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Effects of Practice with Imposed Communication Delay on the Coordination and Effectiveness of Distributed Teams

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Effects of Practice with Imposed Communication Delay
on the Coordination and Effectiveness of Distributed Teams

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Effects of Practice with Imposed Communication Delay
on the Coordination and Effectiveness of Distributed Teams

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Abstract

The current study tested whether introduction of audio transmission delays during skill acquisition would benefit the performance effectiveness of distributed teams in a novel transfer context. Two-person university student teams (N=40) performed a simulated firefighting task in 4 practice trials and a novel transfer condition. Intra-team communications were systematically perturbed with closed-loop transmission delays ranging from 2 to 6 seconds. On average, teams were able to improve performance over time despite transmission delay, with significant differences in performance observed between certain groups both over the course and at the end of the experiment: Short (2s blocked) practice delay was associated with low relative performance during practice and in the presence of a novel (4s) transfer delay, whereas longer (4s, 6s) practice delays were associated with improved performance in both practice and transfer, regardless of presentation schedule (blocked versus random). The introduction of relatively long or random communication delays accelerated team skill acquisition and benefited transfer performance. Team composition (i.e., cognitive ability) failed to moderate the observed practice-performance relationships. Study findings can be used to design more effective training systems for distributed teams that must adapt to transmission delays known to perturb feedback control and impair team performance.
Effects of Practice with Imposed Communication Delay on the Coordination and Effectiveness of Distributed Teams

The fulfillment of many organizational goals is dependent upon two or more individuals pooling their knowledge, skills, and abilities to work together on a shared task. To be effective, members of a work team must be able to track each other’s work and provide timely feedback to one another. Often team members are distributed, located in different offices, regions, or countries (Salas, Stagl, Burke, & Goodwin, 2007). The technology used to enable coordination and communication among distributed team members can introduce system latencies. Technologically-induced delays require team members to depend on delayed feedback about system status and the consequences of their task-relevant behaviors. Delayed feedback has an empirically demonstrated negative effect on team performance, whereby both task effectiveness (Armstead, 2007; Chong, Kawabata, Ohba, Kotoku, Komoriya, Takase, & Tanie, 2002; Rantanen, McCarley, & Xu, 2004) and coordination (Henning, Smith, & Armstead, 2007) degrade as a function of increasing delay. Because feedback is critical to team performance, team effectiveness is degraded when members must coordinate their efforts from different locations in the presence of transmission delays (Griffith, Mannix, & Neale, 2002).

Researchers have long speculated that practice under delayed feedback conditions might benefit team performance (Brady, 1971) but systematic experimental investigations are limited. The current study explores the extent to which distributed teams improve performance through repeated practice with systematically-manipulated audio transmission delay.
Teamwork

In 2001 (Devine & Phillips), it was estimated that half of American organizations were using teams to achieve business objectives. As organizational demands become more complex, it is likely that the number of organizations employing team structures will increase (Bell, 2007; Cooke, Salas, Cannon-Bowers, & Stout, 2000). The prolific use of teams in the modern workplace has been an impetus for the scientific investigation of team performance (Priest, Stagl, Klein, & Salas, 2006).

A team is herein defined as a collection of two or more persons who coordinate their efforts to accomplish a common goal (Salas, Dickinson, Converse, & Tannenbaum, 1992). Teams vary considerably with respect to purpose, duration (Devine & Phillips, 2001), and structure (Artman, 1999). The complexity of the team task requires the cooperation of multiple persons, thus team members’ roles are necessarily interdependent. The stipulation of interdependence among members differentiates teams from groups (Bowers, Salas, Prince, & Brannick, 1992).

Regardless of topography, all work teams are created to accomplish something, and to determine their degree of success team performance must be measured and evaluated in some way. Because teams are composed of multiple interdependent members, the theory and measurement techniques used to understand individual task performance are considered to be insufficient for understanding team performance (Baker & Salas, 1992). This explains why the scientific literature draws a distinction between taskwork and teamwork (Cannon-Bowers & Salas, 1998). The former relates to a team member’s ability to perform the necessary functions and tasks relevant to his/her individual role. Taskwork can be successfully accomplished without the cooperation of
other team members and can be assessed using traditional performance metrics.

Individual role competency is necessary, but not sufficient, for team success. Teamwork, then, refers to the coordination of individual efforts (Brannick, Prince, Prince, & Salas, 1995); the set of moment-to-moment activities, or *processes*, team members engage in to move the team toward its goal (Marks, Mathieu, & Zaccaro, 2001). Thus, metrics of teamwork should account not only for team outcomes but also the processes used to achieve them.

Herein, the term *effectiveness* is used to refer to team performance outcomes and the term *coordination* is used to refer to team processes (Brannick et al., 1995). Effectiveness is an emergent construct that develops over time and is directly influenced by the processes employed (Kozlowski & Ilgen, 2006). Coordination, then, should be viewed as the epitome of teamwork (Brannick et al., 1995) and researchers generally assume that better coordination leads to greater effectiveness (LePine, Piccolo, Jackson, Mathieu, & Saul, 2008). Yet coordination is difficult to measure (Baker & Salas, 1992).

While effectiveness is traditionally assessed as some function of objective task completion and/or subjective rating of overall performance or team member satisfaction (Kozlowski & Ilgen, 2006), coordination is both contextually- and compositionally-driven, and often episodic in nature (Marks et al., 2001). Because coordination varies as a function of available resources and previous performance, variability with respect to process is to be expected both between and within teams. Researchers thus argue that coordination, rather than effectiveness, is a more meaningful indicator of team functioning (Brannick et al., 1995).
Coordination is dependent upon the ability of team members to track each other’s performance, adjusting their own behavior as elements of the situation change. Two critical team processes that have been identified are communication (Salas, Cooke, & Rosen, 2008) and adaptation (Burke, Stagl, Salas, Pierce, & Kendall, 2006). Direct, reliable patterns of communication afford team members a mutual means of providing and receiving performance feedback (Baker, Day, & Salas, 2006). Team members use this and other forms of feedback to understand changes in situational demands, knowledge which can be used to facilitate meaningful changes in team member behaviors and coordination. Behavior change that promotes successful performance within a dynamic context is indicative of adaptive team performance (Burke et al., 2006).

Distributed Teams

Most of the research conducted to date has focused on colocated teams (Priest et al., 2006), but it is no longer necessary for all team members to be located in the same place. Members of large organizations often need to be able to communicate with one another to share information efficiently despite geographic separation. Technological advances have led to affordable computer-mediated technologies that expedite communication (Baltes, Dickinson, Sherman, Bauer, & LaGanke, 2002). Organizations use this technology in efforts to optimize performance, drawing on the collective knowledge, skills, and abilities of geographically- and/or temporally-dispersed personnel (Salas, Stagl, Burke, & Goodwin, 2007). As these technologies become more abundant, so will the use of distributed teams. Fiore, Salas, Cuevas, and Bowers (2003, p.16) notes that distributed teams “represent an important subcategory of teams that may eventually become a dominant form of team interaction. Simultaneous to this growth, we must
better understand what facilitates or hinders distributed coordination.” Priest et al. (2006) echo this sentiment, expressing need for team researchers to fill a void with respect to the understanding of team dynamics in distributed situations.

Both team coordination and team effectiveness are likely to be affected by the distribution of team members, because of changes in the way team members must interact (Fiore et al., 2003). A meta-analysis conducted by Baltes et al (2001) found that distributed arrangements, as opposed to face-to-face arrangements, negatively impact team effectiveness, time taken to complete tasks, and team member satisfaction.

Computer-mediated communication reduces the amount of cues available to help users interpret meaning of interpersonal communications (Driskell, Radtke, & Salas, 2003). The use of computer-mediated communications introduces another potentially adverse factor that can be expected to further complicate teamwork: technologically-induced feedback delays (Griffith et al., 2002).

**Transmission Delays**

Currently, the rate at which digital information is transmitted between distributed team members is a function of—at a minimum—bandwidth and processing speed. Both system attributes have finite value. Thus, at any given time there is both a maximum quantity of information that can be transmitted from one location to another (bandwidth) and a maximum speed at which said information may be accessed via remote workstation (processing speed). Lesser bandwidths and/or processing speeds produce slower transmission rates; the slower the transmission rate, the longer an individual must wait to receive information. The time that elapses as a signal traverses its path is referred to as *transmission delay* (Krauss & Bricker, 1967). Changes in network traffic can cause
fluctuations in the duration of transmission delay, a phenomenon referred to as *jitter* (Gutwin, Benford, Dyck, Fraser, Vaghi, & Greenhalgh, 2004).

Transmission delay is inherent to all computer-mediated systems and, by extension, to all distributed situations (Billard & Pasquale, 1993; Ruhleder & Jordan, 2001). Delays range from relatively imperceptible (e.g., conversations between cell phone users) to extensive (e.g., communications between ground and space crews) and are often classified according to duration (Angrilli, Charubini, Pavese, & Manfredini, 1997). Delays may be visual, auditory, or haptic. Auditory transmission delays, in particular, have a debilitating effect on performance for individuals (Smith, 1962) and teams. Both team coordination (Allison, Zacher, Wang, & Shu, 2004; Armstead, 2007; Chong et al., 2002; Rantanen et al., 2004) and team effectiveness (Angiolillo, Blanchard, Isrealeski, & Mane, 1997; Brady, 1971; Henning et al., 2007) degrade as a function of increasing delay. Jitter subjects users to variable transmission delays, which may further complicate the delay-performance relationship.

During a discourse occurring in real time, an individual utters something and then waits for an acknowledgement or response from his/her conversant. When an auditory transmission delay is present, some time passes before the original utterance reaches its intended recipient. The person receiving the message may believe that he/she is providing an immediate response. But because of transmission delay, the response is not heard for some time. Like other forms of delayed feedback, transmission delays have a negative effect on communication and performance. Auditory transmission delay is a salient problem associated with distributed communication (Caldwell, 2000; Gutwin et al., 2004).
Short audio transmission delays affect verbal communication in a number of ways, including a change in the frequency and duration of both responses and interruptions (Kraut & Fish, 1997). A delay of just 200 msec can disrupt conversation (Olson & Olson, 1997; Ruhleder & Jordan, 2001). The longer the delay, the fewer voice events produced (Kraus & Bricker, 1967). Participants try to convey greater meaning with each speech event (Kraut & Fish, 1997), resulting in longer speech events. So, too, when an individual is waiting for a response but receives none, he/she may begin talking again. When a delay is present, responses are not received as quickly as the speaker has intended. Thus, these subsequent talk spurts may result in overlapped speech (Ruhleder & Jordan, 2001). Interruptions and overlapped speech become more prevalent with increasing delay. According to one study, delay resulted in a nearly three-fold increase in number of interruptions (Anderson, O’Malley, Doherty-Sneddon, Langton, Newlands et al., 1997).

Generally, research suggests that persons experiencing short transmission delays are more likely to express frustration and/or confusion with respect to the conversation (Olson & Olson, 1997) and to want to terminate the conversation earlier than those not subjected to delay (Kraut & Fish, 1997). The observed effects of transmission delay may be self-perpetuating. Kraut and Fish (1997) explain that as participants experience the negative effects of delay (e.g., slowed, less frequent responses and increased interruptions), they perceive the conversation as less interactive, which seems to cause them to respond in kind. Conversants are not inclined to want to continue with a conversation when it is perceived as one-sided.
Because delay impairs communication, considered a critical team process (Salas et al., 2008), delay has at least an indirect effect on overall task performance (Caldwell, 1994). Communication affects how readily information can be shared amongst team members (Billard & Pasquale, 1993). Furthermore, delayed responses and increased interruptions affect each participant’s understanding of verbal communications. Delays result in team members having dissonant views of a shared system. This effect has been demonstrated in the laboratory with delays as brief as 300 msec (Angiolillo et al., 1997). Olson and Olson (1997) suggest that understanding is affected because participants can no longer follow the flow of the conversation. Conversants subjected to a transmission delay lose a shared sense of meaning. Delays also affect the quality of shared information. In the presence of a delay, responses seem to come in a sluggish manner – even though a response was provided immediately. Therefore, information that was once fresh and pertinent to the situation may have changed by the time it is received by the intended recipient (Caldwell & Paradkar, 1995). Anderson et al. (1997) demonstrated that a mere 500 msec transmission delay in one direction (1 sec round-trip delay) caused a 36% performance decrement on a map task.

Participants are often unaware that a delay is present. Brady (1971) found that participants remained oblivious to a delay despite having participated in a 10-minute conversation under a constant transmission delay of 600 msec. Despite no conscious awareness of the delay, the typical effects of delay were observed; participants became confused and produced more overlapped speech. In situations where participants are not aware of a delay, they tend to attribute communication issues to the other conversant (Angiolillo et al., 1997). When participants are privy to the presence of a delay, they are
capable of fairly accurate estimates of the duration of short delays (i.e., delays of 1-6 seconds; Angrilli et al., 1997). Wang (2002) supports this finding with respect to short delays (i.e., 2-6 seconds), but very short delays (i.e., less than 2 seconds) are often underestimated and longer delays, (i.e., over 6 seconds) are often overestimated. The accuracy of delay perception was moderated by gender in this study, whereby males were more accurate with respect to estimation of shorter delays and females were more accurate with respect to estimation of longer delays. Expectation of a delay, however, has failed to alleviate negative performance effects in laboratory studies (Brehmer, 1995). This implies that participants cannot sufficiently modify their behavior to accommodate for perceived delay.

To the extent that distributed teams are necessary, ways to address the delay-coordination problem are needed. Simply alerting team members to the possibility of a delay does not eliminate its effect on performance (Brehmer, 1995). There are three possible means through which solutions might be found. First, technologies may be developed to better minimize or eliminate delays. In fact, according to Gutwin et al. (2004), this is the strategy employed by most researchers. Although technological advances may soon solve the processing issues responsible for some shorter delays, it may not be feasible to completely eradicate the delay associated with all distributed situations (Baier & Schmidt, 2004; Caldwell, 2009). For example, as space exploration continues to take crews further from home, delays will inevitably persist as inherent features of the distributed coordination effort. A second approach may be to select individuals for team membership based on those attributes associated with better performance under imposed delay. The practicality of human factors design promotes
usability for a wide array of individuals, not simply those possessing qualities presumed to facilitate adaptation to system shortcomings (e.g., delays). A third approach is to train users to become more proficient in adapting to delays.

**Team Training**

Training consists of at least two phases: *skill acquisition*, through which participants practice relevant tasks to achieve some level of proficiency (Cannon-Bowers, Rhodenizer, Salas, & Bowers, 1998), and *transfer*, through which trainees directly apply the newly learned skills to the job. Effective team training does the following: (1) provides an overview of the team’s purpose and structure, (2) provides time for team members to learn new skills, and (3) offers some degree of performance feedback (Baker et al., 2006; Salas, Rhodenizer, & Bowers, 2000). Due to the interdependency of team members, team coordination and effectiveness are both improved by cross-training team members with respect to individual roles and functions (Volpe, Cannon-Bowers, Salas, & Spector, 1996).

The simplest form of training is *practice*. In fact, researchers have long speculated that practice with delay might help to reduce its negative performance effects (Brady, 1971; Caldwell, 2009). Rantanen et al. (2004) assert that individuals experienced in performing under delays can “understand them, anticipate them, and adapt to them” (p.370) but offer no substantive test of their claim. While some laboratory studies have demonstrated that individuals can learn to improve performance over time despite delay (Simpson, Barron, Rothrock, Frecker, Barton, & Ligetti, 2007), performance trajectories are generally negatively impacted by increasing delay (Gibson, 2000), and skills individuals acquired under delay conditions are not likely to transfer to novel situations.
(Sterman, 1989). Prior research with teams across multiple days of training suggests that performance gains under a fixed delay condition are modest and inconsistent (Kao & Smith, 1977).

There are, however, many different ways to practice new skills. Few studies have systematically explored the effects of manipulations of the practice context on the delay-performance relationship. Brehmer (1995) imposed a system response delay for six consecutive trials and compared performance against a control condition. Individuals in the delay condition were able to improve performance somewhat over time but, overall, were still outperformed by participants in the control condition. Simpson et al. (2007) tracked user performance over twelve trials. Some participants received training under no delay, the rest received training under a constant delay of 1.5 seconds. Delay conditions were switched during transfer. The authors observed that performance improved more quickly when participants were permitted to practice in the absence of a delay. Performance of those practicing in the absence of delay was negatively affected by the addition of a 1.5 sec delay in transfer. The authors surmised that practicing under delay improved transfer performance, suggesting “users comfortable working with a delay improve their performance when no delay is present but the converse is not true” (p.57). Neither of these studies provides insight into whether further manipulations of the practice context can mitigate the relationship.

Brehmer (1995) designed a follow-up to his first study, in which individuals practiced the task with or without delay and then half the members of each condition performed the task with delay or without delay (4 conditions). In the transfer with delay conditions, practice with delay led to greater performance than practice without delay
with respect to overall effectiveness; changing from shorter (i.e., 0 delay) to longer delay resulted in performance decrements when compared with individuals experiencing a constant practice-transfer delay. In transfer without delay condition, practice with delay performance was as good as that of participants practicing without delay; changing from a longer to a shorter (i.e., 0 delay) resulted in improvements in performance. This suggests that certain practice conditions may be more or less effective in buffering against a novel delay.

It should be appreciated that transmission delays are not necessarily constant. For example, delays are known to vary as a function of jitter (Gutwin et al., 2004). Training provides participants an opportunity to practice a skill within a specific (set of) context(s). Given finite resources, it would not be feasible to train participants to perform across all possible contexts. Therefore, it might be possible to develop training programs that would facilitate trainees’ ability to transfer newly learned skills to novel situations. Practice over a range of delays might help teams to develop strategies for handling novel delays. This approach is consistent with the goal of fostering team adaptability (Burke et al., 2006).

The effects of practice have been shown to vary depending on whether individuals acquire skills as a part of a blocked or a random practice program (Cannon-Bowers et al., 1998). In a blocked practice program, individuals practice one component skill continuously before moving on to another component. In a random practice program, however, components are practiced in varied order. Random practice programs are associated with lower levels of performance during skill acquisition, but higher levels of performance in novel transfer tasks (Catalano & Kleiner, 1984; de Croock, Van...
Merrienboer, & Paas, 1998). This observed effect has been found across age groups (Kerr & Booth, 1978), skill level, (Hall, Domingues, & Cavazos, 1994), and task domain (Carlson & Yaure, 1990; Hebert, Landin, & Solomon, 1996; Jacoby, 1978; Jelsma & Pieters, 1989; Lee & Magill, 1983; Shea & Morgan, 1979).

Individuals participating in a random practice program continuously adjust to differing demands, whereas those participating in blocked practice programs need only react to the same demand. The blocked schedule is predictable (Del Rey, Whitehurst, & Wood, 1985). Burke et al. (2006) suggest blocked schedules result in the adoption of fixed behavior patterns that impede adaptability. Therefore, persons placed in a novel transfer task following a blocked practice program will not have had the opportunity to develop a strategy to adjust to a change in demand. On the other hand, for individuals who have participated in a random practice program, the transfer task may be perceived as an extension of practice (Catalano & Kleiner, 1984). Thus the transfer task generates higher contextual interference for blocked practice participants than it does for random practice participants and, therefore, causes those in the former category to perform at a lower level (Jelsma & Pieters, 1989; Li & Wright, 2000).

Varying the length of transmission delay during skill acquisition might be a valuable training intervention for distributed teams. The training literature remains relatively silent, to date, regarding the specific effects of variations in the practice environment on team skill acquisition and transfer performance. However, the robust empirical support for random task component practice schedules suggests that a similar pattern might emerge for random and blocked delay contexts. This effect is expected to extend to teams.
Team-Based Simulations

To study the effects of practice under delay conditions, it is important to select an appropriate task. The task must necessarily be team-based, whereby performance will be affected by the introduction of a communication delay, and affords teams the opportunity to improve performance over time (Rantanen et al., 2004). Likewise, the task must allow for the systematic measurement of team effectiveness and various indices of team coordination (Baker & Salas, 1992). A viable solution is the use of a low-fidelity simulation (Bowers et al., 1992), or microworld, such as *Networked Fire Chief* (NFC; Omedei & Wearing, 1993).

Microworlds are created to simulate dynamic, real-world situations (e.g., firefighting) whereby participants are instructed to respond to a problem that develops over time as a function of both pre-programmed parameters and user-system interactions (Chapman, Nettelbeck, Welsh, & Mills, 2006). Microworlds offer researchers tremendous flexibility with respect to scenario development (Brehmer & Dorner, 1993). Thus, researchers may make use of a task that closely emulates the demands, behaviors, and contexts found in the field, without sacrificing experimental control.

Microworld scenarios can be adapted for use with individuals or teams of varying size. Member roles can be designed to be interdependent, with team members collocated or distributed. Scenarios can be repeated, either verbatim or with similar parameters, to provide teams with ample opportunity to develop and practice their skills (Fiore, Cuevas, Scielzo, & Salas, 2002). The dynamic nature of the task means that there is no single way to solve task problems in the microworld. Multiple measures of coordination can be developed (Howie & Vincente, 1998). Thus, the microworld is an ideal forum for
studying the effects of transmission delay on teamwork over time and in response to changes in situational demands.

**Current Study**

The current study responds to recent calls for the study of factors affecting distributed communication (Fiore et al., 2003; Timmerman & Scott, 2006) by investigating whether the negative performance effects of long audio transmission delays (i.e., 4 seconds) can be reduced through training. Specifically, this study seeks to determine whether the delay context within which two-person distributed teams acquire task-related skills can affect a team’s ability to perform effectively when presented with a novel delay in a transfer setting. If this form of training proves to be effective, this approach would have both applied and theoretical implications. Practically, the results might be directly applied as a means of reducing the degrading effects of transmission delay faced by some teams in challenging task environments. However, the results of this study may generalize to other forms of delayed feedback, a common characteristic of dynamic tasks (Brehmer, 2005). Increasing our knowledge of how practice context affects later performance will contribute to the extant literature on transfer of team learning. This study seeks to provide evidence for the relative effects of random and blocked delay training *conditions*, which would extend the robust findings for use of random versus blocked task *content*.

Herein, two-person teams complete a series of practice scenarios under separate closed-loop delay conditions (blocked, random) before completing a common transfer trial under a novel delay. Because the transfer delay might be perceived as an extension of practice, three different blocked conditions are included (i.e., constant delay practice-
transfer, practice delay-longer-than-transfer, and practice delay-shorter-than-transfer) in an effort to explore whether direction of change makes a difference. The performance effects of relative team cognitive ability are also examined.

Hypotheses

A careful review of the training literature provides some guidance for the formulation of hypotheses concerning the effects of practice context upon team effectiveness and measures of coordination in a transfer setting. Teams practicing under random delay conditions are expected to perform differently than their blocked condition counterparts. In addition, delay duration is expected to have an increasingly detrimental effect on performance. Therefore, the following effects are hypothesized:

*Hypothesis 1:* Team effectiveness (i.e., overall task performance) during transfer will be affected by practice context, such that performance during transfer will be better for teams practicing under: (a) random rather than blocked delay conditions, (b) same-as- and longer-than-transfer rather than shorter-than-transfer blocked delay conditions, and (c) longer-than- rather than same-as-transfer blocked delay conditions.

This is the first known study to explore the effects of transmission delay on teams performing a microworld task that uses objective measures of coordination. It is difficult to speculate how each of the aforementioned processes will be affected by transmission delay in general, or the different delay conditions specifically. Under normal, non-delay conditions, there are several ways teams can manage the firefighting landscape. It is
possible, then, that each process might be affected differently by each of the delay
conditions. Therefore, the following general hypothesis is offered:

**Hypothesis 2:** Team coordination (i.e., task-related processes) during transfer
will be affected by practice context.

The literature on individual performance in microworlds, as well as that of team
composition, provides sufficient support for a predictable relationship among certain
composition variables and team effectiveness. Generally, mental ability is related to
*individual* performance (Schmidt, 2002). In particular, there is a demonstrated positive
relationship between individual general cognitive ability and observed effectiveness in a
microworld (Rigas, Carling, & Brehmer, 2002). Likewise, higher cognitive ability is
related to team effectiveness in other tasks (Stewart, 2006). Given the current study,
higher relative cognitive ability should result in more effective teamwork, overall, and
potentially buffer the negative effect of transmission delay. Therefore, team cognitive
ability (aggregated, high v low) is expected to interact with practice condition to affect
performance in transfer. Thus:

**Hypothesis 3.** The proposed relationships between practice context and teamwork
(effectiveness and coordination) during transfer will be moderated by team
cognitive ability.
Method

The current study employed a mixed design to explore the relative effects of practice with imposed communication delay(s) upon measures of teamwork (i.e., effectiveness and coordination). Two-person teams participated in a series of practice trials under one of four delay conditions (2s, 4s, 6s, random) before completing a common transfer trial under a novel delay (4s). An aspect of team composition (cognitive ability) was explored as a potential moderator of the practice condition-teamwork relationship.

Participants

Data were collected from 80 undergraduate volunteers (40 teams) enrolled in an introductory psychology course at a large northeastern university. All participants were recruited through the psychology department’s online participant pool and were compensated with course credit. Participants reported a mean age of 18.9 years. The sample was composed of 38 males and 42 females, resulting in 24 same- and 16 mixed-gender teams. None of the participants reported any experience with the Networked Fire Chief (NFC) program. Participants’ reported level of video game experience was normally distributed.

Practice Conditions

Communication delay was operationalized as a closed-loop phenomenon and herein defined as the minimum sum total time, measured in seconds, elapsed between one team member’s vocalization and receipt of the second team member’s response. Consider, for example, that a voice event elicited by one team member is not received by the second team member for 2 seconds. When confirming response is also delayed 2
seconds, then from the standpoint of the first team member, the total closed-loop communication delay is 4 seconds.

Conditions are identified as a function of the nature of communication delay length throughout the practice phase (Trials 1-4). There are four separate conditions: (1) Blocked delay_same, (2) Blocked delay_short, (3) Blocked delay_long, and (4) Random delay. All conditions shared a common transfer delay (Trial 5). See Table 1 for illustration. Participants were randomly assigned to a single condition, with the restriction of an equal sample size in each condition.

**Blocked delay_same Practice.** Dyads (n = 10) responded to a 4-second delay in the practice phase. The delay was consistent throughout each trial. This delay was *identical* to the delay in the common transfer trial.

**Blocked delay_short Practice.** Dyads (n = 10) responded to a 2-second delay in the practice phase. The delay was consistent throughout each trial. This delay was *shorter* than the delay in the common transfer trial.

**Blocked delay_long Practice.** Dyads (n = 10) responded to a 6-second delay in the practice phase. The delay was consistent throughout each trial. This delay was *longer* than the delay in the common transfer trial.

**Random delay Practice.** Dyads (n = 10) responded to a variety of delays presented in random order, the average of which was always 4 seconds. For example, one pair of team members was presented with four successive trials of 6-, 3-, 2-, and 5-second delay, respectively, while another pair responded to four trials with 5-, 3-, 6-, and 2-second delays, *et cetera*. A single delay was applied consistently throughout the duration of each trial. The specific order in which delays were presented was
counterbalanced using a Latin Square design (See Table 2; Alimena, 1962; Bradley, 1958) across teams to balance the effects of presentation order. The average delay in the practice phase was identical to that presented to all teams during the common transfer trial.

**Networked Fire Chief (NFC)**

NFC is a low-fidelity microworld designed to simulate firefighting activities via computerized-based tasks. Team members are presented with a firefighting landscape modeled on a computer display after a plausible real-world environment (See Figure 1). Each landscape is composed of elements representing a variety of entities, including housing, vegetation, water sources, and fire-fighting appliances. Certain elements can be destroyed by fire, while others cannot. Fires spread throughout the landscape as a function of wind speed and direction, as well as the fuel density associated with each consumable element in the landscape. Each of the consumable elements is assigned a point value to encourage team members to prioritize the safety of certain elements in relation to fire risk (e.g., houses over trees over clearings). Team members respond to fire outbreaks by moving firefighting appliances into position and initiating the fight command using a computer mouse. Because firefighting necessarily depletes the resources available to fight future fire outbreaks, appliances must be monitored for water supply levels and eventually moved to designated water sources for refilling. All interactions with the simulated environment are logged, chronologically, on system-generated reports.

Teams participated in five functionally equivalent NFC (Omedei & Wearing, 1993) scenarios, with one scenario per trial. Scenario *equivalency* was achieved through
use of: (1) identical quantities of each element used to create the landscape, (2) consistent number and timing of system events, and (3) a negligible difference between respective *freeburn* scores (i.e., overall performance scores based on no team member-system interaction). Two prototype scenarios were rotated vertically and/or horizontally to produce additional scenarios (Elliott, Welsh, & Nettlebeck, 2007). Each firefighting landscape measured 150 icons by 100 icons, thus composed of 15,000 elements (1289 icons representing houses, 6081 icons representing trees, 7254 icons representing pastures, and 376 icons representing water sources). The maximum duration of each scenario was held constant at 10 minutes (3000 generations, one system update every 200 msec). In addition to an established fire at the onset of each trial, there were seven new fire outbreaks and five wind events programmed to occur during each scenario. The timing, measured in generations, of each fire outbreak and wind event was held constant across all simulations (See Table 3). Each house was worth 15 points, each tree worth eight points, and each clearing worth one point. Freeburn scores ranged from 48.66 to 49.66 points, with a mean of 49.19 points.

Teams were assigned an overall performance goal: Save as much of the landscape as possible, taking into account land priority (Chapman et al., 2006). Teams had a hierarchical structure, whereby each team member was randomly assigned to either a command or subordinate role. Commanders monitored the landscape and relevant environmental conditions (e.g., wind direction/speed) in order to supply directives to subordinates. Commanders were not afforded direct control over the firefighting appliances. Subordinates were able to control each of the six appliances, but were unable to receive visual confirmation of a fire outbreak until one of said trucks was within a
small limited range of the fire (i.e., 2 sector units). Commanders were instructed to direct subordinates to fires using x-y coordinates, taking into consideration land element priorities, wind direction, and any perceived communication delays. Commanders also had continuous access to the team’s overall performance score (updated automatically each generation). This design required that team members communicate with one another to successfully extinguish the fires. Thus, this was not a compensatory team task: one member could not fully compensate for the other’s poor task performance.

**Measures**

Task-specific measures of effectiveness and coordination were collected throughout the experiment. With a few exceptions, each performance measure was found in published research using NFC or similar microworlds and was easily derived from system-generated output. Task-specific measures were then grouped according to conceptual categories advanced in the team and microworld literatures: Effectiveness, Speed, Accuracy, Efficiency (Elliott et al., 2007), and Communication. Although all measures are based directly upon the subordinate’s interactions with the system, each is conceptualized as a team-level phenomenon—subordinates would not be expected to take action without first receiving a command. Objective measurements of intra-team communications (Armstead, 2007) were collected continuously throughout each trial. Team members also completed post-trial surveys aimed at obtaining individual perceptions of/reactions to the delay condition(s) experienced and any perceived effect(s) on team effectiveness and coordination. A measure of cognitive ability was administered to determine the effect of individual differences on effectiveness and coordination. All NFC-derived measures constitute team-level variables. Communications and post-trial
reactions were collected at the individual level and aggregated to represent team-level constructs. A brief description of each measure follows:

**Effectiveness.** This measured the extent to which the team accomplished primary objectives and served as the single indicator of team effectiveness. Effectiveness was operationalized as the summed value of all unburned land elements at the end of a trial, weighted with respect to relative point value (Omedei & Wearing, 1993). Effectiveness scores are system-generated and reflect the coordinated activity of both team members (i.e., there is a single overall performance score generated for each firefighting scenario). Scores associated with Trial 5 were used to assess Effectiveness in the transfer delay.

**Speed.** Teams were expected to vary with respect to how quickly they responded to fire outbreaks. Responses to fire outbreaks require two separate behaviors: (1) initiation of the Move command to direct a firefighting appliance within fighting range of an observed fire outbreak and (2) initiation of the Fight command to begin extinguishing the fire. It was not sufficient to simply move a firefighting appliance into position (i.e., react), a team must also engage in an attempt to extinguish said fire (i.e., respond). Speed, then, is a multivariate construct representing the time lags associated with both Reaction Time and Response Time (Elliott et al., 2007). Scores associated with Trial 5 were used to assess Speed in the transfer delay.

**Reaction Time.** This measured the time lag between the onset of the first fire of each trial and the team’s reaction to said outbreak. Reaction Time was calculated by subtracting the generation associated with the start of the simulation from that associated with the first Move command (D’Agostino, 2009). The History File provided information about when (i.e., generation time) the team issued a Move command.
**Response Time.** This measured the time lag between the onset of a fire and the team’s initial response to said outbreak. Response Time was calculated by subtracting the generation associated with the subordinate’s first relevant Fight command from the generation associated with said fire outbreak. Calculations of Response Time necessitated review of the system-generated *Replay Files*. Trained coders identified the first truck that responded to each of eight fire outbreaks. An average Response Time across all fires was calculated.

**Accuracy.** Teams were expected to vary with respect to how accurately they placed firefighting appliances when responding to fire outbreaks. To minimize the spread of a fire, appliances should be positioned at or near the front of the fire (Omedei & Wearing, 1993). Teams were provided with information about weather conditions and expected to consider the direction of the prevailing wind when positioning appliances to fight fires. Accuracy, then, is based on the degree to which teams considered wind direction when placing appliances (Elliott et al., 2007). Accuracy was operationalized as the number of times the first responding unit was positioned within 45 degrees either direction of the prevailing wind (D’Agostino, 2009). Scores associated with Trial 5 were used to assess Accuracy in the transfer delay.

**Efficiency.** Teams were expected to vary with respect to how efficiently they made use of firefighting appliances. Failure to keep available appliances active has been associated with less effective performance in similar firefighting tasks (Brehmer & Dorner, 1993). Efficiency, then, is based on the degree to which teams minimized their time spent idle (Elliott et al., 2007). Efficiency was operationalized as the time spent idle, summed across all six available appliances (D’Agostino, 2009). Information about
idle time was readily available through the *Statistics File*. Scores associated with Trial 5 was used to assess Efficiency in the transfer delay.

**Communication.** Teams were expected to vary with respect to patterns of intra-team communications. Transmission delays are known to affect frequency of utterances (Kraus & Bricker, 1967), length of utterances (Kraut & Fish, 1997), and degree of overlapped speech activity (Ruhleder & Jordan, 2001). Communication, then, is a multivariate construct representing team behavior with respect to each of these three aspects of speech activity. Intra-team communications were collected throughout the duration of each trial. Presence/absence of speech was analyzed using a computer algorithm (Armstead, 2007). Scores associated with Trial 5 were used to assess Communication in the transfer delay.

**Speech Frequency.** Speech Frequency was operationalized as the total number of utterances, summed across team members, during a single trial.

**Length of Utterance.** Length of Utterance was operationalized as the average length of utterances across both team members during a trial.

**Degree of Overlap.** Degree of Overlap was operationalized as the proportion of total talk time, summed across team members, during which team members engaged in simultaneous speech.

**Cognitive Ability.** All participants were administered the 12-item short form (Arthur & Day, 1994) of Raven’s Advanced Progressive Matrices (APM; Raven, 1965). The APM, developed to assess higher-order cognitive ability, presents a number of progressively more difficult figure series. Participants are required to select, from the options provided, the single form that best completes the series. Participants are provided
two sample items as practice prior to test administration (Bors & Stokes, 1998).

Participants are then instructed to correctly solve as many series puzzles as possible in the allotted 15-minute test period. Individual scores are calculated as the sum total of correct responses per team member. While cognitive ability was observed for individuals, individual scores must be aggregated or combined in some way to derive a team score. According to precedent, team cognitive ability was calculated as the mean of the team’s individual scores (Kozlowski & Ilgen, 2006). A median split was used to create a dichotomous variable representing higher and lower relative ability teams. The observed internal consistency for this measure was adequate, Chronbach’s alpha = .68, and consistent with values published in validation studies (Bors & Stokes, 1998; Arthur & Day, 1994).

Procedure

Following approval from the University’s Institutional Review Board (IRB), the study was included as a part of the Psychology Department’s online experiment list. Prospective participants were offered a brief description of the study, including an explanation that tasks might be performed under imposed delay and that participation would require a substantial time commitment (approximately 1 ¾ hours). Interested parties selected from a list of scheduled sessions.

Each experimental session consisted of the following order of events: an orientation, four successive practice trials, administration of the cognitive ability test, and a single transfer trial (See Appendix A). During orientation, a brief explanation of the study was delivered and participants were asked to sign a consent form, complete a demographic inventory (See Appendix B), and participate in a brief training protocol.
The training protocol was designed to introduce key NFC fire-fighting concepts; verify each participant’s ability to use a computer mouse to initiate relevant commands and correctly interpret an x-y coordinate system; and provide all participants with a single, brief, *individual* practice trial. Participants were also taught how to properly attach heart rate sensors (3 self-applied, self-adhesive, disposable units; See Appendix C).

Immediately following orientation, team members were asked to relax while a 5-minute baseline heart rate was simultaneously recorded for each team member. For each of four practice trials, teams completed a different 10-minute NFC scenario, the presentation of which was randomized according to a Latin Square design (See Table 4). Participants were administered the cognitive ability test during the break between the practice phase and the transfer trial. Lastly, all teams completed an identical transfer trial scenario.

Intra-team communications were audio recorded throughout each practice and transfer trial. Both physiological responses and auditory communications were recorded for use in a separate study, and will not be addressed in subsequent analyses.

Teams were composed of two individuals and assigned to one of the four experimental conditions (Blocked delay_same, Blocked delay_short, Blocked delay_long, or Random delay) using a Latin Square design (See Table 5). Team members were seated in different rooms, each equipped with its own computer terminal, and communicated via a microphone/headset device. Although the NFC task functioned in real time, communication delays were introduced using two TiVo® SVR2000™ digital recording units. A delay was programmed for each channel, separately, and was equal to ½ of the desired delay +/- .1 second. Voice events were sampled at 16 Hz after rectifying and smoothing an amplified audio signal from the microphone/headset apparati.
used by each team member. At the end of each trial, team members were given standardized feedback on their team’s overall task performance, and task objectives were reiterated: Team members were reminded to regularly scan landscape for new outbreaks and progress made fighting existing fires, help one another locate idle vehicles, and to continuously monitor water levels in trucks (D’Agostino, 2009), as well as to prioritize houses over trees over clearings and to limit idle time. An 11-item post-trial survey instrument, developed by Armstead (2007; See Appendix D) and based upon the NASA Task Load Index, was completed independently by each team member as a means of probing his/her personal assessments of team coordination. An additional item was added to the original instrument in an effort to ascertain each team member’s subjective interpretation of the nature of the imposed delay (Brehmer, 1995). To avoid cross-contamination, team members were not permitted to communicate with one another while completing the post-trial survey. All teams were fully debriefed at the close of the session.

Results

Inter-Rater Agreement

Most dependent measures were derived from the NFC system-generated reports. Certain measures of coordination (i.e., Reaction Time, Accuracy) however, required information not available in the History and Statistics Files. Trained raters viewed Replay Files in an effort to identify the first responding unit for each fire. Once a first responding unit was identified (or not, if teams failed to respond to a fire before the end of the trial), raters referred to the History File to determine when and at what coordinates the appliance initiated the fight command. The author and a trained research assistant coded the timing and placement of first responding units for each of eight fires in the
transfer trial (i.e., Trial 5). Inter-rater agreement was assessed for 10 (of 40) transfer trials. Initially, agreement was at 97.5 percent (i.e., raters disagreed with respect to only two of 80 fires). Raters always agreed with respect to whether or not teams responded to a fire, but not always with respect to the time/coordinates of the first responder. A third rater reviewed instances of disagreement. Thus, final values were based on perfect agreement of two independent raters.

Pre-Analysis Data Screening

Univariate Outliers. To the extent that an outlier represents an error in coding or measurement, any extreme observation must necessarily be identified and addressed. To check for univariate outliers, standardized scores were computed for all dependent variables. All observations falling outside 3 standard deviation units from the mean were examined for accuracy. Aside from clerical errors (which were verified and corrected), three potential outliers were identified: Teams 23 and 39 had an unusually long Reaction Time at the start of the transfer trial, and the observed voice events recorded for the subordinate member of Team 31 were unusually long. NFC-generated History Files provided details about Reaction Times, system-generated time-series output provided details concerning team member speech activity. All values were deemed to have been recorded appropriately in the original dataset, therefore no subsequent adjustments were made to these values.

Multivariate Outliers. To check for multivariate outliers, Mahalanobis Distances were calculated for composites of Speed (df = 2) and Communication (df = 3). Observed distances were compared against critical values of the Chi-square distribution, using the generally accepted .001 criterion (13.82 for Speed, 16.27 for Communication).
Neither of the observed distances exceeded critical value, indicating the absence of multivariate outliers.

**Descriptive Statistics**

To the extent that measures of coordination represent team processes that contribute to team effectiveness, each would be expected to correlate with team effectiveness. Table 6 provides descriptive statistics for and correlations between dependent variables. Many of the observed relationships could be compared with those observed in published literature. Reaction Time and Response Time were both negatively related to Effectiveness in the transfer trial, $r = -.03, n.s.,$ and $r = -.48, p = < .01,$ respectively. Accuracy was positively related to Effectiveness in the transfer trial, $r = .24, n.s.$ Efficiency was negatively related to Effectiveness in the transfer trial, $r = -.55, p < .01.$ The directions of all relationships were consistent with prior research (D’Agostino, 2009; Elliott et al., 2007). The direction of each relationship also makes sense conceptually: longer reaction and response times, prolonged idle periods, and failure to consider wind direction represent behaviors that would be expected to have a negative impact on effectiveness. This study also included a novel set of process measures: mean team Communication (i.e., Frequency and Length of Utterances, Overlapped Speech) bore virtually no relationship with Effectiveness in transfer, $r = -.00, r = -.07,$ and $r = .00,$ respectively, $n.s.$ To the extent that Speed is a multivariate construct, Reaction Time and Response Time were expected to correlate with one another. There was only a modest relationship between these measures, $p = .232, n.s.$

The post-trial survey instrument was administered to each team member, independently, as a means of probing his/her personal assessments of team coordination.
Because post-trial survey responses were not directly related to tests of hypotheses, no analyses beyond correlations were conducted using this data. Table 7 provides descriptive statistics for and correlations between dependent variables for the transfer trial.

**Team Learning**

Implicit to hypothesis formation was the assumption that teams would be able to improve performance over time, despite being subjected to technologically-induced delays. Figure 2 illustrates the practice performance trajectories as a function of trial order and experimental condition (See Appendix E for plot of performance trajectories including zero second practice delay frame of reference). Overall, Effectiveness increased throughout the practice phase, $R^2 = .14$, $R^2_{adj} = .14$, $F(1, 158) = 26.37, p < .001$. The slope of the trajectory was significant, demonstrating improvement over the course of the four trials preceding the transfer trial, $\beta = 3.12, t(1, 159) = 5.14, p < .001$.

**Hypothesis Testing**

Forty teams participated in the study, resulting in an equal number of teams (10) per condition. Small sample sizes are associated with low between-subjects power. Similarly designed laboratory studies have elected to employ a more liberal statistical criterion, $\alpha = .10$ (Gorman, Cooke, & Amazeen, 2010). This practice was followed here. A series of factorial (M)ANOVAs were conducted to examine the relative effects of practice condition and team cognitive ability on performance outcomes (i.e., Effectiveness, Speed, Accuracy, Efficiency, and Communication). These analyses allowed for simultaneous testing of multiple hypotheses (i.e., main effects and interactions) and helped to increase statistical power. Contrasts were conducted in
accordance with a priori hypotheses (See Table 8). Summaries of results are arranged by outcome.

**Effectiveness.** Effectiveness during transfer was expected to vary systematically as a function of practice condition, such that (a) teams practicing under random delays were expected to outperform those practicing under blocked delays, (b) teams practicing under same-as and longer-than transfer delays were expected to outperform those practicing under shorter-than transfer delay, and (c) teams practicing under longer-than transfer delay were expected to outperform those practicing under same-as transfer delay (Hypothesis 1). Team Cognitive Ability was expected to moderate the relationship between practice condition and effectiveness such that higher relative ability teams would prove more effective than their lower relative ability counterparts (Hypothesis 3a). Planned comparisons were performed to further explore the hypothesized relationship between effectiveness and practice condition. Results assume unequal variances. Teams in the random practice condition did not outperform blocked practice counterparts, \( t(13.48) = .36, p = .721 \). However, there was a significant difference between shorter-than transfer delay and other blocked delay conditions (i.e., same-as transfer, longer-than transfer), \( t(24.517) = 3.10, p = .005 \). In transfer, teams practicing under longer relative blocked delays (M = 68.69, SD = 13.92) outperformed teams practicing under short blocked delay (M = 57.52, SD = 5.34). There were no significant mean differences between teams in the longer-than and same-as transfer practice delay conditions, \( t(17.21) = -.28, p = .79 \). A 4 (Condition) x 2 (Cognitive Ability) ANOVA was conducted to simultaneously test the hypothesized omnibus effects (See Table 9). Levene’s Test for Equality of Error Variances was significant, suggesting the data violate the assumption of
homogeneity of variance, $F(7,32) = 2.56, p = .033$. There was not a significant interaction between the factors, $F(3,32) = 1.48, p = .239, \eta^2 = .12$, nor was there a significant main effect for cognitive ability, $F(1,32) = .00, p = .982, \eta^2 = .00$ (See Table 8). Therefore, Hypothesis 1 was partially supported. Hypothesis 3a was not supported.

**Speed.** Speed was operationalized as a function of Reaction and Response Times. Prior to statistical analysis, observed distributions for both variables were evaluated for normality using skewness and kurtosis statistics. Response Time fell within reasonable bounds for skewness (df = 40, alpha = .01, critical value = 1.03) and kurtosis (df = 40, alpha = .02, critical range: -1.15 to 2.66), but Reaction Time did not (skewness = 2.77, kurtosis = 9.42). Therefore, Reaction Time was transformed in attempt to better approximate a normal distribution. Initially, a square root transformation was applied, but the distribution was not sufficiently improved (skewness = 1.89, kurtosis = 4.67). A subsequent logarithmic transformation was applied which did sufficiently improve the distribution (skewness = 1.08, kurtosis = 1.55). Speed during the transfer trial was expected to vary systematically as a function of practice condition (Hypothesis 2a). Team cognitive ability was expected to moderate this relationship (Hypothesis 3b). A 4 (Condition) x 2 (Cognitive Ability) MANOVA was conducted to simultaneously test the effects of these factors on Speed (i.e., Response Time and log-transformed Reaction Time). Box’s Test of Equality of Covariance Matrices was not significant, suggesting the data do not violate the assumption of homogeneity of variance-covariance,
Box’s $M = 37.92, F(21,3131.78) = 1.42, p = .097$. The multivariate interaction was not significant, Wilks’ $\Lambda = .93, F(6,62) = .37, p = .898, \eta^2 = .03$, nor was there a significant main effect for either practice condition, Wilks’ $\Lambda = .83, F(6,62) = 1.05, p = .405, \eta^2 = .09$, or cognitive ability, Wilks’ $\Lambda = .99, F(2,31) = .11, p = .894, \eta^2 = .01$ (See Table 10). Therefore, Hypotheses 2a and 3b were not supported.

Accuracy. Prior to statistical analysis, the observed distribution for the Accuracy variable was evaluated for normality using skewness and kurtosis statistics. The observed distribution was evaluated for normality using skewness and kurtosis statistics and fell within reasonable bounds for skewness (df = 40, alpha = .01, critical value = 1.03) and kurtosis (df = 40, alpha = .02, critical range: -1.15 to 2.66). Accuracy during the transfer trial was expected to vary systematically as a function of practice condition (Hypothesis 2b). Team cognitive ability was expected to moderate this relationship (Hypothesis 3c). A 4 (Condition) x 2 (Cognitive Ability) ANOVA was conducted simultaneously test the effects of these factors on Accuracy during transfer. Levene’s Test for Equality of Error Variances was significant, suggesting the data violate the assumption of homogeneity of variance, $F(7,32) = 1.40, p = .239$. There was not a significant interaction between the factors, $F(3,32) = 0.09, p = .965, \eta^2 = .01$, nor was there a significant main effect for practice condition, $F(3,32) = 0.05, p = .984, \eta^2 = .01$. However using a .10 criterion, there was a significant main effect observed for cognitive ability, $F(1,32) = 3.20, p = .083, \eta^2 = .09$ (See Table 9). Regardless of practice condition, lower relative ability teams ($M = 2.91, SD = 1.34$) were more accurate during transfer than were their higher ability counterparts ($M = 2.16, SD = 1.07$), $t(38) = 1.94$. 
This result is opposite to the hypothesized relationship between cognitive ability and performance. Therefore, neither Hypothesis 2b nor Hypothesis 3c was supported.

Efficiency. Prior to statistical analysis, the observed distribution for this variable was evaluated for normality using skewness and kurtosis statistics. Time Spent Idle fell within reasonable bounds for skewness (df = 40, alpha = .01, critical value = 1.03) and kurtosis (df = 40, alpha = .02, critical range: -1.15 to 2.66). Efficiency during transfer was expected to vary systematically as a function of practice condition (Hypothesis 2c). Team cognitive ability was expected to moderate this relationship (Hypothesis 3d). A 4 (Condition) x 2 (Cognitive Ability) ANOVA was conducted simultaneously test the effects of these factors on Efficiency during transfer. Levene’s Test for Equality of Error Variances was not significant, suggesting the data do not violate the assumption of homogeneity of variance, $F(7,32) = 1.91, p = .101$. There was not a significant interaction between the factors, $F(3,32) = 1.75, p = .177, \eta^2 = .14$, nor was there a significant main effect for practice condition, $F(3,32) = 0.62, p = .608, \eta^2 = .06$. However using a .10 criterion, there was a significant main effect observed for cognitive ability, $F(1,32) = 2.96, p = .095, \eta^2 = .09$ (See Table 8). Regardless of practice condition, lower relative ability teams (M = 12484.27, SD = 264.11) spent less time idle during transfer than their higher ability counterparts (M = 13144.05, SD = 278.10), $t(38) = -1.69, p = .100$. This result is in direct contrast to hypothesized relationship between cognitive ability and Efficiency (See Table 9). Therefore, neither Hypothesis 2c nor Hypothesis 3d was supported.
Communication. Communication was operationalized as a function of Frequency and Duration of Utterances, and Overlapped Speech. One case (random condition) was dropped from analysis due to missing data. Prior to statistical analysis, observed distributions for all variables were evaluated for normality using skewness and kurtosis statistics. Frequency of Utterances and Overlapped Speech both fell within reasonable bounds for skewness (df = 40, alpha = .01, critical value = 1.03) and kurtosis (df = 40, alpha = .02, critical range: -1.15 to 2.66), but Duration of Utterance did not (skewness = 1.88, kurtosis = 5.55). Therefore, Duration of Utterances was transformed in attempt to better approximate a normal distribution. A square root transformation was applied, which sufficiently improved the distribution (skewness = .95, kurtosis = 2.22).

Communication during transfer was expected to vary systematically as a function of practice condition (Hypothesis 2d). Team cognitive ability was expected to moderate this relationship (Hypothesis 3e). A 4 (Condition) x 2 (Cognitive Ability) MANOVA was conducted simultaneously test the effects of these factors on Communication. Box’s Test of Equality of Covariance Matrices was not significant, suggesting the data do not violate the assumption of homogeneity of variance-covariance, Box’s M = 61.24,

\[ F(42,1352.66) = .94, p = .577. \]

The multivariate interaction was not significant, Wilks’ \( \Lambda = .67, F(9,70.73) = 1.40, p = .203, \eta^2 = .13 \), nor was there a significant main effect for either condition, Wilks’ \( \Lambda = .94, F(9, 70.73) = .20, p = .993, \eta^2 = .02 \), or cognitive ability, Wilks’ \( \Lambda = .99, F(3,29) = .06, p = .979, \eta^2 = .01 \) (See Table 10).

Therefore, neither hypothesis 2d nor 3e were supported.
Discussion

To the extent that distributed teams are necessary, research needs to examine the human factors under which team coordination is affected (Fiore et al., 2003). A great deal of research has been aimed at creating technologies to support team interaction, but little has focused on the psychosocial effects of its extensive use (Driskell et al., 2003). Often, the various technologies used to enable performance and communication among distributed team members have increased processing demands that result in delayed communications and delayed performance feedback. Delays have been shown to degrade performance and, under some circumstances, alter communication patterns between team members (Armstead, 2007; Chong et al., 2002; Henning et al., 2007). Researchers have long speculated that practice under delayed feedback conditions might help to reduce its negative performance effects (Brady, 1971) but few studies have manipulated the practice context to examine delay-performance relationships in teams.

This study was designed to investigate the effects of practice with transmission delay on measures of teamwork (i.e., effectiveness and coordination). The magnitude of delay experienced during skill acquisition was systematically manipulated, such that some teams learned under a consistent, relatively shorter delay, while others learned under one of two consistent longer delays, and still others were exposed to varied delay lengths during practice. The literature suggests that variations in the learning context should be associated with better adaptability in novel transfer tasks (e.g., Catalano & Kleiner, 1984), but that this effect may be moderated by team composition (i.e., team cognitive ability).
Generally, the hypothesized relationships in which practicing under varied delay lengths would benefit transfer performance were not supported. Although there were statistically significant differences in effectiveness (i.e., overall performance) across conditions, the difference was observed when comparing shorter to combined same-as and longer-than transfer blocked practice delay conditions. Practicing under random delay conditions was not found to improve performance above and beyond practicing under same- or longer-than transfer delay conditions. Surprisingly, none of the measures of coordination were affected by practice context. Cognitive ability was not associated with differences in transfer effectiveness, however lower relative ability teams were significantly more likely to consider prevailing wind direction when positioning appliances and to spend significantly less time idle. However, these ability-coordination effects did not translate into significant differences in team effectiveness.

The important effect of practice context has been demonstrated in a variety of settings for a number of tasks and samples of individuals (Kerr & Booth, 1978; Hall et al., 1994; Lee & Magill, 1983; Shea & Morgan, 1979; Hebert et al., 1996; Jacoby, 1978; Jelsma & Pieters, 1989; Carlson & Yaure, 1990). The robust nature of this context-performance relationship suggests a similar human factors design effect should be found for teams. While random delay was not associated with significantly improved performance during transfer, it was certainly not detrimental to transfer performance. In fact, there were no meaningful differences in effectiveness between the longer-than transfer, same-as transfer, and random delay conditions in the transfer trial. That the overall performance of teams assigned to the shorter-than transfer practice delay condition was substantially worse is intuitive: performing under a new and longer delay
is associated with decreased performance and consistent with past research (Armstead, 2007; Allison et al., 2004; Angiolillo et al., 1997; Brady, 1971; Chong et al., 2002; Henning et al., 2007; Rantanen et al., 2004). Yet this finding has more substantive value: practice with any specific delay does not necessarily prepare a team for performing under a novel delay. Thus, although study hypotheses were not generally supported, the results none the less support the notion that teams can be trained to better handle novel delays, and that the human factors design of the practice context might have an important impact on performance in transfer.

The results associated with the transfer trial suggested a meaningful post hoc analysis. Table 11 provides a summary of team effectiveness scores as a function of trial and condition, and trajectories across trials are plotted in Figure 2. Due to shared trajectories for teams exposed to longer delays during practice (i.e., Blocked Same, Blocked Long, and Random), their mean performance scores were pooled and compared to scores of teams practicing under the shorter (i.e., Blocked Short) delay. A repeated measures ANOVA was used to test the effects of practice condition (i.e., pooled long versus short delays) on effectiveness gains between the first and last practice trial. Following Gorman et al. (2010) in their study of the effects of perturbations on teamwork, tests were conducted at the $p < 0.10$ level. There was a significant main effect for both trial, $F(1,38) = 15.16, p \leq .001, \eta^2 = .29$, and condition, $F(1,38) = 2.87, p = .099, \eta^2 = .07$. A trend-level interaction between Trial and Condition, Wilk’s $\Lambda = .96$, $F(1,38) = 1.76, p = .193, \eta^2 = .04$, suggests accelerated learning under long delays. Therefore, observed differences in practice performance trajectories support the earlier
possibility that the human factors design of practice context does, in fact, have an important impact on team effectiveness.

Measures of coordination were included in this study for exploratory purposes. There is no literature to suggest a hypothesized direction for the effects of practice condition on any of the measures, save those of communication. That there were no systematic practice-related differences in coordination observed between groups is both interesting and surprising. Observed ability-related differences in accuracy and efficiency suggest teams employed different strategies throughout the trial, and these can be regarded as evidence of the dynamic nature of the team task. That strategy differences do not result in differences in overall performance at the end of a trial calls into question how teams are responding throughout the trial. Closer inspection of between-team differences in intra-trial coordination trajectories could potentially explain how coordination leads to effectiveness, and will be the focus of future research.

Some of the findings reported herein are inconsistent with previously published research investigating the impact of practice under delayed feedback conditions on performance. While individuals can learn to improve performance over time despite delay (Simpson et al., 2007), performance trajectories of individuals are generally negatively impacted by increasing delay (Gibson, 2000), and individual skills acquired under delay conditions were not likely to transfer to novel situations (Sterman, 1989). Prior research with teams suggests that performance gains under a fixed delay condition are modest and inconsistent over multiple days of practice (Kao & Smith, 1977). However, research by DeCroock, Paas, and Van Merrienboer (1998), and more recently Burke et al. (2006) and Gorman et al. (2010), suggests that systematically imposing
perturbations in feedback control during skill acquisition can facilitate team learning and benefit team performance under non-perturbed conditions. One possible explanation for the lack of consistency between earlier research and the beneficial training effects reported here is that only high degrees of feedback control perturbation facilitate team learning. Indeed, the 2-second delay, as associated with the blocked_short practice condition in the present study, may not have been as readily perceived as the longer delays. Consistent with this interpretation, Wang (2002) found that team members subjected to very short delays (i.e., less than 2 seconds) often underestimated delay duration, whereas longer delays, (i.e., over 6 seconds) were often overestimated. An underestimated delay might not have provided sufficient motivation for team members to experiment with strategy during practice. Likewise, longer delays might have been overestimated, motivating team members to try to compensate for the delays. Thus, longer delays may have resulted in a higher degree of team adaptation and learning.

Limitations

The results of this study are important both practically and theoretically. Practically, the results can be directly applied in training contexts as a means of reducing the degrading effects of technologically-induced delay on performance. Theoretically, knowledge of how practice conditions affect performance under communication delay conditions contributes to the extant literature on transfer of learning, providing evidence for the beneficial effects of some human factors training conditions. Also this study adds to the literature on teams in general and team training more specifically, by investigating the relationships between outcome and process measures in a novel context – the NFC microworld.
However, certain characteristics of the design of this study may have contributed to the lack of some expected findings. The NFC task may have been too difficult for two-person teams. A less complex simulation may have elicited more variation in performance (particularly with respect to higher performing teams), thus affording a better research opportunity to determine manipulation effects. Support for this possibility is found in an ongoing study using the same simulations, where the addition of a third team member improves the slope of performance trajectories during training. Brehmer (1995) suggested that task complexity in microworlds can affect the degree to which individuals attend to the information available to them. This may explain why delay conditions did not impact coordination (specifically, Accuracy). The task may have been so complex that teams could not process all available information. It is possible that an analysis of communication content could determine whether team members were able to make use of all of this information, and to convey relevant information to their team members.

Another possibility for the lack of some hypothesized relationships is that the actual imposed delay, though conceptualized as round-trip with equal delays in both directions, may have been experienced differently depending on team member role (i.e., subordinate, commander). The commander may have necessarily been required to communicate more often, thus the task effects of a communication delay may have been experienced more often by the subordinate. Measures of coordination were based on subordinate-system interactions and, as such, may also have been adversely impacted by a commander’s failure to appropriately recognize/estimate a delay and adapt accordingly. This possibility is easily assessed by looking at differences in team members...
communication frequencies, regardless of trial, as well as team-level differences in individual estimations of imposed delay. In general, commanders (M = 34.33, SD = 15.31) had significantly more voice events than subordinates (M = 27.36, SD = 20.62), t(39) = 2.29, p = .028. However, there were no meaningful role-related difference in mean estimates of delay during transfer, t(39) = -1.03, p = .309. Despite differences in number of voice events, commanders and subordinates were similar in their estimates of imposed delay during transfer. Therefore, it is unlikely that systematic role-related differences in the experience of the delay differentially affected team members’ efforts to adapt to the delays imposed in this study.

The nature of variability in delay presentation may not have been sufficient. The robust practice effect, as demonstrated time and again in the training and learning literature, has been observed in situations where the task demands vary randomly within a single trial. The technology used in this study to impose delays did not afford the capability to manipulate intra-trial delays. It is possible that such a manipulation of delay would have had a larger impact. Teams in the random condition may have actually been experiencing something more akin to mini blocked practice sessions, as opposed to a truly variable delay practice context.

The duration of experimental session is also something to consider as a reason for the hypothesized effects not being evident. The duration of the experimental session may have affected a number of factors including degree of team learning, member fatigue and engagement with the task. Effectiveness continued to improve across practice, never plateauing. Teams may not have acquired sufficient expertise for their skills to carry over into transfer because experimental sessions lasted only two hours. Team members
may have become fatigued and disengaged from the task, which may have affected results in later trials. Given that teams continued to improve performance throughout the experimental session, disengagement may be a non-issue. Nonetheless, the possibility may be addressed through content analysis of audio recordings (i.e., affective tone, frequency of off-task comments).

Perhaps practice condition failed to exert an observable effect on coordination, not as a result of weak manipulation, but rather because measurement of process needs to be more precise. Processes were measured as the sum total or average of responses at the end of a trial, although teams performed continuously in real time throughout the duration of each 10-minute session. Therefore, process might be better operationalized as a series of observations, rather than the set of single aggregated scores used here, and analyzed as a growth trajectory related to effectiveness. Depending on when one assesses a process or the effect of some intervening variable, the same team might yield very different information. Researchers have begun to appreciate the dynamic nature of team performance (Morgan, Glickman, Woodard, Blaiwes, & Salas (1986), observing that teamwork often occurs in distinguishable episodes (Marks et al., 2001). A more systematic study of team performance might include observations over multiple time points (Baker & Salas, 1992), allowing researchers to differentiate between general and time-specific relationships.

**Future Directions**

The current study is unique in regard to how audio transmission delays were systematically manipulated across team practice trials, and so the reported beneficial effects of this training methodology need to replicated, and hopefully can be expanded to
other team and task contexts. While performance trajectories were positive across conditions, the lack of evidence of asymptotic learning in all but the shortest delay condition suggests the need to study team performance under communication delays over a longer period. So, too, study of retention over multiple transfer trials would help shed light on the degree to which these practice effects continue to benefit team performance in transfer.

Although this study focused on technologically-induced delays, the results have potentially far-reaching implications. Temporal delays are inherent to feedback control loops involving social systems and socio-technical systems. In casual discourse, for example, conversants must attend to and interpret verbal exchange, taking more or less time to articulate responses which results in delayed feedback. At the organizational level, managerial structure may constrain the flow of communications between members whereby hierarchies have a set of intermediaries through whom information must pass. At any given time, members of the same system might differ with respect to the relevance and accuracy of available information. Feedback delays are known to impair decision-making and lead to performance decrements (Baker et al., 2006). Individuals and organizations, alike, struggle to manage – and adapt – to temporal delays (Gibson, 2000). Future research could also determine if systematically introducing other modes of feedback control delay as a training methodology for teams is similarly beneficial to performance because it is unclear if the effects reported here generalize beyond audio communication delays and their direct effects on intra-team coordination.

Future research might also explore the impact of delays on other measures of effectiveness (e.g., satisfaction, viability) and coordination (e.g., number of appliances
sent to a fire) focusing on both intra- and inter-trial differences in coordination.

Temporal dependencies are too often ignored in team research (Kozlowski & Bell, 2003). A developed understanding of how teams adapt their processes to meet changing demands (Burke et al., 2006) necessitates exploration of performance and related variables (e.g., mediators, contextual factors) over multiple time points. Researchers have only begun to investigate the complexity of nested input-process-output (IPO) cycles during teamwork (Koslowski et al., 1999; Salas et al., 2009).

As a part of this study, team members had to communicate in order to successfully coordinate their activities and accomplish team goals. Communication behaviors are overt and lend themselves to both quantitative and qualitative measurement, their effects readily associated with performance outcomes (Svensson & Andersson, 2006). Research has demonstrated that effective teams tend to engage in more overt forms of communication (Oransanu, 1990) and also have more consistent patterns of speech (Kanki, Lozito, & Foushee, 1989). There were no significant differences observed in communication patterns across conditions in the present study, and it is likely that any form of communication, at least in this task, had a complex relationship with effectiveness by way of its influence on other measures of coordination. For example, the lack of communication pattern differences does not rule out differences in communication content. Other researchers have begun to call for systematic analysis of the content of team communications (Bowers, Jentsch, Salas, & Braun, 1998).

Future research could also focus more closely on other mechanisms as possible sources of variability in team performance. The composition of team members, in terms of demographics, knowledge, skills, and abilities, might prove to exert some mediating
effect on team performance under delay conditions. Likewise, the subjective attitudes (e.g., collective orientation) and experiences of team members (e.g., stress appraisals), both at the individual and aggregate level, are likely to have a meaningful effect on performance over time. These potential mediators might have differential impact on teamwork given specific time point in team life cycle (Goodwin, Burke, Wildman, & Salas, 2009; Harrison, Price, Gavin, & Florey, 2002).

**Concluding Remarks**

The present study was designed to examine the relative effects of practice conditions upon team effectiveness and coordination. While most hypotheses were not directly supported, this study demonstrated that the human factors design of practice condition does have a meaningful effect on overall team performance. The results can be directly applied to the design of training programs for distributed teams, as a way to counteract performance degradations caused by technologically-induced transmission and other sources of communication delays. Empirical evidence that practice conditions can affect performance under novel delay conditions contributes to the extant literature on transfer of training, providing preliminary evidence that systematic perturbations of feedback control relationships which are crucial to team coordination and task execution can directly benefit team training.
References


Table 1.
*Delay Length as a Function of Experimental Condition and Trial*

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<thead>
<tr>
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<th>Duration of Delay, seconds</th>
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</tr>
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</tr>
<tr>
<td>Blocked_long</td>
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</tr>
<tr>
<td>Random*</td>
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</table>

* One of four counterbalanced sequences. See Table 2.
Table 2.

*Latin Square used to counterbalance delay presentation order for random practice (T1:T4)*

<table>
<thead>
<tr>
<th>Duration of Delay, seconds</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
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<td>6</td>
<td>5</td>
</tr>
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<td>Order 2</td>
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<td>2</td>
<td>6</td>
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<td>6</td>
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<td>Order 4</td>
<td>6</td>
<td>2</td>
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Table 3.
*Simulated events log*

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<td>Fire</td>
</tr>
<tr>
<td>1</td>
<td>Fire</td>
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<tr>
<td>1</td>
<td>Fire</td>
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<tr>
<td>15</td>
<td>Wind Change</td>
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<td>450</td>
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<td>525</td>
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<td>750</td>
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<td>900</td>
<td>Fire</td>
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<td>1000</td>
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<td>1200</td>
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<td>1350</td>
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<td>3000</td>
<td>End</td>
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Table 4.

*Latin Square used to counterbalance scenario presentation order during practice (T1:T4)*

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<td></td>
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<td>Sequence 1</td>
<td>1</td>
</tr>
<tr>
<td>Sequence 2</td>
<td>2</td>
</tr>
<tr>
<td>Sequence 3</td>
<td>3</td>
</tr>
<tr>
<td>Sequence 4</td>
<td>6</td>
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*NOTE: All participants completed Scenario 4 in transfer*
Table 5.  
Latin Square used to counterbalance assignment to conditions

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<td>Blocked_long</td>
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*NOTE: This pattern was repeated every 16 teams.*
Table 6.
Descriptives and Correlations for Performance Variables, Trial 5

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<th>4</th>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>.23</td>
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<tr>
<td>Accuracy</td>
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<td>.24</td>
<td>-.13</td>
<td>-.66**</td>
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<td></td>
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<tr>
<td>Efficiency</td>
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<td></td>
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<td></td>
<td>-.55**</td>
<td>.10</td>
<td>.35*</td>
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<td>Frequency</td>
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<td>.11</td>
<td>.54**</td>
<td>.42**</td>
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NOTE: * p < .05, ** p < .01.
Table 7.
Correlations Among Condition, Outcome Variables, and Post-Trial Survey Items (Aggregated Using Means), Trial 5

<table>
<thead>
<tr>
<th></th>
<th>Q1</th>
<th>Q2</th>
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<th>Q4</th>
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<tr>
<td>1 Random</td>
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<td>.007</td>
<td>-.089</td>
<td>-.072</td>
<td>-.379*</td>
<td>-.348*</td>
<td>-.035</td>
<td>-.094</td>
<td>-.067</td>
<td>-.069</td>
<td>-.116</td>
<td>.220</td>
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<tr>
<td>2 Long</td>
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<td>.250</td>
<td>.042</td>
<td>-.083</td>
<td>-.084</td>
<td>-.006</td>
<td>.149</td>
<td>.126</td>
<td>.260</td>
<td>.223</td>
<td>.201</td>
<td>.144</td>
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<tr>
<td>3 Effectiveness</td>
<td>.588**</td>
<td>.631**</td>
<td>-.373*</td>
<td>-.507**</td>
<td>-.256</td>
<td>-.190</td>
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<td>.353*</td>
<td>.488**</td>
<td>.634**</td>
<td>.298</td>
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<td></td>
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<td></td>
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<td>4 Reaction Time</td>
<td>.200</td>
<td>.175</td>
<td>.107</td>
<td>-.036</td>
<td>.144</td>
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<td>.359*</td>
<td>.380*</td>
<td>.258</td>
<td>.265</td>
<td>.103</td>
<td>.192</td>
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<td>5 Response Time</td>
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<td>.144</td>
<td>-.092</td>
<td>-.122</td>
<td>-.031</td>
<td>-.136</td>
<td>.207</td>
<td>.007</td>
<td>.159</td>
<td>.112</td>
<td>-.110</td>
<td>-.004</td>
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<td>6 Accuracy</td>
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<td>.040</td>
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<td>-.153</td>
<td>-.105</td>
<td>-.057</td>
<td>.153</td>
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<td>-.324*</td>
<td>-.344*</td>
<td>-.305</td>
<td>-.219</td>
<td>.129</td>
<td>.181</td>
<td>.207</td>
<td>.322*</td>
<td>.075</td>
<td>-.204</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>8 Frequency</td>
<td>-.069</td>
<td>-.151</td>
<td>.262</td>
<td>.200</td>
<td>.107</td>
<td>.114</td>
<td>-.087</td>
<td>-.093</td>
<td>-.003</td>
<td>.030</td>
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<td>-.270</td>
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<tr>
<td>9 Length</td>
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<td>.135</td>
<td>.008</td>
<td>-.063</td>
<td>.318*</td>
<td>.300</td>
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<td>.147</td>
<td>.014</td>
<td>.205</td>
<td>.318*</td>
<td>-.036</td>
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<td>10 Overlap</td>
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<td>-.125</td>
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<td>-.056</td>
<td>.023</td>
<td>.034</td>
<td>.023</td>
<td>.102</td>
<td>.067</td>
<td>-.139</td>
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</table>

**NOTE:** *p < .05, **p < .01. Time Spent Idle is reverse-coded.
Table 8.

*Planned contrasts*

<table>
<thead>
<tr>
<th>Contra</th>
<th>Delay Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blocked_short</td>
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<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>-2</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
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</table>
Table 9.

*Effects of Condition and Team Cognitive Ability on Teamwork (ANOVAs)*

<table>
<thead>
<tr>
<th>Variables</th>
<th>Levene's $(p)$</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>$F$</th>
<th>$p$</th>
<th>$\eta^2$</th>
</tr>
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<tr>
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<td>7,32</td>
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<td></td>
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<td></td>
<td></td>
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<td>Condition</td>
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<td>296.67</td>
<td>1.89</td>
<td>0.15</td>
<td>0.15</td>
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<td>0.08</td>
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<tr>
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<tr>
<td>Accuracy</td>
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*Note: Time Spent Idle is reverse scored*
Table 10.
Effects of Condition and Team Cognitive Ability on Teamwork (MANOVA)

<table>
<thead>
<tr>
<th>Variables</th>
<th>Box's M (p)</th>
<th>Wilk's $\eta$</th>
<th>df</th>
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<th>p</th>
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<td>9,70.73</td>
<td>1.40</td>
<td>0.20</td>
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Notes: Reaction Time is computed using a log transformation.
Length of Utterance is computed using a square root transformation.
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<thead>
<tr>
<th>Condition</th>
<th>B</th>
<th>R</th>
<th>$R^2$</th>
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</table>
Figure Captions

**Figure 1.** Screenprint of firefighting landscape, trial in progress

**Figure 2.** Performance trajectories as a function of condition
Figure 2

The graph shows the Team Effectiveness over five trials for different Practice Conditions. The conditions include Blocked_short (2s), Blocked_same (4s), Blocked_long (6s), and Random (avg 4s).
APPENDIX A: Training Protocol *(Experimenter Script)*

INTRODUCTION/CONSENT PROCESS

**SAY**

Thank you for coming, please choose a seat. We will begin in just a moment . . .

My name is Megan Dove-Steinkamp, I am leading the research this morning. This is __________, who will be assisting me as you complete the scheduled exercises. The exercises in which you will participate this afternoon have been designed as a part of my Thesis research.

To ensure that every one receives the same information, and in the same order, I will read instructions to you from a script. I have asked my assistant to do the same.

You have noticed a set of papers in front of you. Contained in this packet are 2 copies of my research summary. In a moment, you will be asked to read the summary statements. Please appreciate that you are considered a volunteer and, as such, will not be required to participate or complete any of the associated exercises. However, the data that I collect will be severely compromised if I cannot obtain accurate, complete information from each participant. I assure you the confidentiality of your responses – in no way will your name be associated with your individual responses or the overall analyses. Please take a moment to read the research summary.

**DO**

allow time for the participants to read the statement of purpose

**SAY**

In summary: Should you elect to participate in this study, you will be outfitted with a telemetry unit that will measure your heart rate continuously for the next hour and forty-five minutes. You and another willing participant will complete a series of firefighting simulations. You will be seated in separate rooms and will communicate with one another via headset. All team communications during the simulations will be recorded on audiotape. You may experience some delays when communicating with your teammate. These are an intended part of the simulation. Immediately following each simulation, you will be asked to complete a brief paper-and-pencil questionnaire. You will also participate in a short, 12-item test of cognitive ability.

Do you have any questions about what is expected of you this afternoon?

If you are comfortable participating in this experiment, please sign both copies of the consent form. One copy is yours to keep.

**DO**

collect signed consent forms
As with most research, I need to know a little about each of you before we begin. I am distributing a basic demographics inventory to each of you. You may notice that this inventory, like all of our successive paperwork, has been labeled with both a team and participant number. These numbers will follow you and your team throughout each of the tasks you complete this afternoon. This procedure has been adopted to help protect your anonymity. Please do not write your name or leave any identifying information on this or any future paperwork associated with this experiment.

DO distribute demographics inventory

SAY Please take a moment to answer each question honestly and to the best of your ability. When you are finished, turn the inventory face down on your desk.

DO collect completed demographics inventory
TELEMETRY FITTING

**DO**  
*hold up telemetry unit*

**SAY**  
In order for us to measure your heart rate throughout this experiment, we must outfit each of you with a telemetry unit. Each unit has three wires, called leads; two black, one gray. Each of these leads will be connected to a sensor located on your body. A fourth, red wire acts as an antenna and wirelessly transmits signals from your individual telemetry unit to a data collection system in another room. This wire is meant to simply dangle freely from the unit.

**DO**  
*hold up sensors*

**SAY**  
The sensors are small, adhesive tabs that you will personally affix to your skin.

These sensors are not expected to cause you any discomfort, although individuals with especially sensitive skin may experience some redness once the sensors have been removed.

The placement of each sensor is very specific.

**DO**  
*distribute diagram*

**SAY**  
This diagram ought to help you position each sensor. Notice that the silhouette in the diagram depicts the proper location for each of the three sensors; labeled 1, 2, and 3, respectively. It is very important that all sensors are properly positioned and firmly set in place.

Sensor 1 is placed on the left portion of your collarbone and is attached to one of the black leads.

Sensor 2 is placed just under the right portion of your ribcage and is attached to the gray lead.

Sensor 3 is placed just under the left portion of your ribcage and is attached to the remaining black lead.

Try to remember: “light is on the right”.

**DO**  
*hold up sensor-lead set*

**SAY**  
To facilitate the fitting process, we have already clipped each lead to a sensor. In a moment, you will be asked to take a set to the restroom where you may position the sensors in private.
You will simply peel a sensor from the sheet and firmly secure the sensor to your skin, according to the diagram. Be sure to press the sensors firmly against your skin. Sometimes it takes a moment to make certain the sensors stick. Once you have all three sensors in place, allow the leads to dangle freely from beneath your clothing. When you return to this room, we will help you to connect the leads to your telemetry unit.

**DO**  
distribute sensor-lead sets

**SAY**  
You may now go to the restroom to outfit yourselves with the sensors.

**DO**  
wait for participants to return

verify all sensors firmly affixed, troubleshoot

hold up telemetry unit

**SAY**  
We will now help you to connect the loose leads to your telemetry unit.

**DO**  
connect leads, turn on device

**SAY**  
The unit can be clipped to your clothing or set in your lap. If the unit is not securely fastened to your clothing, please remember to be careful not to allow the unit to drop to the floor or to otherwise pull the leads taut. This could result in loss of data and/or damage to the telemetry unit.

Do either of your have any questions about the telemetry units?

Now we will escort you into your separate rooms.

**DO**  
estort participants into rooms according to device label (A or B)

**SAY**  
You will now have about five minutes to relax while we make certain the telemetry units are receiving signals properly. This time will also allow us to record a base rate for your individual heart rhythm. I thank you, in advance, for your cooperation during this period of “down time”.

When I return, I will orient you to the firefighting program and we will begin the team experiment.

Do you have any questions?

OK. I will see you in five minutes.
DO  

shut door upon exit
Thank you for your patience. The telemetry record looks sound and we are ready to begin your orientation to the Networked Fire Chief program.

Allow me just a moment to start the program.

**enable individualized training scenario (file name: Basic NFC Orientation)**

First, I would like to orient you to what is displayed on your monitor.

Perhaps the most important part of the screen is the landscape, which comprises the majority of your screen. The landscape you are viewing is composed of 5 different icons: houses, trees, clearings, water sources, and a single fire truck.

Can you recognize each type of landscape element?

**verify that participant can recognize each element (yes/no)**

You may have already noticed the coordinate system along the top and left side of the landscape. You should use this coordinate system to relay important information about fire outbreaks and to direct fire trucks into appropriate positions. Coordinates are best communicated in their intended $x,y$ format (first read the top number, then the number on the left). You can verify coordinates by placing your cursor over a particular icon and reading its coordinates along the lower, left hand portion of the screen.

Find the single yellow fire truck. What are the $x,y$ coordinates for its position?

**verify participant has correctly identified the starting position of firetruck (1, 16)**

The houses, trees, and clearings are consumable, meaning that fire can destroy them. Each type of consumable element has an associated point value. For example, a house is worth 15 points, a tree is worth 8 points, and a clearing is worth 1 point. You will want to consider these values when fighting the fires that break out during each simulation. For your convenience, a table with each element and its associated score is displayed on the wall.
If two fires were to break out simultaneously, one in or near a housing development and one surrounded by clearing, which fire would you prioritize? Why?

**DO** verify participant would prioritize the fire nearest the housing development

**SAY** In the team simulations, fires will break out periodically throughout each 10-minute trial. Your goal is to extinguish as much of the fire as possible, while simultaneously saving as much of the landscape as possible.

You and your partner will control a total of six fire trucks. These trucks can be routed anywhere on the map and all do not have to – and, in fact, probably should not – be assigned to fight a single fire. It is important that you consider the type of landscape affected by the fire so that you can use your resources wisely and perform well on this task.

Of course, there are other pieces of valuable information displayed on your screen. Notice the panel on the left hand side of the screen. At the top of this panel is a time display. Each simulation has been programmed to run for ten minutes. The time display will allow you to keep track of how much time has passed since the beginning of the trial. This orientation trial has been designed to last up to 11 minutes.

Immediately below the time is a compass-like feature that provides you with information about your local weather. Specifically, this feature displays wind direction. The direction and speed of the wind will change periodically throughout each ten-minute trial. You should read this like any compass: North is up, South is down, West is left, East is right.

You should consider the direction of the wind as you move your fire trucks into position. Because fire will spread in the direction of the wind, it would behoove you to move your trucks to some position that anticipates the spread of the fire. This will help you to keep the fire from spreading out of control.

What is the current direction of the wind?

**DO** verify participant has correctly reported current wind direction (NorthEast)

**SAY** Let’s assume that a fire has started at the clearing (14, 14). Given the current wind direction, consider an appropriate place to send your fire truck. Give me the coordinates for this position.

**DO** verify participant has given a reasonable coordinate (perhaps 15, 13)
If the wind were blowing in a different direction, say northwest, to what coordinate would you send your fire truck?

verify participant has given a reasonable coordinate (perhaps 13, 13)

OK. Let’s continue to explore some other features of this program.

Immediately below the weather display is a solid green box featuring a the outline of a smaller, yellow box. The area enclosed by the smaller yellow outline is what is displayed to the left as your visible landscape. Notice that the area of the green box is larger than that of the space enclosed by the yellow outline. This means that you are currently only seeing a fraction of the actual landscape.

During a simulation, fires can break out anywhere – and at any time – on the map. Therefore, you must be able to change your view. To do so, simply take your mouse and click anywhere inside the solid green box.

As you click inside the box, you will notice that the viewable landscape changes. Go ahead and try this a few times.

verify participant can manipulate view

Good. Throughout each simulation, a member of your team will be responsible for continuously monitoring the landscape, checking for both new outbreaks and any progress made fighting existing fires.

Now we need to find our first fire. The orientation simulation has been programmed to set a fire at exactly 8 minutes 30 seconds. What time is displayed right now?

verify participant correctly offered current time

We may have to wait just a moment for the outbreak. In the meantime, let me explain how to move and operate your fire truck.

Each fire truck has been pre-filled with a limited amount of water. When you place your mouse over a fire truck, its current operating capacity is displayed along the lower left hand side of the landscape map. This value is offered as a percentage.

Take your mouse to the fire truck and read me the truck’s current capacity.

verify participant has read correct capacity level (100%)
SAY When a fire breaks, fire trucks must be moved into position. Remember, the exact strategy for placement is dependent upon both the type of landscape elements affected by a given fire as well as current weather conditions. You should also take care to consider the number of other new or existing fires.

To move a fire truck, hold your mouse over the truck and drag the truck into the desired position. Take your mouse and move the fire truck to the right two spaces.

DO verify participant has successfully moved fire truck into position (3, 16)

SAY Notice that fire truck does not immediately appear at the intended location. Instead, the fire truck moves along a route to the desired location. This will be the case with all fire trucks. You will have to remember that each fire truck will take some time to reach its destination. All trucks travel at the same rate of speed. Depending on the distance between the start and stop points, a truck may take more or less time to complete a move command.

Because of the size of the landscape, it may not be possible to reach your destination with one simple drag command. Instead, you may have to move your truck to the outermost area currently visible, use your mouse to reset your landscape view (remember the green box on the left!), and then initiate a second move command.

Move your fire truck to (36, 0).

DO verify participant has successfully moved fire truck into position (36, 0)

SAY When consumable landscape elements (like houses, trees, and clearings) catch fire, you will see flames over the affected icons. If no action is taken to extinguish a fire, these flames will eventually destroy the landscape element, leaving only a charred image.

You may notice, now that we have moved your fire truck into position, that a fire has ignited and already consumed a portion of your landscape.

Once ignited, a fire will continue to spread until either you and you partner successfully extinguish it OR it runs out of consumable materials. The latter will rarely happen in this experiment. Therefore, it is important that you devote some of your firefighting resources to every fire.
You should try to fight this fire before it spreads any further. Remember, you should consider wind direction and travel time when placing your truck.

Use your mouse to move the truck into position. As soon as the truck has moved into position, you should click the truck with your mouse to initiate fire fighting.

**DO**

verify participant has moved into an appropriate position to fight fire

**SAY**

If the truck is fighting a fire, you should see a blue spray of water emitted from the bottom of the truck. The truck will fight a fire one icon at a time. Once an icon is no longer on fire, the truck will move onto the next closest icon currently affected by the fire. This automatic search feature is only effective within a limited range of the truck’s initial position. Do not rely on this feature to completely extinguish a fire while your attention is directed elsewhere.

Fire trucks will stop fighting when they run out of water. Therefore, it is important to pay close attention to each truck’s resource capacity status. Remember this information is displayed along the bottom left hand side of the landscape map.

If a truck has – or is about to – run out of water, you must direct the truck to a water source so that it may refill. Water sources appear as blue ponds or lakes and are distributed haphazardly across the landscape. Once a truck has been taken to a water source, it will automatically refill its tank. With filling, just as with fighting, you will see blue sprays of water at the base of the truck. When full, the truck can be directed to its next position.

Refill your fire truck.

**DO**

verify truck has been refilled properly

**SAY**

This concludes your initial orientation to Networked Fire Chief. Now I need to inform you of your particular duties in the team scenarios.

Although the elements are the same, the scenario you have just experienced is only a simplified version of those created for the team simulations. The team scenarios use maps that are more extensive and have multiple fire outbreaks and changes in wind speed and direction. Six fire trucks will be made available for fighting fires.

In addition to the added complexity of the landscape and the schedule of events, you and your team member will have very different tasks to perform. Specifically, you will:
(Room B) act as the commander. Your job will consist, primarily, of: monitoring the landscape to spot new fires, checking on progress made to fight existing fires, and tracking weather conditions. Your teammate will be responsible for moving trucks into position and fighting the fires.

While you will be able to see everything that is happening on the map, you will not be able to command the six fire trucks. Only your partner will have that capability.

Unfortunately, your partner will not be able to see fires until he/she has a fire truck within limited range of an affected landscape element. It is your job to orient your partner to an appropriate position, using proper coordinates, so that he/she will be able to effectively fight the fires.

Communication is vital for the success of the team. It is up to you to provide all necessary information to your teammate. Your teammate may solicit, accept, qualify, or reject your commands as he/she sees fit.

(Room A) act as the subordinate. Your job will consist, primarily, of: moving and commanding each fire truck. Your teammate will be responsible for giving you commands for proper positioning of your fire trucks.

While you will be able to freely move your fire trucks about the entire landscape, you will not be able to see fires until you have a truck within a limited range of an affected landscape element. It is your job to solicit information about fires from your partner. Only he/she will be able to see all fires as they develop and only he/she will have access to relevant weather information.

Unfortunately, your partner will not be able to move or operate the fire trucks. Although, he/she may be able to help you locate a “lost” truck.

Communication is vital for the success of the team. Your partner ought to provide you with all relevant information about fire outbreaks and his/her firefighting strategy. It is up to you to solicit, accept, qualify (seek more info), or reject commands from your partner as you see fit.

Do you have any questions about your role in the team scenario?

**DO** *answer all questions*
SAY You will wear headphones and a microphone for each trial. All team communications during the simulations will be recorded on audio tape. You may experience some delays when communicating with your teammate. For example, your teammate may not hear your command for several seconds and/or you may not hear your teammate’s response for several seconds. These delays are a part of the simulation and are not evidence of equipment failure. Unfortunately, I cannot provide you with any additional details about the nature of the delays (for example, duration or effective adaptation strategies). Please try to proceed with your task to the best of your ability despite these delays.

Do you have any questions?

Please put on the headphones. You may attach the microphone wherever it is most comfortable.

DO verify headphones & microphone are in place and that microphone is on, initiate “connect remote” set-up

SAY It will take a just a moment to initiate the first trial. We will enable communication between you and your partner as soon as the simulation is ready. When it is time to begin, you will hear a loud beep. The simulation will run for ten minutes. The end of the simulation will be signaled by a double beep.

At the end of the simulation, we will again suspend communication between you and your partner. We will re-enter to the room to distribute a paper-and-pencil survey. Once both of you have completed the survey, we will begin a new trial. You will complete a total of five 10-minute trials.

Do you have any questions?

DO address any questions

SAY OK, please listen for the signal to begin. I will see you again after the trial.

DO close the door
POST-TRIAL SURVEY

**DO**

*reenter room*

*distribute survey*

**SAY**

Here is a copy of the post-trial survey. The survey contains only eleven items, and is aimed at assessing your personal experiences during this simulation. Please consider each item carefully as you answer. You may take as long as you need to thoughtfully complete the questionnaire. Once you are finished, I will collect the survey and we will prepare for the next simulation.

**DO**

*wait by door until participant indicates survey has been completed*

*collect survey*

**SAY**

Do you have any questions about the team simulations?

**DO**

*address questions*

**SAY**

Are you experiencing any problems with the NFC program or the communication or telemetry systems?

**DO**

*address any issues at this time*

**SAY**

Remember that you may experience a communication delay, which is a part of the task. This delay may or may not remain constant throughout the experiment. Just try to do your best to work with your partner to extinguish as much of the fire as possible.

Some things to keep in mind as your strategize with your partner:

(1) prioritize consumable landscape elements: houses are worth more than trees, which are worth more than clearings

(2) consider wind direction, truck speed, and delay when deciding where to position your fire trucks

(3) communicate as often as necessary with your partner and be sure to ask for clarification whenever needed

Alright, we will begin the next simulation in just a moment. Again, a loud beep will be your signal to begin.

**DO**

*close door*
DEBRIEFING

SAY This concludes the final portion of the experiment. I want to sincerely thank you for your participation and cooperation.

You may have noticed that the materials for each exercise have been associated with a set of short numbers. These numbers will serve as your participant and team IDs and will in no way be associated with your identity. The numbers are simply used as an aid as I analyze your responses to each exercise and compare them with the responses of other research participants.

As you may have gathered from the content of each exercise, I am interested in whether delays affect team coordination. I expect to compare your teams’ patterns of communication, task performance, and heart rate – as well as collective cognitive ability scores and survey responses – to those of teams exposed to varied delay conditions in an attempt to infer any existing relationships between these variables.

Unfortunately, the cognitive measure could not be scored during your session. I do not associate names with any of the research materials. Therefore, I will not be able to provide you with any individualized feedback regarding your test performance.

I expect to have all study results compiled and in manuscript form by the end of the academic year. Should you like to find out the conclusions I draw from this research, please feel free to contact me or to pull a copy of my Thesis sometime after this period.

I have provided you a copy of the consent form and urge you to file it in your records for some time. Should you have any questions or concerns about your experiences here today, the form provides valuable contact information.

Do you have any questions about the nature of the study or how your responses will be used?

DO address questions

SAY If you have a “green sheet” for me to sign, I can take care of this now. Credit will be formally awarded through the participant pool later this evening. You will each receive 4 credits for your participation this afternoon.

DO sign sheets
I would like to thank you for your willingness to participate this afternoon.
Have a wonderful day and thank you both very much for all of your effort!
APPENDIX B: Demographics Inventory

Participant Number: __________ Date: __________
Team Number: __________

For each of the following items, please circle the appropriate answer:

Your gender: Male Female

Is English your first language? No Yes

Have you any firefighting experience? No Yes

Have you any previous experience with the Networked Firechief program? No Yes

How often do you play videogames? Never Rarely Sometimes Often

Before today, how frequently have you interacted with your teammate? Never Interacted Rarely Sometimes Interact Often

Your age, as of your last birthday: __________
APPENDIX C: Telemetry Diagram

Telemetry Sensor Placement

1 Left clavicle (collarbone), BLACK lead
2 Right, just below ribcage, GRAY lead
3 Left, just below ribcage, BLACK lead
APPENDIX D: Post-Trial Survey Instrument

Team number: __________  Date: _______________
Participant number: _______  Trial number: _______

Circle the number that best matches your feelings about the statements below.

1. I think my personal level of performance on this task was:

   Very Low 1  2  3  4  5  6  7  Very High

2. I think the team’s level of performance on this task was:

   Very Low 1  2  3  4  5  6  7  Very High

3. The level of stress I experienced during this task was:

   Very Low 1  2  3  4  5  6  7  Very High

4. The level of frustration I experienced during this task was:

   Very Low 1  2  3  4  5  6  7  Very High

5. The amount of effort needed to complete this task was:

   Very Low 1  2  3  4  5  6  7  Very High

6. The mental demands of this task were:

   Very Low 1  2  3  4  5  6  7  Very High

7. The quality of communication on this task was:

   Very Low 1  2  3  4  5  6  7  Very High

8. My ability to concentrate on the task was:

   Very Low 1  2  3  4  5  6  7  Very High
Circle the number that best matches your level of agreement to the statements below.

9. I think I am responsible for how well/poorly the team performed on the task.
   Strongly Disagree 1  2  3  4  5  6  7  Strongly Agree

10. I think my partner is responsible for how well/poorly the team performed on the task.
    Strongly Disagree 1  2  3  4  5  6  7  Strongly Agree

11. I think the system is responsible for how well/poorly the team performed on the task.
    Strongly Disagree 1  2  3  4  5  6  7  Strongly Agree

Please estimate the duration of any delay you believe you may have experienced during this trial: __________ seconds
APPENDIX E: PILOT DATA

Teams participating in the pilot portion of the study (n = 6) responded to a 0-second delay through the entirety of the practice phase (4 trials). A 4-second delay was imposed during a fifth trial. The pilot study served the dual purposes of establishing baseline performance for this specific task and demonstrating that performance did, in fact, degrade as a result of communication delay. Performance trajectories for all experimental conditions, including the pilot sample, are plotted in the figure below.

Performance trajectories as a function of practice condition.