. Cambridge, MA: Harvard University Press.

Jonassen, D. H., Tessmer, M. 1996. An Outcomes-Based Taxonomy for Instructional Systems Design, Evaluation and Research. Training Research Journal, 2: 11-46.

Kirwan, B. and Ainsworth, L. K. 1992. A Guide to Task Analysis. Bristol, PA: Taylor and Francis.

Klimoske, R., and Mohammed, S. 1994. Team mental model: Construct or metaphor? Journal of Management, 20: 403-437.

Lajoie, A. S. and Sterling, B. 1999. A Review and Annotated Bibliography of the Literature Pertaining to Team and Small Group Performance (1989 to 1999). Army Research Institute for the Behavioral and Social Sciences for Fort Knox KY, Armed Forces Research Unit.

Langan-Fox, J., Code, S., and Langfield-Smith, K. 2000. Team mental models: techniques, methods, and analytic approaches. Human Factors, 42(2): 242-271.

Martin, L., and Flin, R., 1997. Building fire commander situational awareness from team shared mental models. IEE Colloquium, 137: 2/1-2/7.

Mathieu, J. E., Heffner, T. S., Goodwin, G. F., Salas, E., and Cannon-Bowers, J. A. 2000. The influence of shared mental models on team process and performance. Journal of Applied Psychology, 85: 273-283.

McIntyre, R. M. and Salas, E. 1995. Measuring and managing for team performance emerging principles from complex environments, in Guzzo and Salas (eds.), Team Effectiveness and Decision Making in Organizations. San Francisco: Jossey-Bass, 149-203.

Minionis, D. 1994. Enhancing team performance in adverse conditions: The role of shared team mental models and team training on an interdependent task. Ph.D. dissertation. Fairfax, VA: George Mason University.

Minionis, D. P., Zaccaro, S. J., and Perez, R. 1995. Shared Mental Models, Team Coordination, and Team Performance. Paper presented at the 10th annual mtg of Society for Industrial and Organizational Psychology. Orlando, FL.

Morgan, B. B., Jr., Glickman, A. S., Woodard, E. A., Blaiwes, A., and Salas, E. 1986. Measurement of team behaviors in a Navy environment. Orlando, FL: Naval Training Systems Center. NTSC Report No. 86-014.

Nadimian, R. M., Griffiths, S., and Burns, C. M. 2002. Ecological interface design in aviation domains: work domain analysis and instrumentation availability of the harvard aircraft. Paper presented at the Human Factors and Ergonomics Society 46th Annual Meeting, Baltimore, MD.

Norman, D. A. 1983. Some observations on mental models. In Genter and Stevens (eds.), Mental Models, 7-14. Hillsdale, NJ: Lawrence Erlbaum Associates.

Norman, D. A., and Draper, S. W. (eds.) 1986. User centered system design: New perspectives on human-computer interaction. Hillsdale, NJ: Lawrence Erlbaum Associates.

Orasanu, J. 1990. Shared mental models and crew performance. Cognitive Science Laboratory Technical Report #46. Princeton, NJ: Princeton University.

Orasanu, J. M. 1994. Shared problem models and flight crew performance. Aviation psychology in practice (A96-10209 01-53). 255-285. Aldershot, United Kingdom: Avebury Technical.

Orasanu, J. and Connolly, T. 1993. The Reinvention Of Decision-Making. In G. Klein, J. Orasanu and R. Calderwood (eds.), Decision Making in Complex Worlds. Norwood, NJ: Ablex Publishers.

Orasanu, J. and Fischer. 1992. Say It Again, Sam! Effective Communication Strategies To Mitigate Pilot Error. In Proceedings of the 10th International Symposium on Aviation Psychology. Columbus, OH, May 1999.

Orasanu, J. and Salas, E. 1993. Team decision making in complex environments. In G. A. Klein, J. Orasanu, R. Calderwood, and C. E. Zsambok (eds.), Decision making in action: Models and methods, 327-345. Norwood, NJ: Ablex Publishers.

Orasanu, J. 1993. Decision making in the cockpit. In E. L.Wiener, B. G. Kanki, and R. L. Helmreich, (eds.). Cockpit Resource Management, 137-172. San Diego, CA: Academic Press.

Orlady, H. and Orlady, L. 2002. Human Factors in Multi-Crew Flight Operations. Ashgate, UK.

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

Prince, C. W., and Salas, E. 1993. Training and research for teamwork in the military aircrew. In E. Wiener, B. Kanki, and R. Helmreich (eds.), Cockpit resource management. 337-366. San Diego, CA: Academic Press.

Rasmussen, J. 1985. Role of Hierarchical Knowledge Representation in Decision making and System Management. IEEE Transactions on Systems, Man and Cybernetics, 15(2): 234-243.

Rasmussen, J. and Vicente, K. J. 1989. Coping with human errors through system design: implications for ecological interface design. International Journal of Man-Machine Studies. 31: 517-534.

Rentsch, J. R. and Hall, R. J. 1994. Members of Great Teams Think Alike: A Model of the Effectiveness and Schema Similarity Among Team Members. Advances in Interdisciplinary Studies of Work Teams (1). 223-261.

Rentsch, J.R., Heffner, T.S., and Duffy, L.T. 1994. What you know is what you get from experience: Team experience related to teamwork schemas. Group and Organization Management, 19: 450-475.

Roberts, K. H. and O'Reilly, C. A. 1976. Interpersonal, work group, and organizational communication: A systematic approach to understanding organizations. Berkeley, CA: Institute of Industrial Relations. Technical report, Contract No. N00014-69-A-0200-1054.

Rouse, W. B. 1991. Design for Success. New York: Wiley.

Rouse, W. B. and Morris, N. M. 1986. On looking the black box: Prospects and limits in the search for mental models. Psychological Bulletin, 100(3): 349-363.

Rouse, W.B., Cannon-Bowers, J.A., and Salas, E. 1992. The role of mental models in team performance in complex systems. IEEE Transactions on Systems, Man and Cybernetics, 22(6): 1296-1308.

Salas, E., Dickinson, T. L., Converse, S. A., and Tannenbaum, S. I. 1992. Toward and understanding of team performance and training. In R.W. Swezey and E. Salas (eds.), Teams: Their training and performance, 3-29. Norwood, NJ: Ablex Publishers.

Salas, E., Montero, R. C., Glickmann, A. S. and Morgan, B. B. 1988. Group Development, teamwork skills, and training. Paper presented at the Annual Meeting of American Psychological Association, Atlanta, Georgia.

Schraagen, J. M. and Rasker, P. C. 2001. Communication in Command and Control Teams. Proceedings of the Sixth International Command and Control Research and Technology Symposium.

Serfaty, D., Entin, E. E., and Johnston, J. H. 1998. Team coordination training. In J. Cannon-Bowers, and E. Salas, (eds.), Making decisions under stress: Implications for individual and team training, 221-245. APA: Washington, DC.

Shepherd, A. 2001. Hierarchical task analysis. New York: Taylor and Francis.

Smith-Jentsch, K. A., Johnston, J. H., and Payne, S. C. 1998. Measuring team-related expertise in complex environments. In J. Cannon-Bowers, and E. Salas (eds.), Making decisions under stress: Implications for individual and team training, 61-87. APA: Washington, DC.

Stasser, G., and Davis, J. J. 1981. Group decision-making and social influence: A social interaction model. Psychological Review, 88: 523-551.

Stout, R., Cannon-Bowers, J. A., and Salas, E. 1996. The role of shared mental models in developing team situation awareness: Implications for training. Training Research Journal, 2: 85-116.

Stout, R. J., Cannon-Bowers, J. A., Salas, E., and Milanovich, D. M. 1999. Planning, shared mental models, and coordinated performance: An empirical link is established. Human Factors, 41(1): 61-71.

Stout, R., and Salas, E. 1993. The role of planning in coordinated team decision making: Implications for training. Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, Santa Monica, CA, 1238-1242.

Stout, R. J., Salas, E., and Fowlkes, J. E. 1997. Enhancing teamwork in complex environments through team training. Group Dynamics: Theory, Research, and Practice, 1: 169-182.

Vicente, K. J. 1997. Should an interface always match the operator's mental model? CSERIAC Gateway, Volume VIII: Number 1.

Vicente, K. J. 1999. Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work. Mahwah, NJ: Lawrence Erlbaum.

Vicente, K. J. 2002. Ecological interface design: progress and challenges. Human Factors. 44(1): 62-78.

Vicente, K. J., and Rasmussen, J. 1992. Ecological interface design: Theoretical foundations. IEEE Transactions on Systems, Man & Cybernetics. 22(4): 589-606.

Volpe, C. E., Cannon-Bowers, J. A., Salas, E., and Spector, P. E. 1996. The impact of cross-training on team functioning: An empirical investigation. Human Factors, *38:* 87-100.

Wegner, D. M. 1987. Transactive memory: A contemporary analysis of the group mind. In B. Mullen and G. R. Goethals (eds.), Theories of group behavior, 185-205. New York: Springer-Verlag.

Wickens, C. D., & Carswell, M. 1995. The proximity compatibility principle: Its psychological foundation and relevance to display design. Human Factors, 37: 473-494.

Wigg, K. M. 1998. Assess the practical aspects of the bridge between knowledge management and information technology. Proceedings of Data Warehousing and Knowledge Management. Bryanston, South Africa: AiC Conferences.

Appendix A.

Experiment I: background documentation

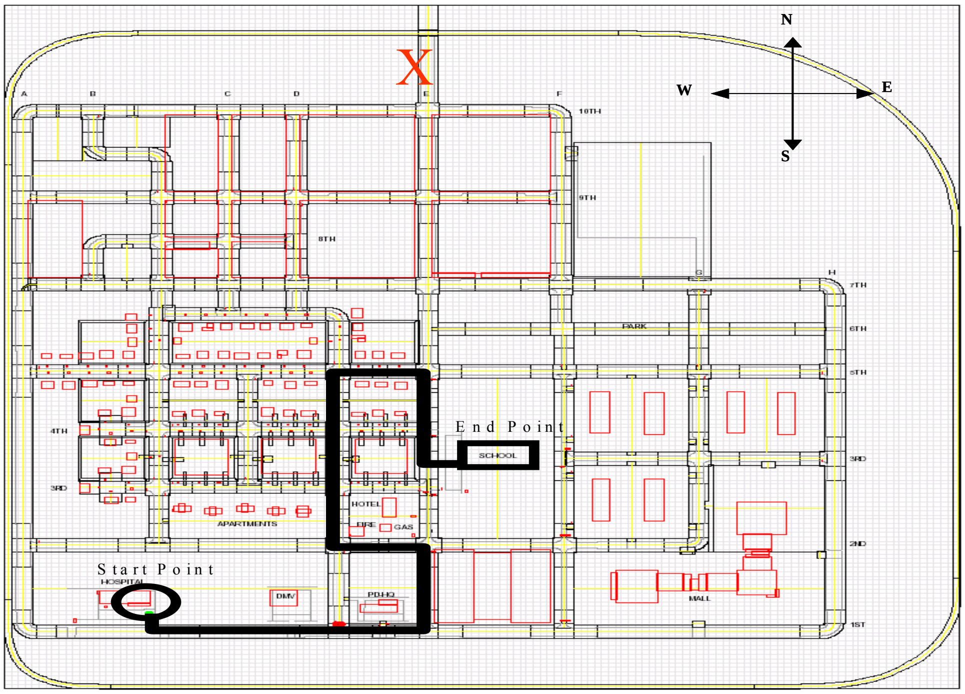


Figure A-1. Automobile simulator map.

Map Orientation

- This is an urban environment.
- The streets running east/west are numbered streets.
- The streets running north/south are lettered streets.
- Speed limit is 35 MPH unless otherwise posted.
- Map is oriented north as indicated in the upper right corner of the map.
- The route will be indicated by a solid line as indicated on the map.
- All roads, driveways, parking lots etcetera can be driven on.
- The road at the top of the map in the center is unusable.
- Distinctive buildings and areas are labeled (i.e., hospital, apartments).
- Other, non-distinctive buildings will repeat throughout the scenario and would not be effective landmarks.
- There are streetlights, street signs, and one-way signs resembling those on a normal city street.
- There may be other vehicles and pedestrians that are not depicted on the map.
- Circle indicates Start Point, Square indicates End Point.

Sample Textual Directions

Starting Point: Hospital parking lot.

- Exit Parking lot and turn east on 1st Street.
- Check Point: Pass DMV on your left.
- At second intersection turn, turn North onto E Street.
- Turn West on 2nd Street.
- Check Point: There will be a gas station and a fire station on your right.
- When you reach the fire station turn North on D Street.
- Take your turn East onto 5th Street and travel one block.
- Turn South on E Street (School Zone: Speed Limit drops to 25 Mph).
- Turn east into the school parking lot.

Destination: School parking lot.

Introductory brief

During this experiment, you will be operating an automobile simulator. You will be asked to participate in a total of six driving scenarios: one training scenario and five experimental runs. The training scenario is designed to familiarize you with the controls of the simulator and the type of scenario that you will operate in. The experimental runs are scenarios during which team performance and behavior will be observed and recorded. In each experimental run, you will be asked to drive to a specified location in the city; please do your best to obey all traffic laws (i.e., speed limit [*35 unless otherwise posted*], traffic signals, stop signs, turn signal usage, etc.). This is a team operation, and you are **both** responsible for these tasks.

This experiment will last approximately 1.5-2.0 hours. At the beginning of each scenario, the navigator and sometimes the driver will be given a sheet with the textual directions and navigation map with a highlighted route (you will have one minute to review the route). The simulation starts when the driver turns the ignition key and ends when the vehicle is shut down. Please do not discuss the scenario with your teammate until the simulation is started. You will leave from the Starting Point (SP) and should attempt to stay on the given route as best as possible. If you deviate from the route, please attempt to get back on the route in the most expedient manner. There will be other cars on the road in each scenario. During the experimental runs please refrain from giving hand signals, gestures or physically pointing to objects; the only form of communication you should use is verbal communication.

You will be provided various breaks during the course of the experiment; furthermore, you may request a break at any time that you desire. We ask, if possible, that you avoid requesting a break during the periods when you are actually operating the simulator. However, if you are feeling sick during the simulation or need to stop it for any reason, please let us know and we will stop the simulation immediately.

Throughout the course of the experiment, feel free to verbalize your thought process. Each run will be video taped for further review. During this experiment, we plan to examine team performance while you are conducting a navigation task under a time constraint. Please do your best to act naturally and drive the vehicle in the same manner in which you would drive your own vehicle. We would like to get the best estimate of a ‘real-life’ response. This will help us ascertain the consequences of different information structures on team performance.

Please help yourself to something to drink if you would like. We also have Internet available on various computers should you need to access your e-mail or the World Wide Web during the course of the experiment.

Automobile simulator description

GE Capital I-Sim's PatrolSim™ is a compact, high-performance driving simulator for the law enforcement and government marketplace. It utilizes GE Capital I-Sim's state-of-the-art simulation technology, which provides a highly realistic and immersive training environment. The PatrolSim offers more than 60 specific scenarios for law enforcement driver training.

The PatrolSim driving simulator provides an open-seat driving station in a low-cost, high fidelity driving environment that is suitable for training and research applications. Its Operator Console provides interactive, real-time control of the driving environment. PatrolSim incorporates GE Capital I-Sim's proprietary vehicle dynamics, traffic scenario and road surface software to provide accurate stimuli for the driver.

PatrolSim is a stand-alone, expandable and upgradeable system capable of simulating conditions for police vehicles, fire trucks, ambulances, pickups and public works vehicles. Highlights include:

- Open-seat driving configuration with typical police cruiser dash, including all instrumentation and controls.
- Expanded horizontal field of view (FOV) provides up to 270 degrees.
- Advanced graphics.
- Powerful scenario-creation editing tools allow instructors to quickly create and edit scenarios and run them within minutes.
- Scenario traffic incorporates artificial intelligence; vehicles behave as in real life or can be controlled in real time.
- Open architecture Windows™-based software running on off-the-shelf commercially available PC computer platforms.

End of run questionnaire - NASA task load index (TLX)

We are interested not only in assessing your performance but also your experiences in the different conditions. Basically I want to examine your "workload."

Since workload is something experienced individually, it can be difficult to estimate. Because workload may be influenced by many different factors, we would like you to evaluate several factors individually rather than lumping them into a single evaluation of overall workload. This set of six rating scales was developed by NASA. Please read the descriptions of the scales carefully. If you have a question about any of the scales, please ask us about it, as it is important that they be clear to you. I will leave the descriptions on the table for reference during the rest of the experiment.

Please evaluate the scenario by marking each scale at the point that matches your experience. Each line has two endpoint descriptors that describe the scale. Note that "performance" goes from "good" on the left to "bad" on the right. Please place an X **anywhere** along each scale between a pair of tick marks. Consider each scale individually. These ratings are an important part of the experiment and I appreciate your efforts.

Rating scale definitions

Title	Descriptions
MENTAL DEMAND	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
EFFORT	How hard did you have to work (mentally and physically) to accomplish your level of performance?
PERFORMANCE	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
FRUSTRATION LEVEL	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Position (Driver or Navigator)______ __
Team Number___________________ _
Information Level _________________ _ Map
Scenario_________________ ______
Run order____________________ ______
Date______________________________

Mental Demand

Low High

Physical Demand

Low High

Temporal Demand

Low High

Effort

Low High

Performance

Good Poor

Frustration

Low High

For the following questions, please focus on the interaction between you and your teammate, not the difficulty due to road conditions, etc.

What did you find most difficult about this scenario? Why?

What did you find easiest about this scenario? Why?

End-of-experiment questionnaire

Position (Driver or Navigator)___________
Team Number _______________________

Date_______________________________

Age: _____
Male or Female (circle one)
Years with a valid driver's license: _____

1) How familiar are you with the team member with whom you participated in the experiment?

1 2 3 4 5

(Unfamiliar: just met) (Very familiar: communicate with them daily)

2) Have you ever performed coordinated tasks with this team member?

1 2 3 4 5

(Never) (Frequently: work with them daily)

3) How difficult was it to coordinate your actions with your teammate? (Circle number)

Scenario	1=Very Difficult	2=Difficult	3=Easy	4=Very Easy
	Difficulty Level			
A: Both driver and navigator had maps/directions	1	2	3	4
B: Only the navigator had map/directions	1	2	3	4
C: Both driver and navigator had maps/directions. The navigator wore eye devices limiting vision.	1	2	3	4
D: Only the navigator had map/directions. The navigator wore eye devices limiting vision.	1	2	3	4

Please address any reasons why you believe this was so:

4) Have you ever had any type of formal training on teamwork (i.e., sports, crew resource management, a short course etc.)?

1 2 3 4 5 None

(Informal) (Formal: classroom instruction)

If so, please specify what type of training.

5) Which form of directions did you find most useful during normal navigating: textual, map with route, or a combination? Explain.

6) Which form of directions did you find most useful during abnormal periods of navigating (e.g.., getting back on your route after a wrong turn): textual, map with route, or a combination? Explain.

7) Regarding communication techniques used by your teammate, what would you like him or her to continue to do in future scenarios, improve upon, or do differently?

8) Regarding communication techniques used by you, what would you like to continue to do in future scenarios, improve upon, or do differently?

Scenario maps

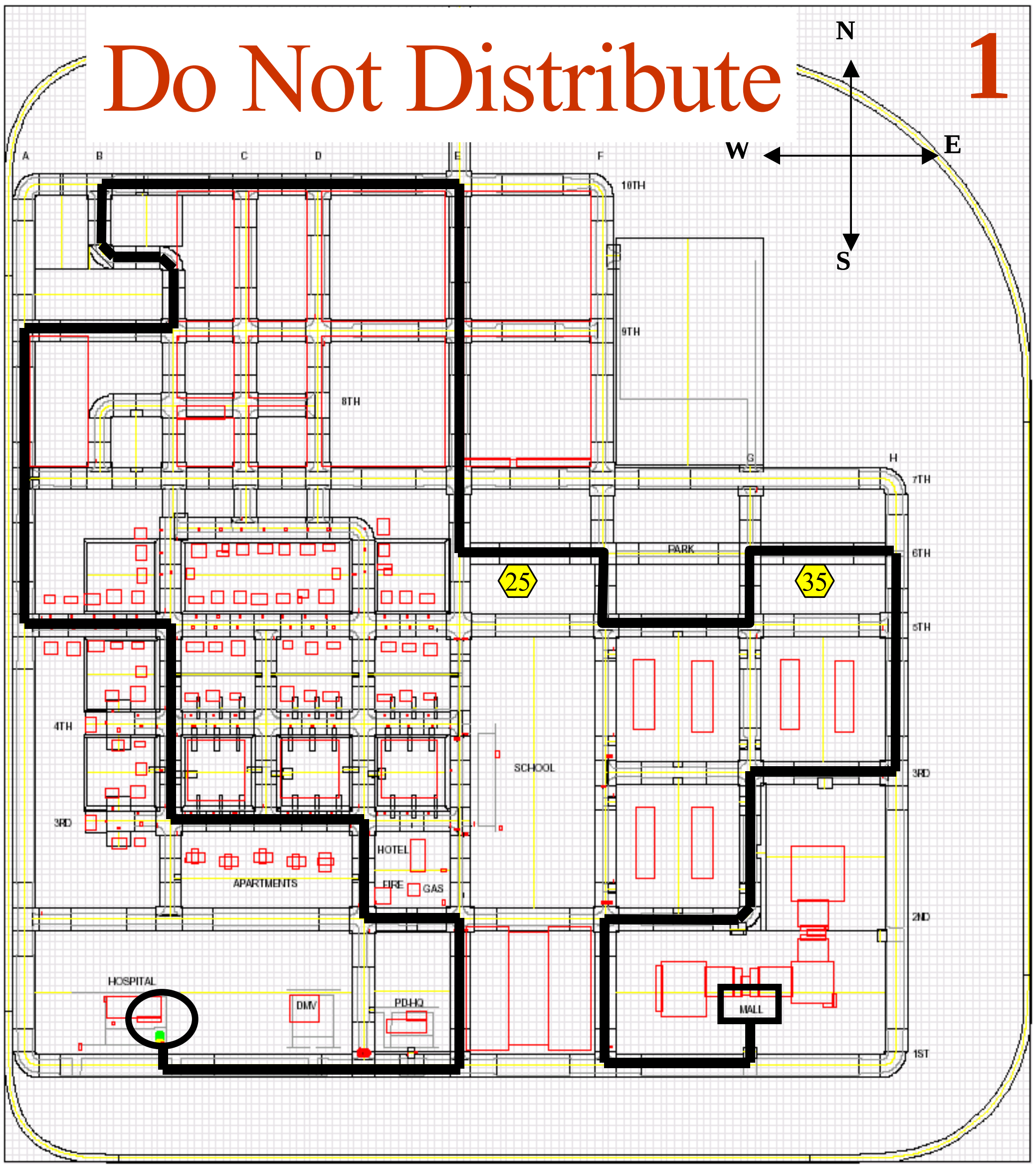


Figure A-2. Scenario 1 map.

Scenario 1 Textual Directions

Starting Point: Hospital parking lot.

•Exit Parking lot and turn East on 1st Ave.
•Pass DMV on your left.
•At second left turn, just past police HQ, turn North onto E Street (this is a one way street).
•Turn West on 2nd Ave.
•There will be a gas station and a fire station on your right.
•When you reach the fire station turn North on D Street.
•After one block turn West on 3rd Ave.
•Turn North on B Street.
•At your second intersection turn West on 5th Ave.
•Turn North on A Street.
•At your second intersection turn East on 9th Ave.
•Turn North on B Street.
•You will come to a "T" intersection, at this intersection turn East on 10th Ave.
•Travel on 10th Ave for three blocks.
•At your third intersection turn South on E Street.
•Travel South on E Street for approximately .3 miles.
•At your third intersection turn East on 6th Ave.
•Turn South on F Street.
•At your first intersection turn East on 5th Ave.
•Turn North on G Street and make your first turn East on 6th Ave.
•You will come to a "T" intersection, at this intersection turn South on H Street.
•Turn West on 3rd Ave.
•Turn South on G Street.
•Turn West on 2nd Ave.
•At your first intersection turn South on F Street for one block.
•You will come to a "T" intersection, at this intersection turn East on 1st Ave.
•Turn north into the Mall parking lot.
•Drive up to the entrance of Dills.

Destination: Mall parking lot at the entrance of Dills.

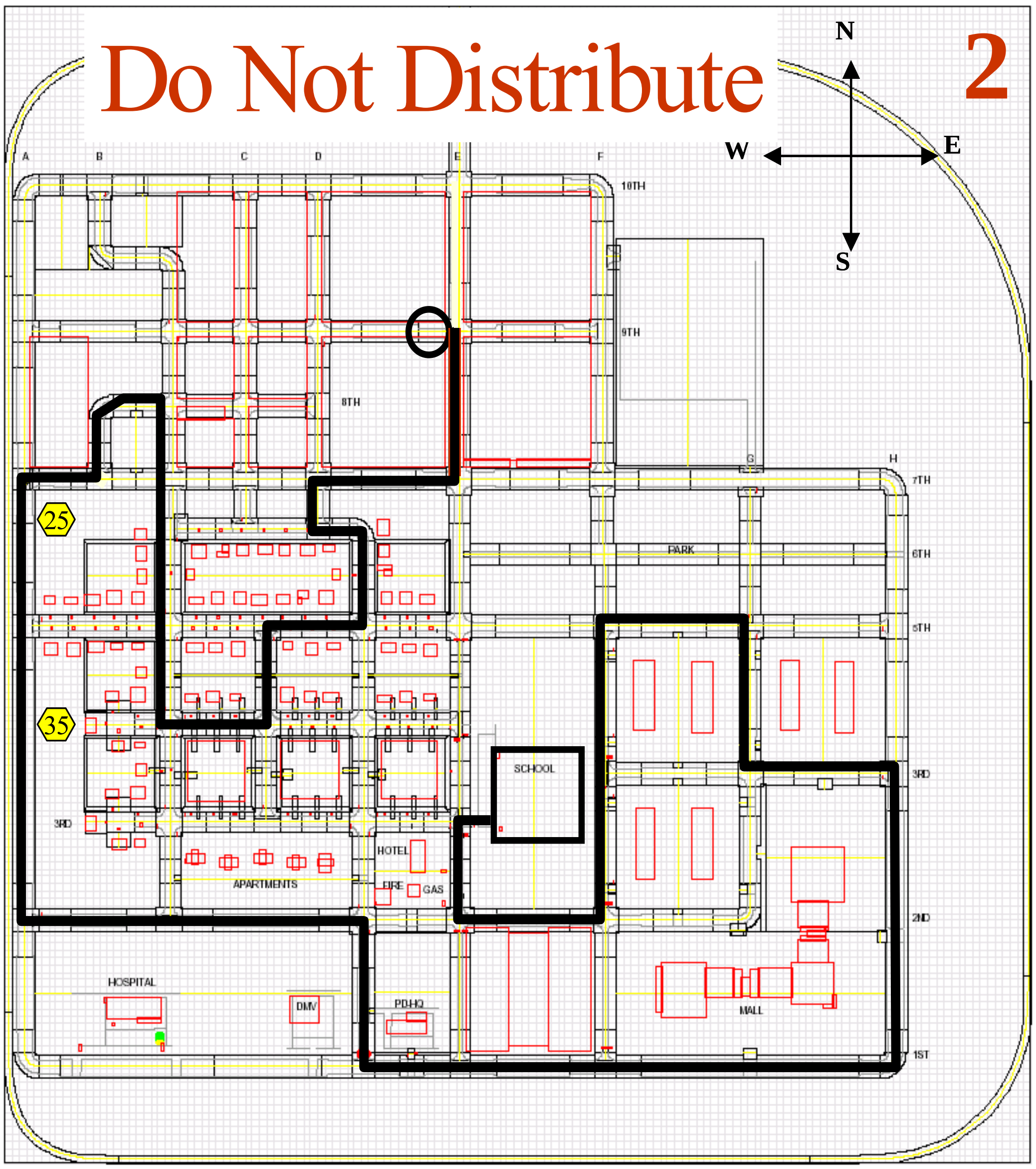


Figure A-3. Scenario 2 map.

Scenario 2 Textual Directions

Starting Point: Facing East at the intersection of E Street and 9th Ave.

•Turn South on E Street.
•Turn West on 7th Ave and travel one block.
•Turn South on D Street, D St. will intersect with 6th Ave, continue on D Street to the East and South.
•Turn West on 5th Ave for one block.
•Turn South on C Street.
•Turn West on 4th Ave.
•Turn North on B Street for three blocks.
•At your third intersection turn West on 8th/Green.
•Turn West on 7th Ave.
•Turn South on A Street for approximately .3 miles.
•Turn East on 2nd Ave.
•Travel on 2nd Ave for approximately ¼ of a mile.
•Turn South on D Street.
•You will come to a "T" intersection, at this intersection turn East on 1st Ave, Police HQ will be on your left and DMV will be on your right.
•Travel East on 1st Ave for approximately .3 miles.
•Turn North on H Street.
•Travel on H Street for approximately .2 miles.
•Turn West on 3rd Ave for one block.
•Turn North on G Street.
•Turn West on 5th Ave.
•At the first intersection turn South on F Street.
•Turn West on 2nd Ave.
•At you second intersection turn North on E Street (This is a one way street).
•Turn East into the school Parking lot and pull up to the front entrance.

Destination: School parking lot at the entrance.

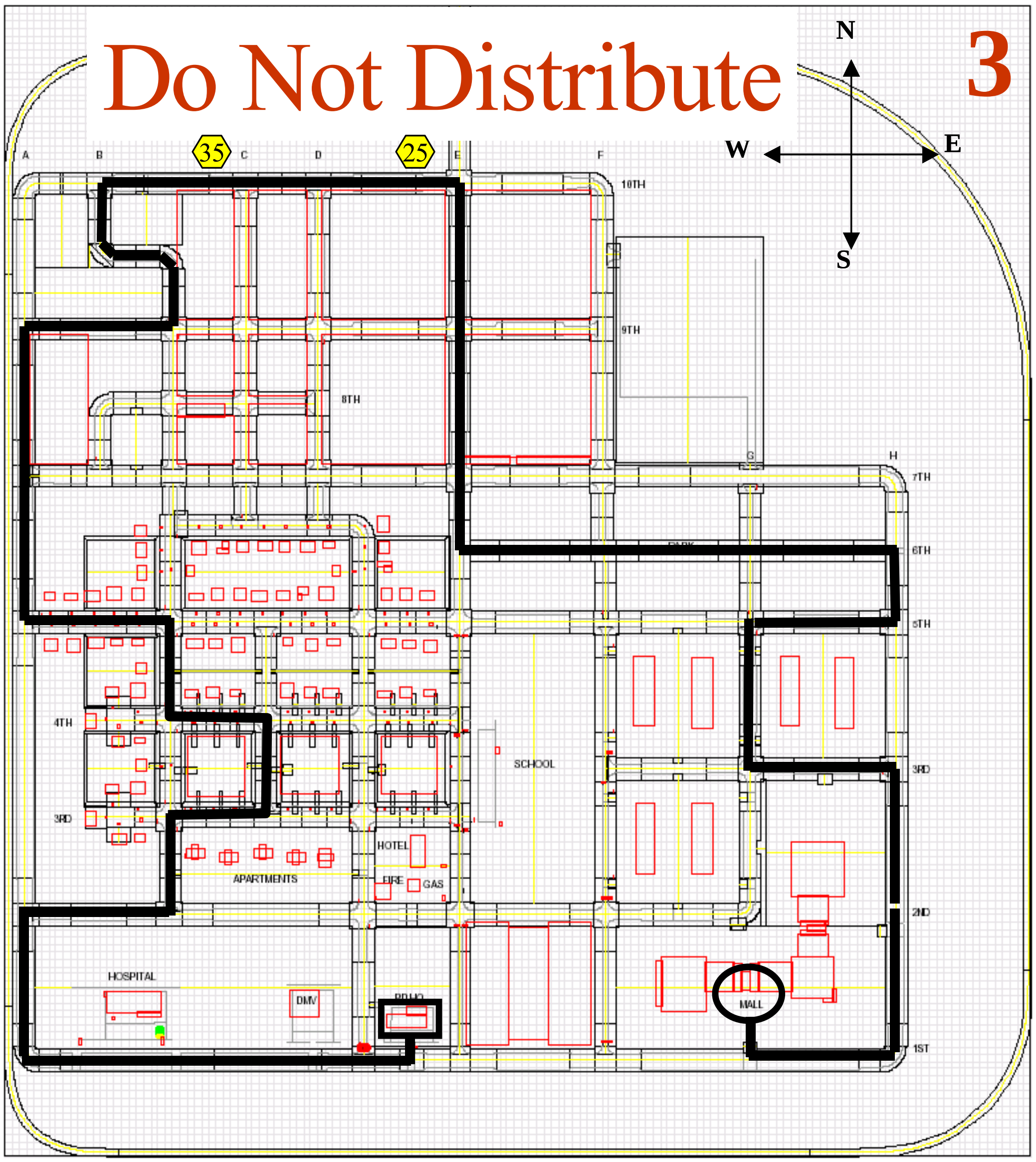


Figure A-4. Scenario 3 map.

Scenario 3 Textual Directions

Starting Point: Mall parking lot at the entrance of Dills.

•Exit the mall parking lot and turn East onto 1st Avenue.
•Travel one block and turn North on H Street.
•Turn West on 3rd Avenue.
•At the first intersection turn North on G Street.
•Turn East on 5th Avenue.
•You will come to a T-intersection, turn North on H Street.
•Take your first turn West on 6th Avenue.
•Travel on 6th Avenue for three blocks, at the third intersection turn North on E Street.
•At your third four way intersection turn West on 10th Avenue.
•Turn South on B Street.
•Turn West on 9th Avenue.
•You will come to a T-intersection, turn South onto A Street.
•At the second intersection turn East on 5th Avenue.
•Turn South at the first intersection on B Street.
•At the first intersection turn East on 4th Avenue.
•Take your first turn South onto C Street.
•At your first intersection turn West on 3rd Avenue.
•Turn South on B Street.
•You will come to a T-intersection, at this intersection turn West on 2nd Avenue.
• Turn South on A Street.
•Turn East on 1st Avenue, the hospital will be on your left.
•Drive past the Department of Motor Vehicles.
•Turn into the Police Department Head Quarters.

Destination: Police Department.

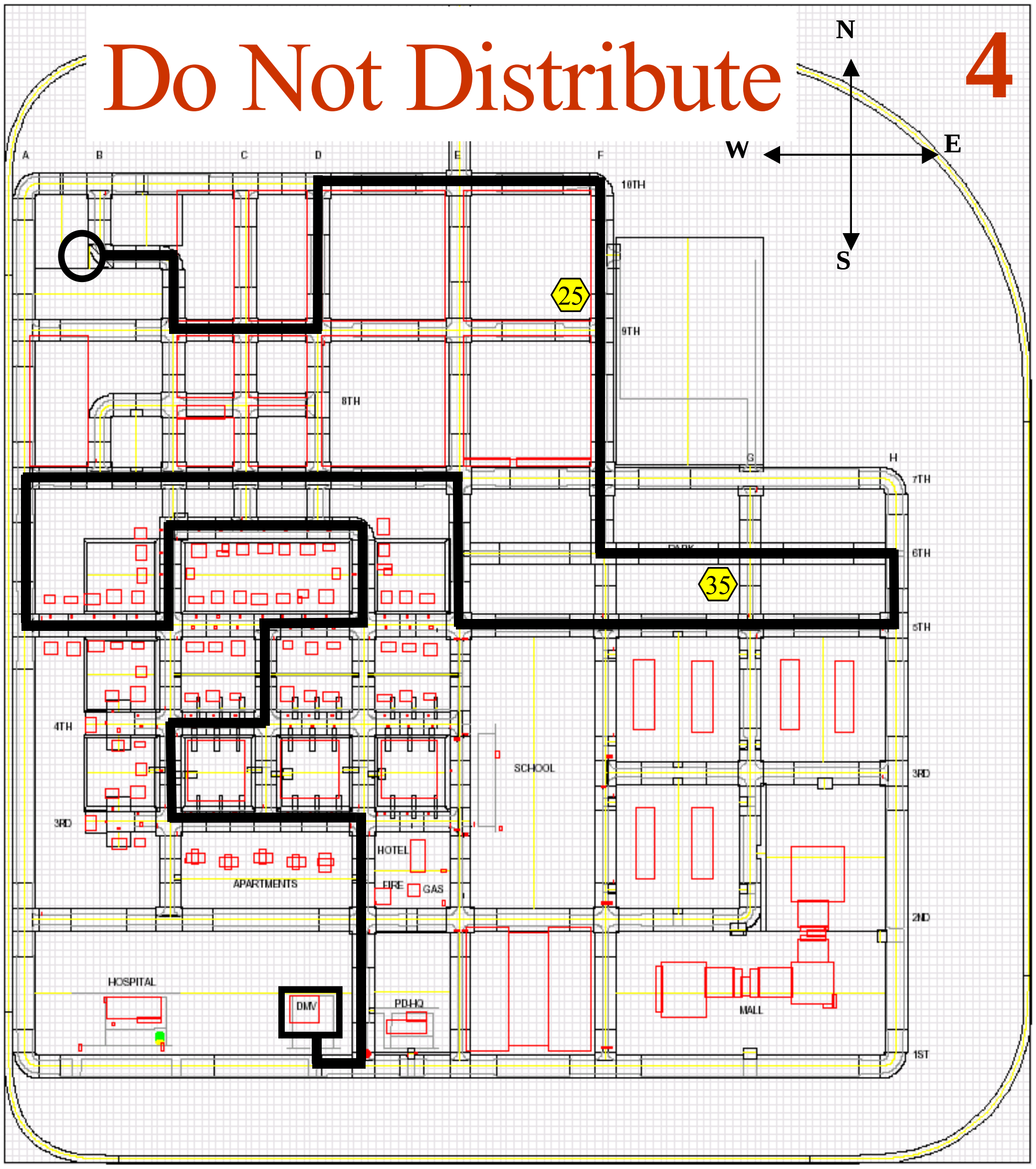


Figure A-5. Scenario 4 map.

Scenario 4 Textual Directions

Starting Point: Facing East at the bend in the road on B Street.

- Follow B Street East and South until you reach 9th Ave.
- Turn East on 9th Ave and travel for two blocks
- At your second intersection turn North on D Street
- You will come to a T-intersection, turn East at this intersection onto 10th Ave
- At your second intersection turn South on F Street
- At your third intersection turn East on 6th Ave
- Turn South on H Street
- Take your first intersection West on 5th Ave
- Turn North on E Street
- At your first four way intersection turn West on 7th Ave
- You will come to a T-intersection, turn South on A Street.
- Travel one block on A Street and turn East on 5th Ave
- At your first intersection turn North on B Street
- Turn East on 6h Ave
- Turn South on D Street
- At your first intersection turn West on 5th Ave
- Turn South on C Street
- Turn West on 4th Ave
- Turn South on B Street
- At your first four way intersection turn East on 3rd Ave
- At your second intersection turn South on D Street
- You will come to a T-intersection, turn West on 1st Street.
- Turn North into the parking lot of the Department of Motor Vehicles and park near the front entrance

Destination: Department of Motor Vehicles

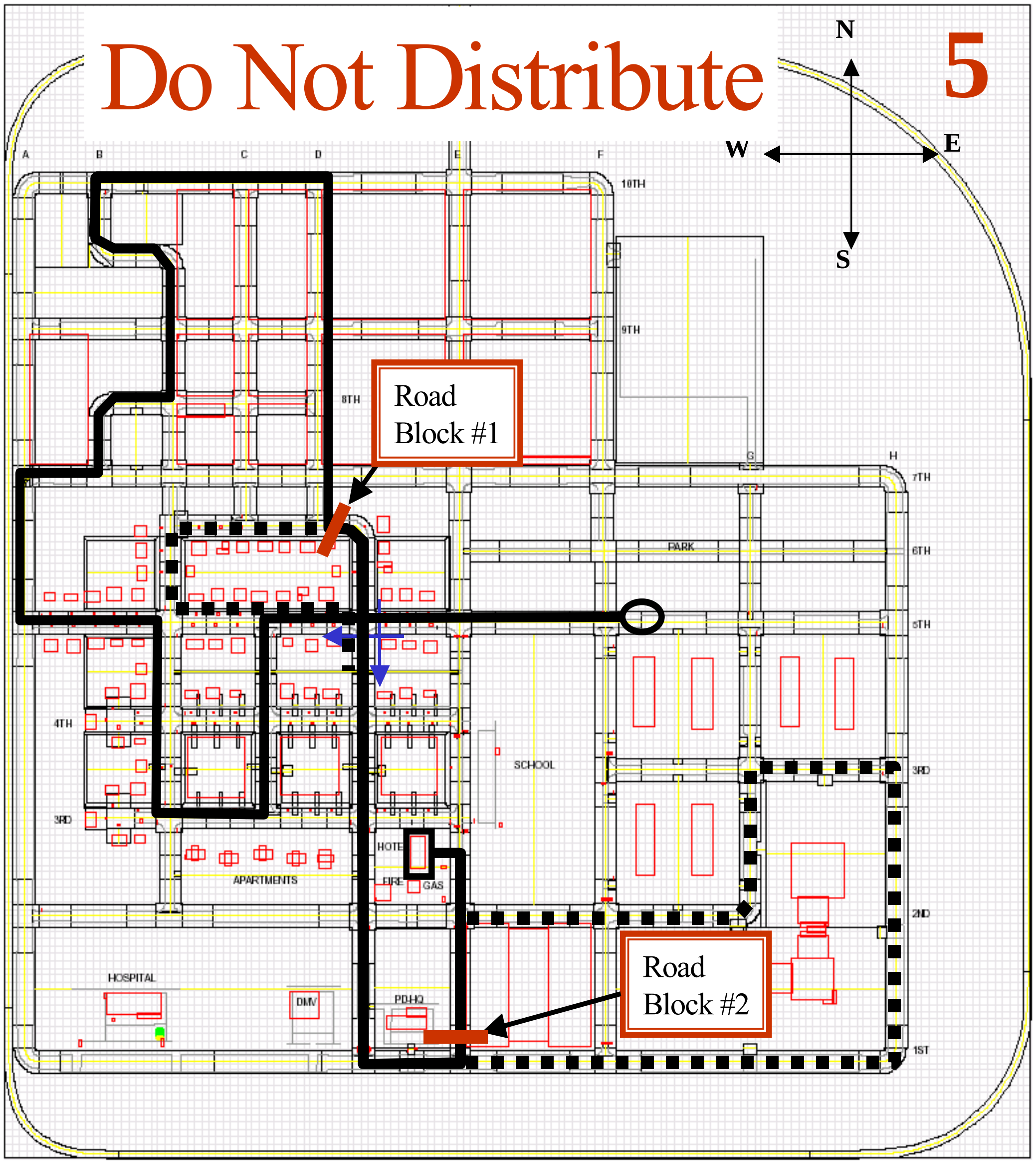


Figure A-6. Scenario 5 map.

Scenario 5 Textual Directions

Starting Point: Facing West at the intersection of 5^{th} Ave and F Street.

- Travel West approximately .3 miles on 5^{th} Ave.
- Turn South at your fourth intersection on to C Street.
- At your second intersection turn West on 3^{rd} Ave.
- At your 1^{st} intersection turn North on B Street.
- At your second intersection turn West on 5th Ave.
- You will come to a "T" intersection, turn North on A Street.
- Turn East on 7^{th} Ave.
- Make an immediate turn North on Green.
- Follow this to B Street and Turn North on B Street.
- You will come to a "T" intersection, turn East on 10th Ave.
- At your second intersection turn South on D Street.
- Follow D Street all the way to 2^{nd} Ave.
- Turn East on 1st Ave.
- Turn North on E Street.
- Turn West into the Hotel parking lot.
- Drive up to the entrance, under the overhang.

Destination: Hotel parking lot.

Automobile participant effects (p-Values)

Table A-1.
Automobile participant effects on communications.

		Age	Gender Mix	Experience	Experience Spread	Familiarity	Coordinated Task Experience	Teamwork Training	Training (Run)
Requests	Relevant Info	0.31	0.10	0.40	0.31	0.60	0.62	0.60	0.07
	Non Relevant Info	0.49	0.08	0.40	0.49	0.62	0.17	0.40	0.40
	Total Info	0.33	0.09	0.42	0.33	0.56	0.63	0.62	0.08
	Action	0.88	0.08	0.75	0.88	0.13	0.20	0.16	0.95
Transfers	Relevant Info	0.00	0.66	0.24	0.00	0.13	0.12	0.20	0.85
	Non Relevant Info	0.33	0.00	0.90	0.33	0.48	0.59	0.70	0.85
	Action	0.56	0.22	0.44	0.56	0.94	0.99	0.30	0.63
	Total	0.00	0.29	0.48	0.00	0.22	0.22	0.47	0.99
Acknowledgements	General	0.12	0.81	0.00	0.12	0.14	0.07	0.12	0.36
	Specific	0.87	0.39	0.18	0.87	0.02	0.02	0.00	0.87
	Total	0.41	0.55	0.30	0.41	0.48	0.69	0.10	0.35
Total	Comms	0.01	0.25	0.38	0.01	0.20	0.28	0.98	0.89
Anticipation	Ratio	0.00	0.67	0.39	0.00	0.83	0.62	0.31	0.94

Table A-2.
Automobile participant effects on performance.

Appendix B.

Experiment II: background documentation.

Introductory Briefing For Participants

During this experiment you will be operating the NUH-60 Black Hawk full motion simulator. You will be asked to participate in a total of four flight scenarios: one training scenario and three experimental runs. The training scenario is designed to familiarize you with the controls of the simulator and the type of scenario that you will operate in. The experimental runs are scenarios during which team performance and behavior will be observed and recorded. In each experimental run, you will be asked to conduct a normal take-off and then navigate to and land at a specified location using a standard route card and Flight Information Publications; please do your best to follow all flight profile instructions (i.e., airspeed, altitude, heading, climb rate, etc.). These are team operations and you are **both** responsible for these tasks.

This experiment will last approximately two to three hours. At this time, we will designate one of you as the pilot and one of you as the co-pilot/navigator. You will remain in these positions throughout the experiment. At the beginning of each scenario, the navigator, and sometimes the pilot, will be given a map with a route posted; you will also be given a route card with headings, altitudes, airspeeds, and checkpoints, approach plates for local airfields, and a description of the landing area. The runs are each approximately 15 minutes long and a break is given between them. The collection of data begins when you are given the route information and ends when the aircraft has landed. Please do not discuss the scenario with your teammate until the simulation is started. You will leave from the Starting Point (SP) and should attempt to stay on the given route as best as possible. If you deviate from the route, please attempt to get back on the route in the most expedient manner. During the experimental runs, please refrain from giving hand signals, gestures or physically pointing to objects; the only form of communication you should use is verbal communication.

You will be provided breaks during the course of the experiment; furthermore, you may request a break at any time that you desire. We also ask, if possible, that you avoid requesting a break during the periods when you are actually operating the simulator. However, if you are feeling sick during the simulation or need to stop it for any reason, please let us know and we will stop the simulation immediately.

Throughout the course of the experiment, feel free to verbalize your thought process. Each run will be video taped for further review. During this experiment, we plan to examine team performance while you are conducting a navigation task under a time constraint. Please do your best to act naturally and fly the aircraft in the same manner in which you would while conducting a real world mission. We would like to get the best estimate of a ‘real-life’ response. This will help us ascertain the consequences of different information structures on team performance.

End-of-run questionnaire – NASA task load index TLX

We are interested not only in assessing your performance but also your experiences in the different conditions. Basically I want to examine your "workload."

Since workload is something experienced individually, it can be difficult to estimate. Because workload may be influenced by many different factors, we would like you to evaluate several factors individually rather than lumping them into a single evaluation of overall workload. This set of six rating scales was developed by NASA. Please read the descriptions of the scales carefully. If you have a question about any of the scales, please ask us about it, as it is important that they be clear to you. I will leave the descriptions on the table for reference during the rest of the experiment. You will be asked to complete two of these rating scales for each run.

1. Individual Workload Assessment: Please evaluate the scenario by marking each scale at the point that matches ***your*** experience. Each line has two endpoint descriptors that describe the scale. Note that "performance" goes from "good" on the left to "bad" on the right. Please place an X **anywhere** along each scale between a pair of tick marks. Consider each scale individually.
2. Crew-member Workload Assessment: In the same manner as above, please evaluate the scenario by marking each scale at the point that matches your assessment of ***your crew-member's*** experience.

These ratings are an important part of the experiment and I appreciate your efforts.

Rating scale definitions

Title	Descriptions
MENTAL DEMAND	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
EFFORT	How hard did you have to work (mentally and physically) to accomplish your level of performance?
PERFORMANCE	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
FRUSTRATION LEVEL	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Position	Pilot / Navigator
Crew Number	1 2 3 4 5 6 7 8 9 10
Run	T 1 2 3
Information	A B
Scenario (leg)	T 1 2 3
Date	

Assessment of ***Your*** Workload

Mental Demand

Low High

Physical Demand

Low High

Temporal Demand

Low High

Effort

Low High

Performance

Good Poor

Frustration

Low High

Position	Pilot / Navigator
Crew Number	1 2 3 4 5 6 7 8 9 10
Run	T 1 2 3
Information	A B
Scenario (leg)	T 1 2 3
Date	

Assessment of ***Crewmember's*** Workload

Mental Demand

Low High

Physical Demand

Low High

Temporal Demand

Low High

Effort

Low High

Performance

Good Poor

Frustration

Low High

Position	Pilot / Navigator
Crew Number	1 2 3 4 5 6 7 8 9 10

Run	T 1 2 3
Information	A B
Scenario (leg)	T 1 2 3
Date	

Using the descriptions in the table below, please rank importance of the types of information during different phases of flight for this particular flight. Place a '1' next to the information type that is the most important, a '2' next to the information type that is the next most important etc., until you reach '6' the least important:

- For you to provide to your crewmember:

Phase of Flight							
Before Take-off	During Take-off	En-route	Before Landing	During Landing	After Landing	**Information Type**	**Description**
						Current Flight Information	The current airspeed, altitude, heading, climb rate etc. of the aircraft
						Future Flight Information	The future airspeed, altitude, heading, climb rate etc. that you will be required to fly
						Current Environmental Information	Description of the environment, terrain, checkpoints, etc. that you are currently flying in/over
						Future Environmental Information	Description of the environment, terrain, checkpoints, etc. that you will be flying in/over in the near future
						Aircraft Instrumentation Status	Status of the aircraft instrumentation (fuel, engine instruments, etc)
						Other	Any other type of information that was important for mission completion

If you used 'other' for any phase of flight, please specify the information below.

Position	Pilot / Navigator
Crew Number	1 2 3 4 5 6 7 8 9 10
Run	T 1 2 3

Information	A B
Scenario (leg)	T 1 2 3
Date	

- For your crewmember to provide to you:

Phase of Flight							
Before Take-off	During Take-off	En-route	Before Landing	During Landing	After Landing	**Information Type**	**Description**
						Current Flight Information	The current airspeed, altitude, heading, climb rate etc. of the aircraft
						Future Flight Information	The future airspeed, altitude, heading, climb rate etc. that you will be required to fly
						Current Environmental Information	Description of the environment, terrain, checkpoints, etc. that you are currently flying in/over
						Future Environmental Information	Description of the environment, terrain, checkpoints, etc. that you will be flying in/over in the near future
						Aircraft Instrumentation Status	Status of the aircraft instrumentation (fuel, engine instruments, etc)
						Other	Any other type of information that was important for mission completion

If you used 'other' for any phase of flight, please specify the information below.

End-of-experiment questionnaire

Please answer the following:
Age: Male Female

Rank:

Date of Flight School Graduation (month/year):

Total # of Flight Hours: _____________ Total # of Simulator Hours:__________

Total # of Military Flight Hours: FW: __________ RW:____________

Total # of Civilian Flight Hours: FW:__________ RW:____________

Please list all aircraft in which you are qualified:

Please circle all types of mission experience that you have had:
Observation/Scout Attack Transport Medevac

Search and Rescue External cargo Drug Interdiction Training/Instructor

Other___________________________

Please circle the most accurate responses.

How well do you know your testing partner?
a) not at all, first time meeting
b) we've met, briefly or social occasions
c) same unit but do not work together
d) same unit and work together, but do not fly together on a regular basis
e) fly together frequently (battle rostered)

Approximately how many hours have you flown with your testing partner in the last year?
a) 0 b) 1 – 25 c) 25 – 50
d) 50 – 75 e) 75 – 100 f) 100+

Approximately how many hours have you flown with your testing partner overall?
a) 0 b) 1 – 100 c) 100 – 200
d) 200 – 300 e) 300 – 400 f) 400+

How difficult was it to coordinate your actions with your teammate? (Circle number)

Scenario	1=Very Difficult	2=Difficult	3=Easy	4=Very Easy
	Difficulty Level			
A: Both pilot and navigator had maps/instructions.	1	2	3	4
B: Only the navigator had map/instructions. The navigator wore eye devices limiting vision.	1	2	3	4

Please address any reasons why you believe this was so:

Which form of directions did you find most useful during normal navigating: textual, map with route, or a combination? Explain.

Which form of directions did you find most useful during abnormal periods of navigating (e.g., IMC, EP): textual, map with route, or a combination? Explain.

Scenarios

The following scenarios will be used for the data collection runs.

Flight instructions to pilots and co-pilots for all scenarios.

a. Follow all airspeed, altitude and ground track requirements of the waypoint cards.

b. After all takeoffs, climb straight ahead to 400 feet AGL before turning to desired heading/course.

c. All climbs will be performed at 500 feet per minute; descents will be performed as necessary.

d. All instrument turns will be performed at standard rate (3^{o} per second).

e. Perform all radio communications (calls to Ground and Air Traffic Controllers, tactical sites, Approach Controllers, etc.) that would be required during any actual mission.

f. Force trim will be disabled.

Scenario A: nominal condition run

The simulator operator will:

1. Set visibility to 3 statute miles, ceilings to 1500 feet, winds and turbulence to zero.
2. Set time of day at 12 noon.
3. Disable the GPS.

Pre-mission briefing:

You are assigned the mission of transporting two passengers (captured Al Qaeda operatives) from Campbell Army Airfield to FARP 1. The mission is critical and must be completed to avoid an international incident. The only reason to abort or modify the mission will be in the event of an emergency situation requiring a landing as soon as possible. Due to security concerns, a special VMC flight corridor to the FARP has been established. The GPS is inoperative and you must navigate by pilotage and dead reckoning. You must follow altitude, airspeed and ground track restrictions in accordance with the waypoint card in order to comply with the corridor requirements. Maintain visual flight rules (VFR).

Weather for the mission is winds calm, 1500 feet overcast, 3 statute miles visibility (ETA through 1 hour).

Use ATC frequencies per the DOD FLIP. FARP 1 frequency is 34.15.

Special instructions to simulator operator: None

Table B-1.
Scenario A, nominal condition run waypoint card.

WPT	WPT Description/ Coordinates	Course / Distance (nm/km)	ETE	Maneuver Description
				VMC takeoff 230° from Campbell Army Airfield
1	Road Intersection N36º32.91' W087º39.93'	226° / 10.5/19.3		Cruise Flight 900' MSL, 100 KIAS
2	Mouth of Inlet (Bridge) N36º28.52' W087º44.11'	239° / 7.1/13.2		Cruise Flight 1300' MSL, 110 KIAS
3	FARP 1 N36º25.00' W087º49.99'	240° / 5.8/10.8		Cruise Flight 1100' MSL, 90 KIAS

Scenario B: nominal condition run

The simulator operator will:

1. Set visibility to 3 statute miles, ceilings to 1500 feet, winds and turbulence to zero.
2. Set time of day at 12 noon.
3. Disable the GPS.

Pre-mission briefing (read to participating pilot):

You are assigned the mission of transporting several boxes containing aircraft parts from FARP 1 to FARP 2. Your aircraft has a takeoff weight of 18,500 pounds. Due to security concerns, a special VMC flight corridor at terrain flight altitudes has been established. Your flight route will over-fly suspected unmarked mine fields, therefore, you should not decide to land the aircraft along the route unless there are no other alternatives. The GPS is inoperative and you must navigate by pilotage and dead reckoning. You must follow altitude, airspeed and ground track restrictions in accordance with the waypoint card in order to comply with the corridor requirements. Maintain visual flight rules (VFR).

Weather for the mission is winds calm, 1500 feet overcast, 3 statute miles visibility (ETA through 1 hour).

FARP 1 frequency is 34.15 and FARP 2 is 43.35. Use ATC frequencies per the DOD FLIP if necessary.

Special instructions to simulator operator: Approximately 2 minutes into the flight, activate a Decreasing % RPM R. This will require ECU lockout operations.

Table B-2.
Scenario B, nominal condition run waypoint card.

WPT	WPT Description/ Coordinates	Course / Distance (nm/km)	ETE	Maneuver Description
				VMC takeoff from FARP 1
4	Road Intersection N36º28.77' W087º53.31'	332º / 4.6/8.6		Cruise Flight 1000' MSL, 80 KIAS
5	End of Inlet N36º34.75' W088º00.67'	322º / 8.3/15.5		Cruise Flight 1400' MSL, 90 KIAS
6	FARP 2 N36º40.27' W088º02.98'	348º / 5.7/10.7		Cruise Flight 1100' MSL, 80 KIAS

Scenario C: off-nominal condition run

The simulator operator will:

1. Set visibility to 1 statute mile, ceilings to 250 feet, winds to zero and turbulence to Level 1.
2. Set time of day at 12 noon.

Pre-mission briefing (read to participating pilot):

You are assigned the mission of repositioning the aircraft from FARP 2 to Campbell Army Airfield for AVIM-level maintenance. Due to the weather, you have been briefed to proceed via a preplanned route that, due to security concerns, must be followed. A special VMC flight corridor, at contour flight altitudes, has been established to Campbell Army Airfield. You must follow altitude, airspeed and ground track restrictions in accordance with the waypoint card in order to comply with the corridor requirements.

Weather for the mission is winds calm, 250 feet overcast, 1 statute mile visibility, with light turbulence (ETA through 1 hour). Weather at Seaside Army Airfield, which can be used as an alternate if necessary, is forecast to be winds calm, 1500 feet overcast, 3 statute miles visibility (ETA through 1 hour).

FARP 2 frequency is 43.35. Use ATC frequencies per the DOD FLIP.

Special instructions to simulator operator**:** Approximately 2 minutes into the flight, reduce visibility to 0.50 sm. Within the next minute, before a decision can be made whether to abort or land, reduce visibility to zero causing inadvertent entry into IMC. When asked, provide the aircraft with an IFR clearance via radar vectors, and advise the crew to expect the ILS Runway 23 Approach into the airfield. See Simulator Operator waypoint card for altitude, airspeed, and heading guidance. Approximately 1 minute into task number five, activate the number one engine light with no other indication of engine failure, do not fail the engine.

Give this card to flight crew:

Table B-3.
Scenario C, off-nominal condition run waypoint card.

WPT	WPT Description/ Coordinates	Course / Distance (nm/km)	ETE	Maneuver Description
				VMC takeoff from FARP 2
7	Mouth of Inlet N36º41.56' W087º56.04'	085º / 5.7/10.7		Cruise Flight 1000' MSL, 120 KIAS
8	Road Bend N36º43.43' W087º43.25'	086º / 10.5/19.2		Cruise Flight 1500' MSL, 110 KIAS
9	Campbell Army Airfield N36º40.29' W087º29.29'	112º / 11.6/21.5		Cruise Flight 1100' MSL, 120 KIAS

For use by simulator operator:

Table B-4.
Simulator operator route card.

Task	Maneuver	Maneuver Description	≈ETE
1	Initial Climb & Acceleration Instructions	Turn to heading 070 and climb straight ahead to 2000' MSL, at 120 at 1000 fpm.	1+30
2	Straight and Level Flight	Maintain heading 070, 2000' MSL, 120 KIAS.	1+00
3	Straight Climb	Climb straight ahead on heading 070, from 2000' to 4000' MSL at 1000 fpm, maintain 120 KIAS.	2+00
4	Straight and Level Flight	Maintain heading 070, 4000' MSL, 120 KIAS.	2+00
5	Straight Descent	Descend straight ahead on heading 070, from 4000' to 2100' MSL at 500 fpm, maintain 120 KIAS.	4+00
6	Straight and Level Flight	Maintain heading 070, 2100' MSL, 120 KIAS.	1+00
7	Right Standard Rate Turn	Turn right from heading 070 to heading 140, maintain 2100' MSL and 120 KIAS and intercept the ILS 23 inbound course. Cleared for the approach.	0+30
8	ILS 23, Campbell AAF	Maintain inbound course 225^{o}, glideslope and 120 KIAS.	2+24

Campbell Army Airfield approaches

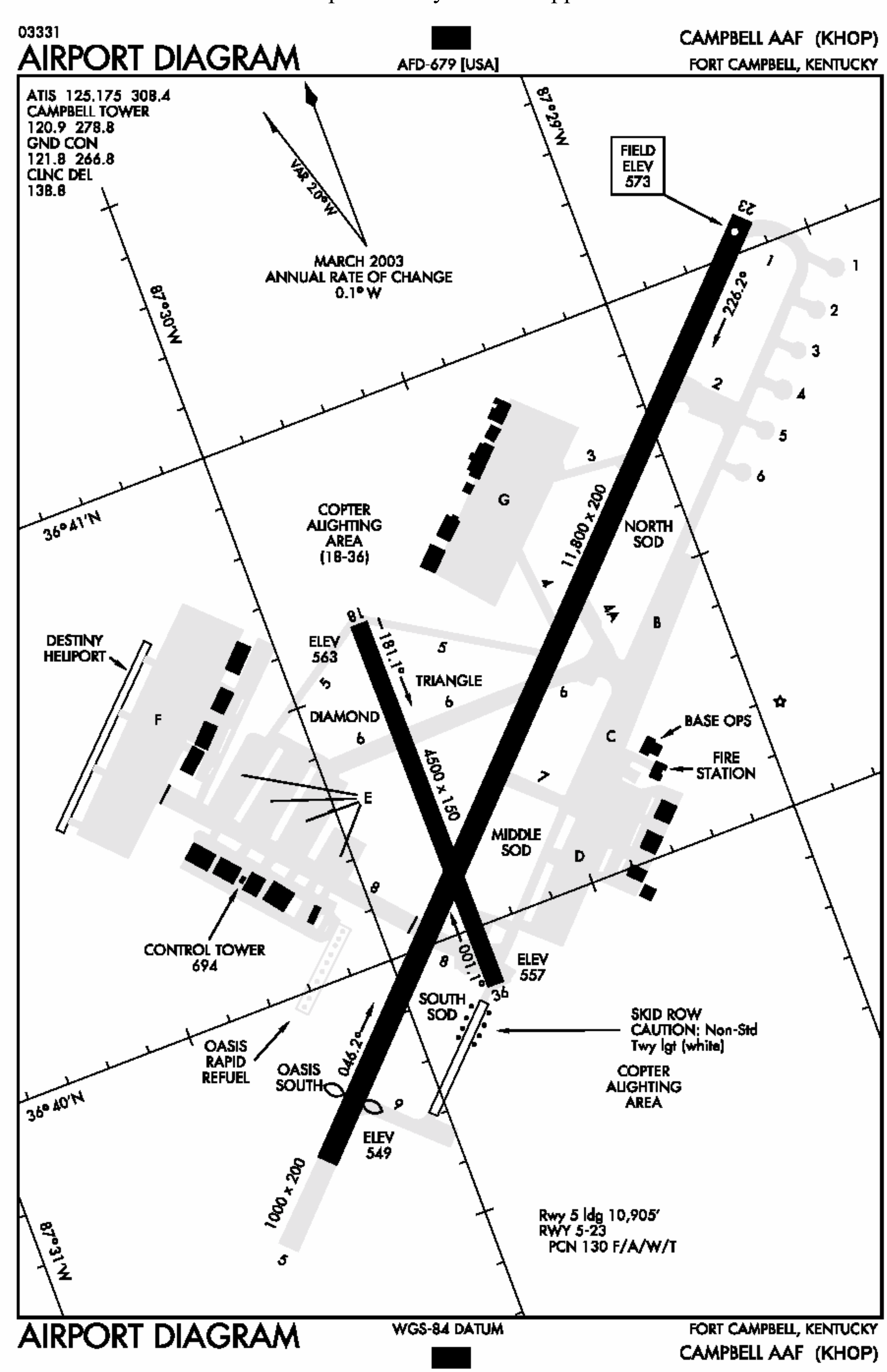


Figure B-1. Campbell Army Airfield airport diagram.

Table B-5.
Campbell Army Airfield approach minimums.

RADAR INSTRUMENT APPROACH MINIMUMS

CAMPBELL AAF (KHOP)

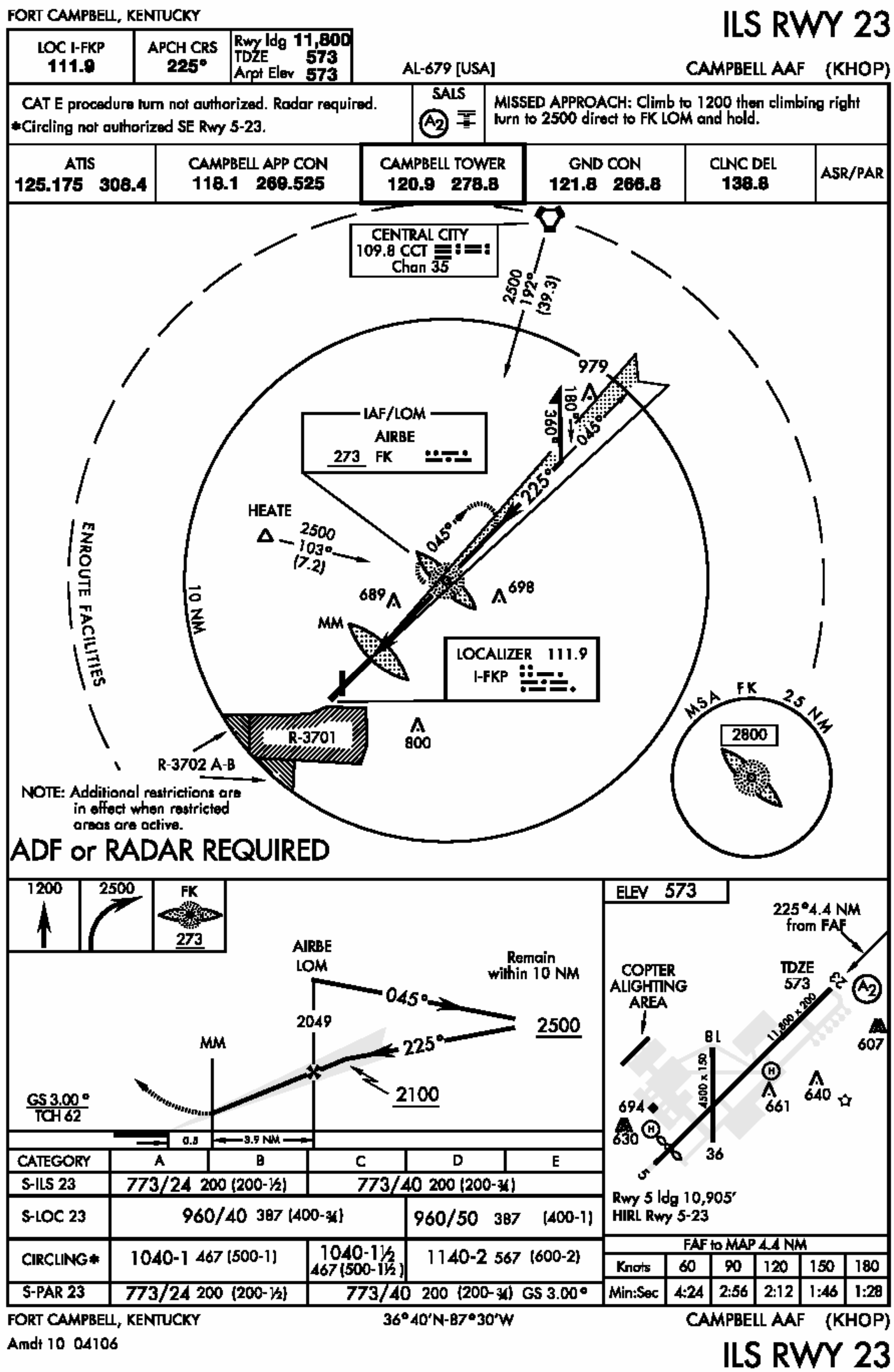
RADMINS

CAMPBELL AAF (KHOP), (FORT CAMPBELL), KY (03079 USA) **ELEV 573**

RADAR ① **- (E)** 134.350x 237.5x 395.9x 258.3x 290.9x

	RWY	GS/TCH/RPI	CAT	DH/ MDA-VIS	HAT/ HAA	CEIL-VIS
PAR	23	3.0/62/1183	AB	**773/**24	200	(200-½)
			CDE	**773/**40	200	(200-¾)
ASR	23		AB	**980/**40	407	(500-¾)
			CD	**980/**50	407	(500-1)
			E	**980/**60	407	(500-1¼)
	5 ②		ABC	**940-**1	383	(400-1)
			DE	**940-**1¼	383	(400-1¼)
CIR ③	5, 23		A	**1020-**1	447	(500-1)
			B	**1040-**1	467	(500-1)
			C	**1040-**1½	467	(500-1½)
			DE	**1140-**2	567	(600-2)

① Civil GCA 132.025. ② Apch not auth when R-3701, R-3702A, in use. ③ Cir not auth SE of Rwy 5-23.



CATEGORY	A	B	C	D	E
S-ILS 23	773/24 200 (200-½)		773/40 200 (200-¾)		
S-LOC 23	960/40 387 (400-¾)			960/50 387 (400-1)	
CIRCLING*	1040-1 467 (500-1)		1040-1½ 467 (500-1½)	1140-2 567 (600-2)	
S-PAR 23	773/24 200 (200-½)		773/40 200 (200-¾) GS 3.00°		

Figure B-2. Campbell Army Airfield ILS RWY 23.

Plan view of flight legs

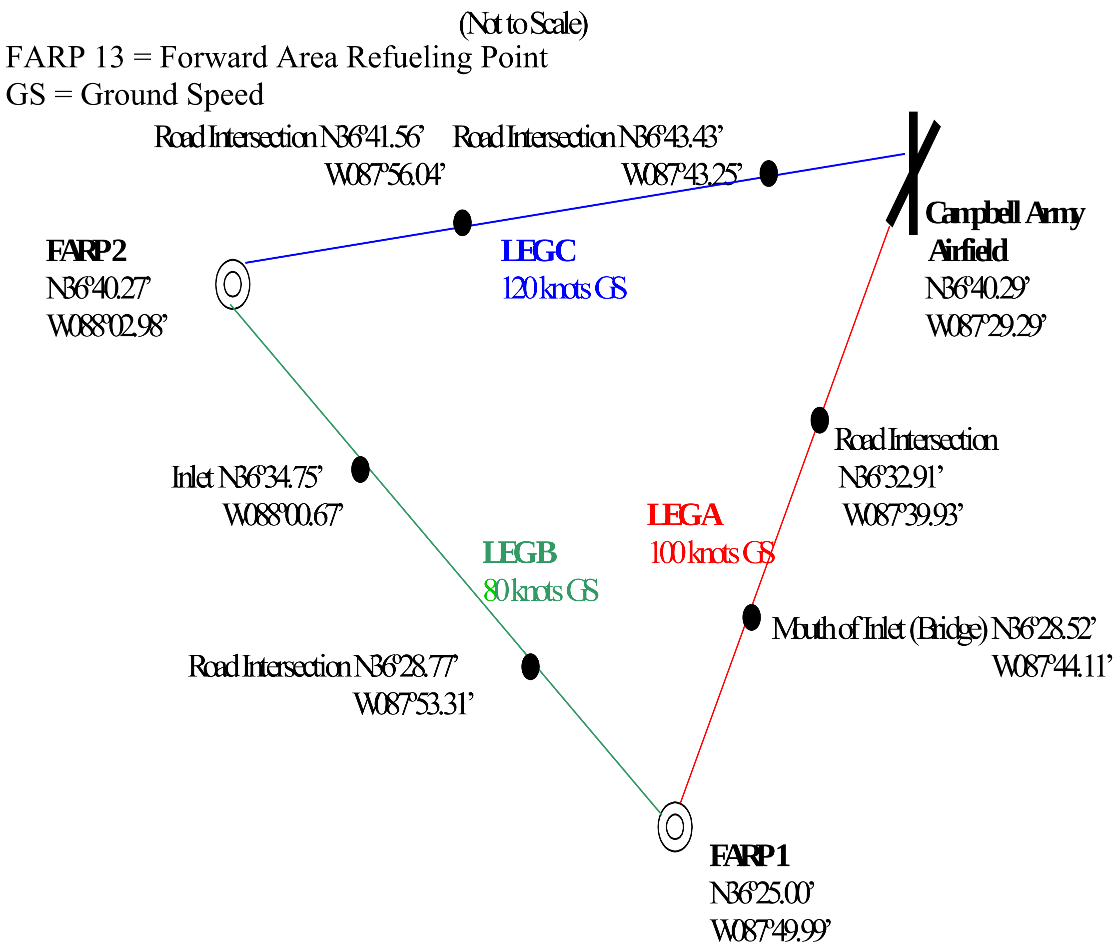


Figure B-3. Plan view of flight legs.

Helicopter participant effects (*p*-Values)

Table B-6.
Helicopter participant effects on communications (nominal).

		Nominal						
		Flt Hrs	Familiarity	Hrs Spread	UH-60 Qual	Hrs with Partner	Training (Leg)	Order
Requests	Relevant Info	0.43	0.15	0.48	0.01	0.28	0.78	0.76
	Non Relevant Info	.	.	.	.	.	.	.
	Total Info	0.43	0.15	0.48	0.01	0.28	0.78	0.76
	Action	0.78	0.66	0.43	0.19	0.29	0.88	0.85
Transfers	Relevant Info	0.31	0.25	0.49	0.36	0.92	0.69	0.26
	Non Relevant Info	0.46	0.89	0.08	0.15	0.90	0.90	0.39
	Action	0.07	0.60	0.05	0.05	0.38	0.74	0.54
	Total	0.49	0.41	0.98	0.77	0.91	0.73	0.31
Acknowledgements	General	0.00	0.27	0.00	0.73	0.71	0.72	0.22
	Specific	0.51	0.81	0.11	0.55	0.85	0.84	0.98
	Total	0.01	0.56	0.00	0.88	0.90	0.92	0.47
Total	Comms	0.69	0.95	0.27	0.68	0.83	0.89	0.83
Anticipation	Ratio	0.37	0.68	0.76	0.50	0.88	0.45	0.15

Table B-7.
Helicopter participant effects on communications (off-nominal).

		Off Nominal				
		Flt Hrs	Familiarity	Hrs Spread	UH-60 Qual	Hrs with Partner
Requests	Relevant Info	0.91	0.05	0.56	0.24	0.91
	Non Relevant Info	0.90	.	0.45	0.35	0.54
	Total Info	0.80	0.09	0.24	0.50	0.61
	Action	0.18	0.60	0.07	0.11	0.98
Transfers	Relevant Info	0.17	0.62	0.18	0.79	0.23
	Non Relevant Info	0.46	0.91	0.73	0.77	0.93
	Action	0.89	0.72	0.88	0.11	0.47
	Total	0.18	0.53	0.16	0.58	0.27
Acknowled	General	0.53	0.55	0.36	0.98	0.94
	Specific	0.75	0.82	0.27	0.25	0.65
	Total	0.78	0.44	0.93	0.52	0.74
Total	Comms	0.10	0.42	0.10	0.28	0.53
Anticipation	Ratio	0.05	0.63	0.04	0.08	0.37

Table B-8.

Helicopter participant effects on performance.

	Diagnosis Time	Radio Calls	Nav Errors	Process Errors	Total Errors
Training	X	0.04	0.47	0.54	0.63
Flight Hours	0.09	0.38	0.45	0.28	0.43
Flight Hours Spread	0.22	0.31	0.27	0.14	0.14
UH-60 Qualifications	0.36	0.55	0.47	0.54	0.63
Familiarity	0.79	0.80	0.29	0.89	0.58
Hrs. with Crew	0.93	0.69	0.08	0.95	0.13
Order	X	0.14	0.81	1.00	0.81