The Team Coordination Game: Zero-Fidelity Simulation Abstracted from Fire Emergency Response Practice

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Crisis response engenders a high-stress environment in which teams gather, transform, and mutually share information. Prior educational approaches have not successfully addressed these critical skills. The assumption has been that the highest fidelity simulations result in the best learning. Deploying high-fidelity simulations is expensive and dangerous; they do not address team coordination. Low-fidelity approaches are ineffective because they are not stressful.

Zero-fidelity simulation develops and invokes the principle of abstraction, focusing on human-information and human-human transfers of meaning, to derive design from work practice. Our principal hypothesis is that crisis responders will experience zero-fidelity simulation as effective simulation of team coordination. We synthesize the sustained iterative design and evaluation of the Team Coordination Game. We develop and apply new experimental methods to show that participants learn to cooperate and communicate, applying what they learn in practice. Design implications address how to employ the abstraction principle to develop zero-fidelity simulations.

Categories and Subject Descriptors: H.5.3 [**Information Interfaces and Presentation**]: Group and Organization Interfaces—*Computer supported cooperative work, Evaluation/methodology*; K.8.0 [**Personal Computing**]: General—*Games*

General Terms: Design, Experimentation, Human Factors

Additional Key Words and Phrases: Zero-fidelity simulation, game interface design, education games, information distribution

ACM Reference Format:
Toups, Z. O., Kerne, A., and Hamilton, W. A. 2011. The team coordination game: Zero-fidelity simulation abstracted from fire emergency response practice. ACM Trans. Comput.-Hum. Interact. 18, 4, Article 23 (December 2011), 37 pages.
DOI = 10.1145/2063231.2063237 http://doi.acm.org/10.1145/2063231.2063237

1. INTRODUCTION

Educators generally assume that to benefit learning, simulations must model working environments with high fidelity. Such simulators employ complex algorithms, high-end graphics, and mimetic props to re-create concrete reality [Tate et al. 1997; St. Julien and Shaw 2003; Entertainment Technology Center 2005; Backlund et al. 2007]. In

This work is supported by the National Science Foundation, under grants IIS-0803854 and IIS-0742947. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF or TEEX.
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DOI 10.1145/2063231.2063237 http://doi.acm.org/10.1145/2063231.2063237

crisis response [Palen et al. 2010] and other contexts characterized by intense collaboration, human-centered components of practice, such as human-human interaction and distributed cognition [Hollan et al. 2000; Hutchins 1995a, 1995b] may be more experientially significant than concrete environmental components. Our panel of disaster response experts reported that failures in team coordination are the most significant limiting factor in critical emergency response, but that a gap separates this need from prevailing education methods. Human-centered components of practice demand focus on simulation design. We argue that for learning team coordination, direct emulation of the real world is unnecessary. Thus, we forge a new tack for simulation design.

Team coordination, a form of distributed cognition consisting of cooperative action and communication, is essential to crisis response. Team members develop situation awareness and shared mental models by gathering information from multiple perspectives. In these perspectives, information takes different forms: embodied in the environment, communicated by voice and gesture, and encoded in artifacts. Due to the urgent nature of response, team members must communicate clearly and efficiently under stress, balancing urgency against the need to keep limited communication channels open. Despite the importance of team coordination, education has previously done little to address it; our evidence indicates that educators have not previously been clear on how to design curricula.

We formulate a didactic alternative to high-fidelity: *zero-fidelity simulation*, in which human- and information-centric elements of a target environment are abstracted. Developing information distribution amidst a team of participants encourages them to communicate with each other. We derive the design of a zero-fidelity simulation from observation of, and engagement with, fire emergency response education, including live burn training, developing the Team Coordination Game (TeC). We distribute information among team members, pushing them to rely on one another. TeC game mechanics center around gathering information, making sense of it, cooperating, and communicating. Team coordination forms a primary component of the core mechanic of the game, the suite of actions taken repeatedly to engage in play. Unlike prior practices—for example, classroom communication or tabletop incident command exercises—players experience stress and excitement. Unlike existing high-fidelity practices, for example, burn training exercises [Texas Engineering Extension Service 2000; Toups and Kerne 2007], stress is derived from the threat of failure in an abstract environment and from competition between teams, rather than from physical danger [Thiel et al. 2003]. Zero-fidelity simulation shifts the focus of education and reduces the costs, in resources and safety.

Prior approaches assume that a re-creation of concrete reality is essential for successful, immersive simulation, and thus to reap educational benefits [Beaubien and Parker 2004; Hays and Singer 1989; Kozlowski and DeShon 2004; Thorndike and Woodworth 1901]. Our principal hypothesis is that crisis responders will experience zero-fidelity simulation as effective simulation of team coordination. The effectiveness component of our hypothesis addresses how team members learn to better cooperate and communicate under stress, whereas the simulation component addresses how participants understand the need to coordinate in the simulation and connect play to practice. To support our hypothesis, we show how TeC improves participants' ability to coordinate in and out of play. Actual responders, both expert and novice, identify the need to communicate effectively during play and connect this to practice. As future work, we will investigate the transferability hypothesis, that zero-fidelity simulation principles produce simulations with a high probability of improving work in other domains because high-fidelity components of the environment that restrict transferability are not simulated. While we recognize the value of high-fidelity simulation in training-environment-specific tasks, such as putting out fires or cutting concrete during a rescue, we demonstrate that zero-fidelity simulation is a valuable and economical approach that addresses the team coordination crisis response education gap. We challenge the need to always strive for higher fidelity.

In this article, we synthesize and build on our work with TeC in and out of the emergency response domain [Toups et al. 2009; Toups et al. 2009a; Toups et al. 2011]. We present new data from our study of TeC with fire emergency responder (FER) students, as well as a pilot deployment with a panel of expert disaster responders. We find that participants enjoy the game and learn to coordinate more effectively. They employ strategies to engage in multimodal communication. They identify the need to communicate efficiently in play and connect playing the game to emergency response practice. We develop design principles for constructing information distribution from work practice and employing it in game designs. We close by developing the transferability hypothesis.

2. TEAM COORDINATION

"A team is a group of individuals working together toward a shared and valued goal" [Salas et al. 1992]. The present work addresses crisis response teams, which are characterized by high stress, hard time constraints, and life-or-death consequences. To work together effectively, team members need to synchronize activity while distributed across space. Communication enables this synchronization, but it must be carried out carefully, thoughtfully, and quickly. Responders must consider what information, including the state of the environment, personal activity, and/or directives to others, is important to others and when and how to communicate it.

2.1. Shared Mental Models and Situation Awareness

Mental models are cognitive structures through which individuals maintain and manipulate representations of how objects function and processes operate [Gentner and Stevens 1983; Jonassen and Henning 1996]. The model is an internal form of simulation, based on experience. It enables high-level problem solving, and can be used to predict future outcomes. When a mental model is shared among team members, it facilitates team coordination. Individuals can predict one another's actions and react accordingly, with reduced communication overhead [Cannon-Bowers et al. 1993; Mathieu et al. 2000].

Situation awareness is a related theory that describes the level at which individuals are conscious of their environment, the status of their team, and the events unfolding around them, as well as their ability to predict future outcomes [Endsley 2000]. A component of situation awareness within a team involves observing the activities of others and how they align with and differ from the norm [Heath and Luff 2000].

2.2. Distributed Cognition

Distributed cognition theory takes a holistic view of a working environment, describing cognitive processes spread among individuals and artifacts as they mutually interact [Hutchins 1995a, 1995b]. The theory provides a framework for analyzing information processing within teams, and modeling the way in which information flows among participants and artifacts over time. It suggests that information tasks can be isolated to inform new artifact designs that better support practice [Hollan et al. 2000]. Distributed cognition posits that information relevant to a task is represented in multiple forms, such as mental models, the environment, and artifacts. Those working in a distributed cognition environment iteratively transform its elements from original forms into new workable forms, applying these forms to situations at hand. Workable forms are communicated through physical and computational media, facilitating information transfer.

Distributed cognition serves as a basis for understanding fire emergency response work practice. FERs continuously communicate to provide the right team members with the right information to make decisions and take action [Toups and Kerne 2007]. Embodied sensory understanding, such as heat from a wall, is noted, transformed into a description incorporating knowledge of the structure, and perhaps communicated by radio, where it can be recorded by an incident commander on a map. We derive zero-fidelity simulation from FER work practice as distributed cognition in action.

2.3. Implicit Coordination

In an *explicit coordination* mode, team members need to communicate frequently to synchronize action and communicate information. In many team environments, such as crisis response, wide-area communication bandwidth is limited and unreliable: radios share a single channel and are half-duplex.[1] Those receiving must expend time and cognitive effort to hear and understand. These costs are known as *communication overhead* [Serfaty et al. 1993; MacMillan et al. 2004]. High-performance teams reduce communication overhead by communicating efficiently [Entin and Serfaty 1999], they speak less and act more. Thus, *implicit coordination* is the ability of team members to cooperate with little communication. Shared mental models and situation awareness contribute to implicit coordination. Cross-training, where team members learn the jobs of others on the team, fosters shared mental models [Cannon-Bowers and Salas 1998; Cannon-Bowers et al. 1998; Marks et al. 2002; Schaafstal et al. 2001]. FERs practice cross-training; each team member knows how to perform every other basic job.

2.4. Fire Emergency Response Work Practice: A Distributed Cognition Interface Ecosystem

While the present work applies generally to disaster response, our iterative design and theory-building processes have been specifically informed by work practice in the subdomain of fire emergency response. We work from fire emergency response in small-scale structural fires, observing practice in the United States of America. Fire emergency response is undertaken by small teams distributed throughout the incident, coordinated by an incident commander (IC) [Toups and Kerne 2007; Landgren 2006; Jiang et al. 2004; Landgren and Nulden 2007; Wieder et al. 1993; Carlson 1983; U.S. Department of Homeland Security 2008]. Multiple response teams, or *companies*, are dispatched to any incident and cooperate around the fireground (Figure 1). A company officer leads each team, which consists of firefighters and/or engineers.[2] Normally, each company is associated with a firefighting vehicle; an apparatus, such as an ambulance, engine, or ladder truck.

The fireground and surrounding space constitute a dangerous and dynamic interface ecosystem [Kerne 2005] of distributed cognition, connecting responders, victims, firefighting equipment, communication media, and information artifacts. Upon arriving at an incident, multiple companies distribute in and around the fireground. Companies and their apparatuses are placed at strategic locations, and are moved as needed. Human operators work on and from these platforms. Firefighters and rescue workers deploy from them, taking equipment into the fireground; equipment, such as firehoses and radios, may be technologically supported by the apparatus itself (pumps and water sources, or high-power repeaters, respectively). Each apparatus, and in many cases, each human worker, is equipped with a half-duplex radio to facilitate long-range, broadcast communication.

[1] A duplex communication device can send and receive data; a *full-duplex* device can send and receive simultaneously, a *half-duplex* device must switch between a send mode and a receive mode.
[2] We refer to workers in these roles, collectively, as *fire emergency responders* (FERs).

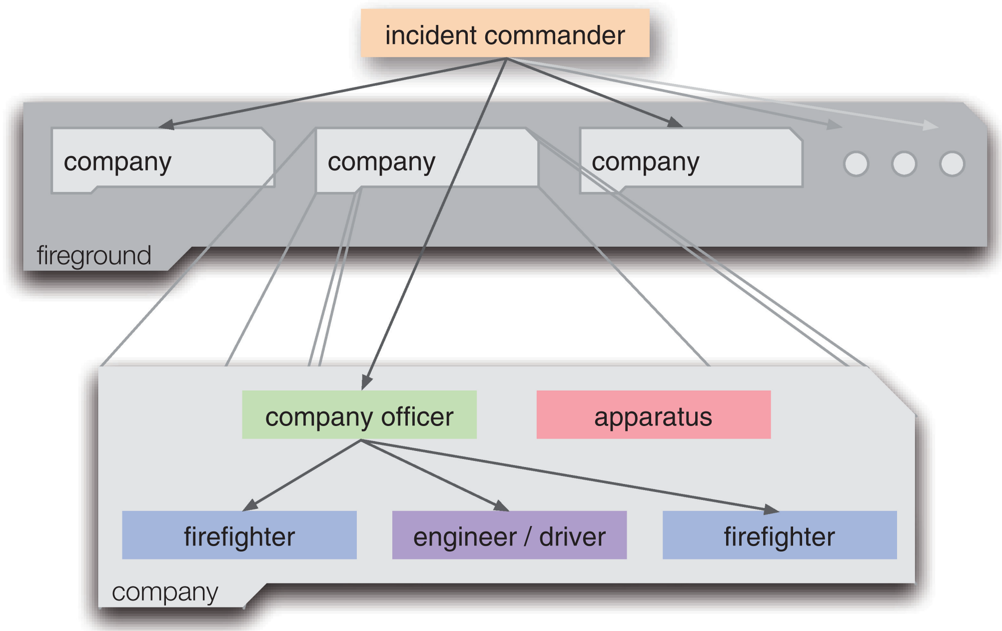

Fig. 1. Hierarchy of multiple companies deployed to an incident. The incident commander coordinates the companies from a distance, outside the fireground. Companies, in turn, are coordinated by officers. Each company is associated with an apparatus.

A key role in emergency response is the incident commander (IC), who oversees the response effort, makes strategic decisions, and directs activity. In accord with the Incident Command System, the first-arriving company officer takes on the transient role of IC [U.S. Department of Homeland Security 2008]. If a better-qualified officer arrives, that officer may take over. The IC physically positions an incident command post (ICP) some distance away, so as to observe the fireground in context, avoid inhibiting the response effort, and maintain safety. In its most basic form, the ICP may simply be an officer with a radio. If the IC is a dedicated command unit (normally a battalion chief or fire chief), her/his vehicle will be equipped with information artifacts, computers, and advanced communications gear that support managing strategy and tracking resources [Jiang et al. 2004; Toups and Kerne 2007]. As dictated by incident complexity, the IC may grow the staff to reduce the burden of coordination.

Communication is essential in the fireground ecosystem. Teams share information with command staff and receive strategic directives (Figure 2). FERs combine face-to-face and radio communication [Toups and Kerne 2007]. Face-to-face is preferred because it is fast and easy to disambiguate. Gesture, body language, and speech, function as essential components of face-to-face communication. Due to the distributed nature of disaster response, radio is frequently necessary. While radio reaches all responders simultaneously, it is slow and hard to understand. With most radios, cross-talk, when multiple users transmit simultaneously, causes all communication to be lost. FERs must thus take care to be efficient in using the radio's limited bandwidth.

The IC strategically directs the companies, while the FERs take situated action. Each company member is operating from a particular perspective, and acts as the eyes and ears of the IC at the fireground [Toups and Kerne 2007]. This approach has the advantage of enabling response and reconnaissance over the large scale of any

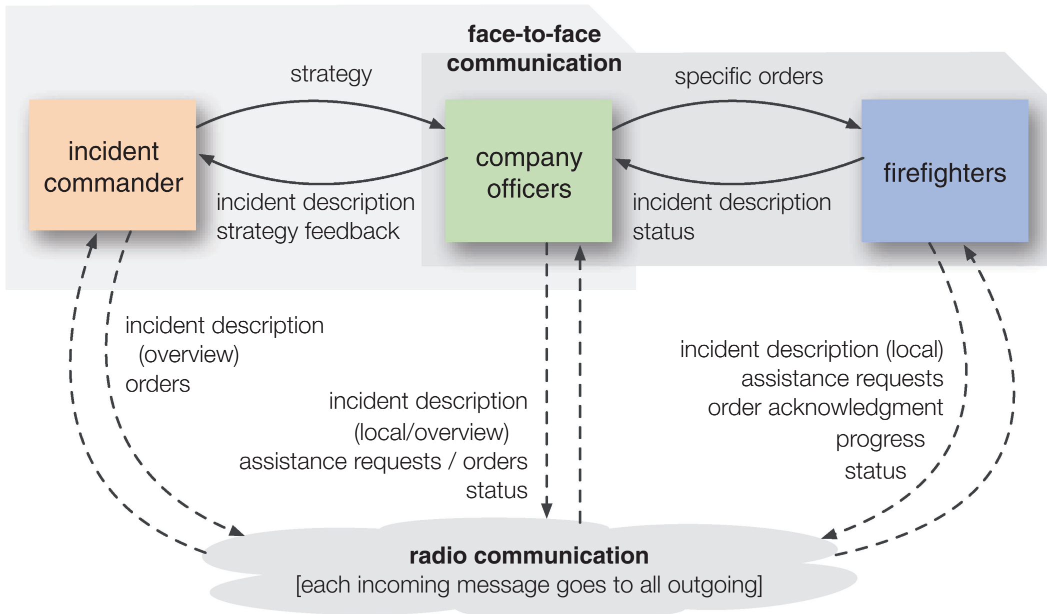

Fig. 2. Information flows in fire emergency response teams through face-to-face and radio communication. An incident commander forms strategy, based on observations and communicated information. Through company officers, the strategy is transformed and communicated to firefighters, who execute it through situated action based on local information. [Toups and Kerne 2007]

incident. Teams provide one another with relevant information, while synchronizing remote action (Figure 2). This combination of cooperation and communication in the distributed cognition environment is *team coordination*.

2.5. Design Principles for Teaching Team Coordination

Connecting our observations with theory, we developed design principles to engage participants in team coordination [Toups and Kerne 2007]. We identified a need to distribute information among team members, creating interdependence. Varying information form engages participants in distributed cognition. FERs modulate use of face-to-face and radio communication based on environment affordances and information needs, so we recommended forcing participants to mix communication modalities.

3. ZERO-FIDELITY SIMULATION

We derive the *zero-fidelity simulation* paradigm[3] by synthesizing the design principles for teaching team coordination [Toups and Kerne 2007] with distributed cognition [Hollan et al. 2000] and simulation theory [Salas et al. 1992]. The principles suggest that the situated mutual engagement of participants and information in response to crisis provokes coordination. The requirements do not demand mimesis of the concrete environment, only information distribution and mixed communication modalities. The intentional omission of concrete mimesis makes zero-fidelity simulation hardly recognizable as a form of simulation with the lens of prior theory.

[3]Previously, we referred to zero-fidelity simulation as "non-mimetic simulation."

3.1. Simulation Fidelity: Physical, Functional, Psychological, or Abstract

Simulation fidelity has long been considered to be multidimensional, with many classification schemes [Alexander et al. 2005; Beaubien and Parker 2004; Hays and Singer 1989; Kozlowski and DeShon 2004]. Three fundamental categories are physical, functional, and psychological. *Physical fidelity* refers to the level at which a simulator resembles the environment or equipment [Allen 1986]. *Functional fidelity* refers to how a simulator recreates the internal characteristics of the environment, the way it acts [Allen 1986]. The concept of *psychological fidelity*, the most relevant here, has arisen to describe simulations in which the focus is not on recreating the real world, but selecting out concepts for students to learn [Kozlowski and DeShon 2004]. Hays and Singer [1989] note that while psychological fidelity was considered in early simulations, it was assumed that the best way to achieve it was as a byproduct of high physical fidelity. Kozlowski and DeShon use psychological fidelity to argue for low physical fidelity simulators, but maintain direct correspondence with real world tasks, avoiding abstraction. Like theater, psychological fidelity involves participants in suspension of disbelief, so that they feel they are performing real-world tasks [Alexander et al. 2005; Beaubien and Parker 2004]. In all cases, the simulator is directly capturing real-world environments and processes.

Prior simulations have sought the highest possible fidelity. The assumption is that high fidelity breeds effectiveness [Beaubien and Parker 2004; Hays and Singer 1989; Kozlowski and DeShon 2004; Thorndike and Woodworth 1901]. Gagné [1954] suggested that training devices might be constructed to teach specific skills without a complete simulation. According to Hays and Singer [1989], much simulation research ignores these findings. Salas et al. [1992], through an analysis of existing team research, indicate that team skills, such as communication, can be isolated from the activities the team performs.

Lave and Wenger [1991] assert that learning must be situated socially and operationally to be effective, but Reder and Klatzky [1994] refute this claim in studying skill transfer. Through an extensive review of existing literature, they conclude that fully situated learning is frequently unnecessary, and may be detrimental because learning situations may not be flexible enough to capture all contingencies in reality and may be cost prohibitive. Learning in more abstract contexts enables flexibility. They note, however, that situated learning is valuable in social environments.

The zero-fidelity simulation tack focuses simulation resources, which are inherently limited, on human-centered components of practice and experience to engage team members in cooperation and communication. The game design captures the psychological and social aspects of fire emergency response, abstracting from the concrete environment, without intending for participants to suspend disbelief. Zero-fidelity simulation resituates team coordination components of emergency response from the source environment, while eschewing concrete operational and functional fidelity.

3.2. Prior Work: Team and Crisis Response Simulations

Some prior mimetic simulations specifically address teamwork in simulated stressful environments, including the Distributed Dynamic Decisionmaking simulation (DDD) [Kleinman and Serfaty 1989; Song and Kleinman 1994], *C3Fire* [Granlund et al. 2001; Johansson and Branlund 2003; C3Fire 2009], the MedTeams' Emergency Team Coordination Course [Small et al. 1999; Shapiro et al. 2004], and *Marine DOOM* [Riddell 1997]. In DDD, participants collectively make decisions about how resources should be allocated to solve a problem that changes over time; it has been used for military training as well as understanding how fast-response teams operate and how to modify them effectively. In *C3Fire*, participants are presented with a map of terrain and direct virtual units to respond to emergencies. The MedTeams' Emergency Team Coordination Course [Small et al. 1999] provides a high-fidelity simulation of medical emergencies for team training. Participants work with robotic dummies whose medical conditions are simulated. Teams of students work together to deal with crises on simulated patients. *Marine DOOM* was a short-lived modified version of id Software's *DOOM* [Petersen et al. 1993] set up so that four-person teams could learn to cooperate in military contexts. Each of these simulations addresses team coordination by directly re-creating the concrete environment.

3.3. Restored Behavior

Schechner [1985], in the domain of performance studies, identifies ways in which action learned in one context is then recalled and reproduced in others. He investigates contexts of ritual and theater, including re-creations of historical sites with simulated participants. These *restored behaviors* are effectively strips of action, like the strips of film used by a film editor. Behavior strips can be remixed, embellished, altered, and otherwise transformed in practice. We shift from theater to contexts of games and learning. Restored behavior is a basis of zero-fidelity simulation. Behaviors (skills) are learned in a safe simulated environment, then restored (applied) later in real-life environments. As with acting, these environments are not necessarily the same, supporting the proposition that zero-fidelity simulations can be transferred across domains.

3.4. Zero-Fidelity Simulation Examples

In this section, we interpret a pair of prior games as zero-fidelity simulations. We also describe a hypothetical zero-fidelity simulation of distributed cognition in an aircraft cockpit, based on Hutchins's [1995b] ethnography.

3.4.1. Prior Zero-Fidelity Simulations. One example of a prior zero-fidelity simulation is *Chess*. *Chess* was played as a simulation of war in sixth century Persia [Daryaee 2005]. It includes a variety of units, each with different maneuvering capabilities. Players need to plan moves in advance and consider what decisions their opponents might make; behaviors that can then be restored in alternate domains, such as a battlefield. *Chess* does not take into consideration the effectiveness of certain units against one another, reinforcements, hidden units, or diplomatic solutions to conflict. It teaches the ability to think ahead and mentally model expected responses from an opponent. *Chess* comes with no expectation that players believe they are fighting a war.

A second zero-fidelity simulation is *Hush* [Antonisse and Johnson 2008], in which the player takes on the role of a Tutsi mother during the 1994 Rwandan genocide. The player's avatar must remain hidden from Hutu patrols hunting her and her baby. To stay hidden, one must be quiet; to quiet the avatar's child, she must sing. The core mechanic is a rhythm game, in which the player times key presses to letters appearing on the screen. Visuals of photographs from the genocide, along with sounds of shouts, cries, and gunfire create tension. While *Hush* is not a mimetic simulation of hiding from Hutu patrols, it captures the abstract tension experienced in this historical setting. The game play activities simulate keeping the child quiet while under stress.

3.4.2. Contrasting a Hypothetical Zero-Fidelity Cockpit Simulation. To contrast high- and zero-fidelity simulation, consider a typical flight simulator. Such simulators are designed to account for atmospheric conditions, aerodynamics of a simulated aircraft, and so forth, creating as realistic an experience as possible [Rehmann et al. 1995]. The interface includes a dashboard, modeled closely on the gauges of actual aircraft and might even include a flight yoke. High-fidelity flight simulators teach pilots to control aircraft and respond to emergent conditions without endangering humans or equipment.

According to Hutchins [1995b], co-pilots look up information about the aircraft and enter relevant transformations into instruments while communicating, enabling the pilot to maintain situation awareness and plan landing. To teach these socio-technical aspects of landing aircraft, a zero-fidelity simulation would focus on information translation and exchange between co-pilots. It might completely eschew accurate cockpit design and aircraft physics.

The zero-fidelity socio-technical flight simulator would focus on the distributed cognition of aircraft landing. The abstraction involves information lookup and transformation under real-time stress. The user would need to communicate resultant information to a co-participant engaged in a cognition-intensive task. Such a simulation would be alternatively focused and less expensive than a high-fidelity flight simulator.

4. GAME DESIGN

Salen and Zimmerman [2004c] frame games as rules and play. *Rules* are the mathematical and logical structures that define the boundaries of the game, while *play* is the freedom to make choices and act within the rules. Game mechanics are the play choices that players make. The *core mechanics* of a game are the set of actions that players repeat.

The Team Coordination Game's core mechanics engage information transformation and communication tasks essential to effective coordination. The simulation exchanges the media of the environment, from physical to digital, and from fire to conceptual threats. Players take on roles analogous to FER's incident commander and company members. They are stimulated by entities—threats, goals, and score—that provoke a sense of crisis through game play and afford coordinated response. The media of communication, radio, and face-to-face communication, are unchanged from the source distributed cognition environment. Players are motivated by rules that create real-time stress and information distribution and require cooperative response. Participants are assigned diverse perspectives that they must interrelate in order to succeed, so that they are mutually reliant for information, representational transformation, and action. Dividing information along participant roles reflects FER work practice. Real-time stress ensures that participants must make quick decisions about what information to share, and how to share it. In this way, the play of TeC focuses on the human-centered aspects of team coordination.

4.1. Gameplay in TeC: Roles

Players take on alternative roles with different capabilities and information access, reflecting FER practice. Four players make up a team: three seekers and one coordinator. *Seeker* players move an avatar in the virtual environment terrain, searching for goals while avoiding threats (Figure 3). A *coordinator* observes the virtual world with limited detail. S/he communicates with the seekers to direct them. The team is structured to simulate an FER team. Information access and action capabilities reflect FER practice, following the zero-fidelity simulation principle of participant roles [Toups et al. 2009]. Game time is limited. The team members are pushed to mutually communicate, sharing information in order to work together effectively.

4.1.1. Seeker. A seeker is the combination of a human seeker player with an avatar in the virtual environment. Seeker players move their avatars in the virtual world using the keyboard, interacting with other game entities and terrain. Each seeker has a limited, local perspective that provides rich detail about the game at his/her location

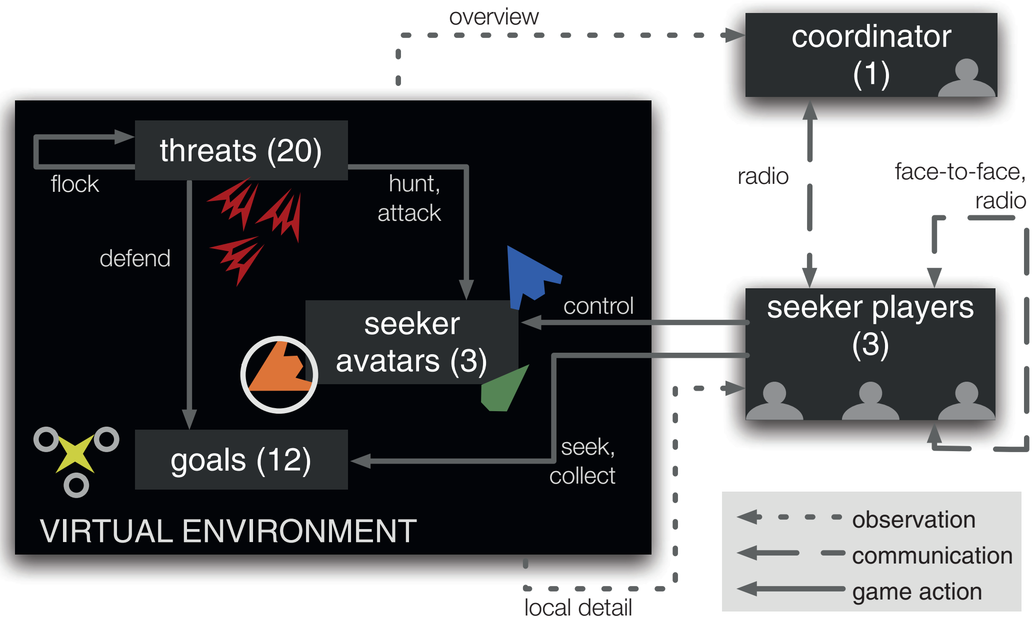

Fig. 3. Game mechanics of TeC. Human players are to the right of the diagram, communicating with one another; game entity interactions take place on the left side of the diagram, in the virtual environment. Information flows are similar to those in FER work practice (Figure 2).

(Figure 4). Seekers are like firefighters in FER work practice. They accomplish cooperative tasks in dangerous environments and feed information back to the coordinator.

Each seeker is assigned limited hit points (HP), which the game system reduces each time the seeker comes into contact with a *threat*.[4] As long as the avatar has at least 1 HP, the seeker is *in*, and able to participate. Once an avatar has no more HP, the seeker avatar's state changes to *out*. Certain regions of the terrain contain *bases*, where seekers are *safe*. While safe, a seeker regenerates HP and cannot be attacked.

4.1.2. Coordinator. The coordinator observes and communicates, like an IC. The coordinator can only interact with the virtual environment through the seekers by communicating with them. The coordinator's view lacks the detail of the seekers', providing an overview that shows the locations of all online seekers (Figure 5). This role reflects that of the IC, who must observe, develop strategy, and communicate.

4.2. Real-Time Stress: Threats Hunt Players

TeC creates real-time stress by populating the virtual environment with *threats*. Threats are game entities that, when in contact with a seeker's avatar, reduce the avatar's HP. Threat behavior is driven by a physically based flocking simulation [Reynolds 1987]. To create real-time stress, threats exhibit additional behaviors that draw them to players and goals using particle choreography techniques [Sims 1990], such as patrolling or guarding a goal. Threats chase detected seeker avatars; when a seeker is running or collecting a goal s/he can be detected from a greater distance. As seekers move into position to collect goals, threats are attracted. This pushes seekers to work and coordinate quickly.

[4]"Coming into contact" with a threat is the same as "being attacked by" a threat.

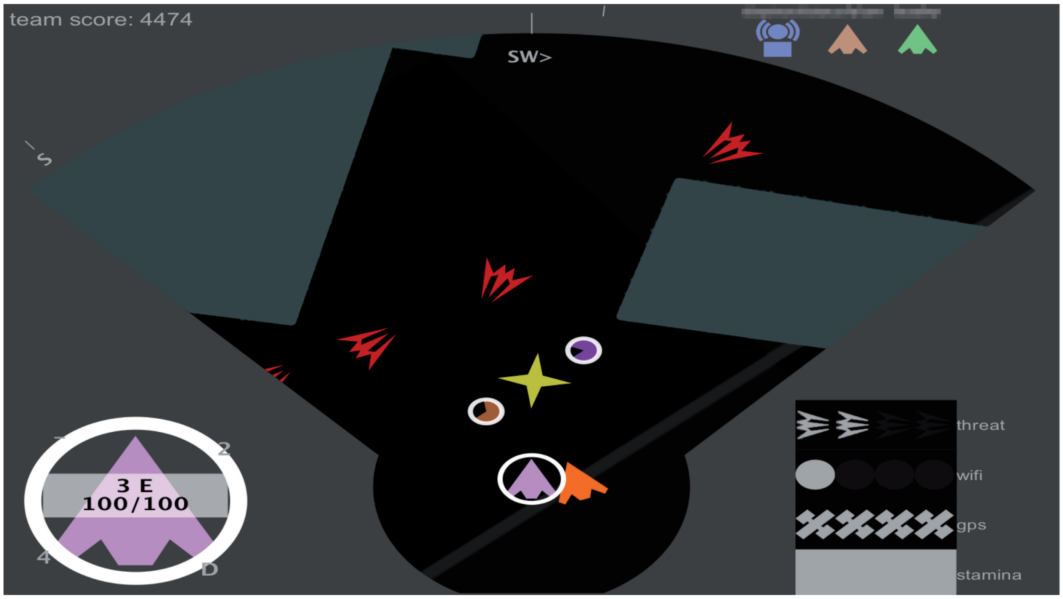

Fig. 4. Screenshot of seeker view in TeC (Team 5, session 4, game 8, 5′15″). The purple and orange players collect a two-seeker cooperative goal while inside a base. Purple knows s/he is in a base because the white shield around the avatar indicates safe status; purple cannot detect any information about orange's status. Threats are nearby. The visualization in the lower left shows that the avatar is located in terrain region (3, E); the direction of other regions are shown on the periphery. It also indicates the seeker full HP (100).

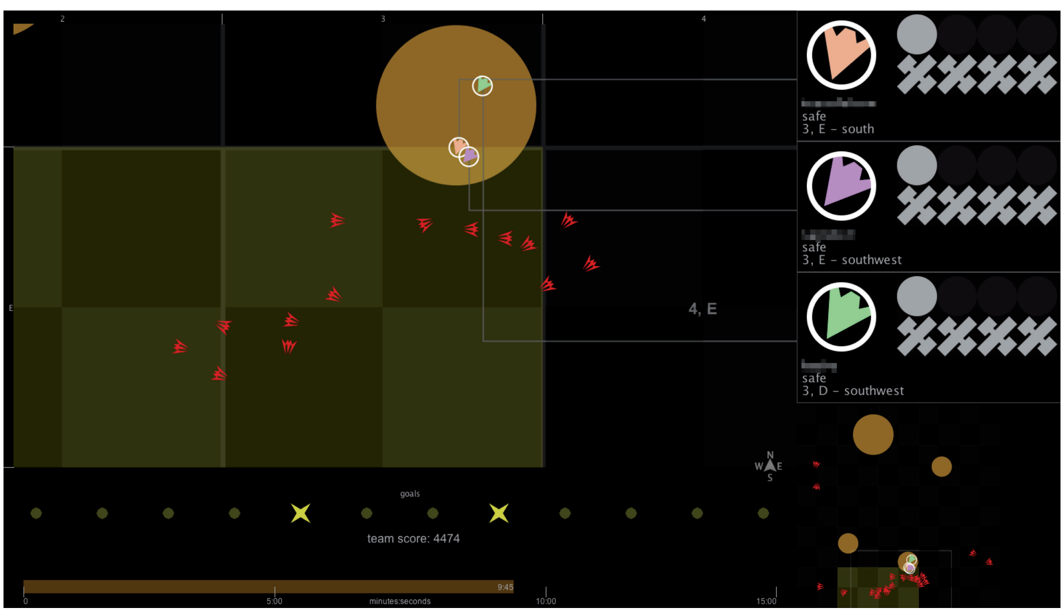

Fig. 5. TeC coordinator view screenshot (Team 5, session 4, game 8, 5′15″). The main view shows terrain with all entities in it; highlighted yellow regions contain goals. Walls (visible to seekers) cannot be seen. The right column shows the status of each seeker; a mini-map is at the bottom. Below the main view is the list of goals (here, two remain uncollected) and the time remaining in bar graph and text form. [Toups et al. 2011]

A time limit is imposed, further contributing to real-time stress. A team's score is improved by collecting more goals faster. This reifies the motivation for players to minimize time taken to collect each goal. Rapid response is further motivated by a score bonus proportional to the time remaining if and when all goals are collected. Real-time stress encourages efficient use of available communication channels, an essential skill in emergency response work practice. Threats and the time limit create a simulated experience of crisis.

4.3. Communication

In TeC, communication is a core mechanic. Coordination for goal collection, collaborative navigation, and threat avoidance requires communication. A fundamental design goal is to encourage participants to engage in multiway communication, like FERs.

To support the design principle of mixing communication modalities, TeC is played in one of two team configuration conditions that impact communication modality availability (Figure 8). In the *co-located condition*, all seeker players are seated around a table with individual computers in front of them, while the coordinator is isolated. Seeker players can communicate with each other by speaking face-to-face, but must use the radio to contact the coordinator. In the *distributed condition*, all players are isolated and must use the radio to speak.

Face-to-face communication is fast and easily disambiguated. Participants can use expression, gesture, and short verbalizations to communicate rapidly. In some cases (seeker-coordinator communication and seeker-seeker in the distributed condition), players need to use half-duplex radios, like those used in fire emergency response. This component of the design is mimetic, using equipment found in work practice. The qualities of the radio that must be overcome in practice are unique. The radio only allows one participant to speak at a time. Radios are controlled using push-to-talk (PTT). The radios used for TeC, like those used by FERs, are characterized by a delay between when a radio begins transmitting and when another begins receiving.

4.4. Cooperative Goals

TeC employs cooperative goals to motivate coordination among seekers. Cooperative goals require that they be collected by two or three seekers simultaneously. An individual seeker may start collecting a goal without teammates, however this attracts threats. If a seeker is taken out while collecting, the team fails. To succeed, team members must synchronize movement into positions around a goal. These rules require that seekers coordinate to collect goals quickly and safely.

4.5. Motivating through Score

To provide external motivation for play, teams receive feedback about their performance through team score [Salen and Zimmerman 2004a; Toups et al. 2009b]. Collecting goals and actively engaging in the game positively affect score. Alternatively, a seeker being taken out of the game by threats reduces score. If the seekers collect all of the goals, the team receives a bonus proportional to the time remaining.

4.6. Information Distribution

Information distribution abstracts work practices to simulate the perspectives of team members in crisis response that stimulate mutual communication. Each TeC player role is characterized by associated game mechanics and interface. Seekers are presented with a limited, local scope with a high-detail view of the virtual environment (Figure 4). This view includes walls that inhibit movement, threats that attack, and detailed views of goals. In the other role, the coordinator has a low-detail overview of the entire game

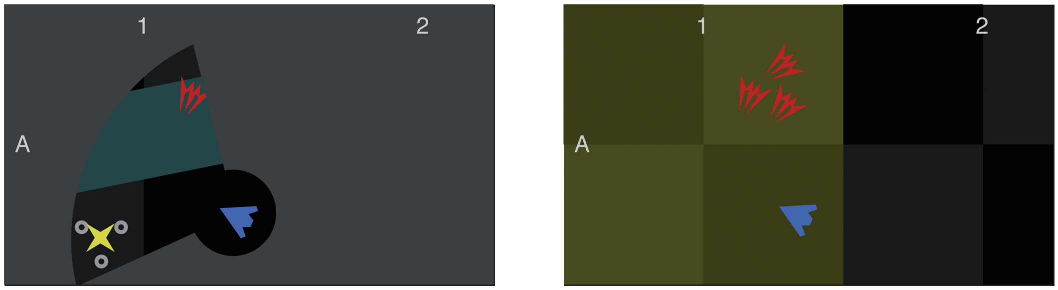

Fig. 6. Example of information distribution between a seeker's perspective (left) and a coordinator's (right). The seeker observes a high-detail, limited scope that includes walls and goal details. The coordinator can see the seeker's location and a shaded region containing the goal, but not the walls. Both see threats while they are in scope.

world that excludes walls, but shows threats and seekers (Figure 5). The regions of the environment that contain a goal are depicted; details are missing.

The game design modulates the visibility of information between these two roles to create information distribution. We employ the technique of *making invisible* to create information distribution across the player interfaces [Toups et al. 2009a]. Contrary to Norman's [2002] principle of "making visible," the principle of making invisible indicates that information should be hidden from some players so that they are reliant on teammates, rather than their own interfaces. Information is also spatially separated across the virtual world, inherently distributing information among seekers.

Information distribution in the face of crisis stimulates players to communicate. Real-time stress game mechanics push players to communicate efficiently. To effectively coordinate, each player must explicitly identify and communicate information that is important, but not visible to others due to information distribution.

4.6.1. Goals. Seekers see detailed representations of goals: exact location, number of seekers required to collect, and progress of the collection process (Figure 6, left). However, seekers only see goals visible in their limited scope. Coordinators are presented with the general locations of all goals in the virtual environment. In their overview map, goals are represented as shaded, grid-aligned square regions (Figure 6, right). However, coordinators cannot directly determine the goal details made available to seekers; they must instead rely on seekers to relay this information to them.

4.6.2. Walls. Game mechanics of travel plus role-based representations of walls provoke distributed cognition. Seekers cannot travel through walls, and thus must circumnavigate them. The coordinator cannot see walls in the virtual environment overview (compare Figures 5 and 4; Figure 6). This interferes with the coordinator's primary visual feedback for tracking seekers' game actions. Navigation thus requires iterative communication among seekers and the coordinator. Seekers sometimes need to inform the coordinator that they must travel around an obstacle; the coordinator may need to update seekers with a new direction of travel while they navigate. The wall model is based on the arrangement of buildings at Texas A&M University.

4.6.3. Bases. If a seeker's avatar is taken out of the game (reduced to 0 HP), the seeker must reach a base to recover HP. A seeker cannot spot bases until her/his avatar is inside one, at which point the player can see s/he is in a safe status. Coordinators can see the exact location of all bases and may thus help seekers find them in the virtual world by communicating their location. Additionally, seekers are unable to determine the HP of a fellow seeker or even if that seeker is currently in a base. This is an example of interseeker information distribution and derives from FER work practice.

Table I. Summary of Evaluations and Resulting Impact on TeC Game Designs

Ver.	Evaluation	Games	Resulting impact on TeC
1.0	**Study A**: TeC with non-FERs	72	goal collection status indicator; PTT status indicator; update scoring rubric
1.5	FER expert* participatory design	8	making threats visible to seekers; seeker location context indicator; PTT status audio
2.0	**Study B**: TeC with FERs	56	–
2.0	**Study C**: pilot deployment with TEEX Disaster Preparedness and Response (DPR)	6	adoption of TeC into DPR curriculum

Note: Each game is played with a four participant team. Resulting changes appear in the version that follows. Prototypes (not shown) changed rapidly. Version 1.0 was used for Study A, Version 2.0 was used for Studies B and C; all are discussed in Results (Section 7).
*TEEX FTA Program Coordinator and Fire Chief Cary Roccaforte.

While FERs can read some amount of body language, they still must communicate about health status.

4.6.4. Spatial Interseeker Information Distribution. The spatial distribution of seekers throughout the virtual environment affects inherent information distribution among them; as in emergency response practice, each participant has a unique perspective. Each seeker possesses rich local information: nearby threats, local goal locations and collection status, nearby walls, and other nearby seekers. Each of these environmental characteristics may be essential for teammates to know.

4.7. TeC Iterative Design

Through an iterative design process over the course of five years, we derived a series of TeC game designs from fire emergency response practice (Table I). We focused information distribution in game play through constant comparison to the source via ongoing ethnographic investigation [Strauss and Corbin 1998] and user studies. Version 1.5 was derived from long-term Study A, with non-FERs. We subsequently reflected on and compared to our source, and worked with Chief Roccaforte[5] in a series of participatory design sessions. From the data, we developed TeC, version 2.0, which we deployed with FER students and expert disaster responders. The evolution of the modulation of visibility was found to motivate communication and better simulate practice. We also found that *making predictable* impacts the ability of participants to build shared mental models and communicate effectively. Details on early versions of TeC can be found in Toups et al. [2009a].

In prototype games, we found that information distribution across roles was confusing to participants. Many seeker players assumed that their coordinator had the same information they did and would reference accordingly. Deriving from crisis response practice, we developed cross-training in the form of an active tutorial. The tutorial computationally explains TeC's information distribution by showing a single user the coordinator and seeker roles at once, while enabling game play. In this way, players cross-train in both roles, enabling them to more effectively form shared mental models.

TeC 2.0 improved information distribution from version 1.0. Seekers were given the ability to observe threats in their local scope [Toups et al. 2009a]. This instantiates the design principle of *making predictable*. When invisible, threats were perceived as random, reducing player agency. This also created too much reliance on the coordinator, who needed to focus on very rapidly reporting threat locations relative to each seeker. Our ethnographic investigation of fire emergency response work practice reveals [Toups

[5]Fire Chief Cary Roccaforte, Program Coordinator for Texas Engineering Extension Service (TEEX) Fire Training Academy (FTA); more detail in § 7.1.2.

Fig. 7. Teams playing the TeC tutorial face-to-face. Left: FER students. Right: TEEX DPR expert disaster responders in Study C.

and Kerne 2007], in concord with our game experiment findings, that this level of micro-management is detrimental to team performance and not in line with the job of the IC.

5. EXPERIMENT DESIGN

The present research synthesizes results from two user studies of TeC [Toups et al. 2009, 2011], and presents a new pilot deployment involving expert responders (Table I). Experiment methods for studies 1 and 2 are described here; the new pilot deployment is similar. We evaluated TeC by having 4-participant teams play over a series of 4 weeks. We present the apparatus, methods, and data collected.

5.1. Apparatus

Participants play TeC on a set of four laptop computers (Figure 7). These computers are outfitted with custom hardware that interfaces TeC with real push-to-talk radios, simulating the emergency response radio modality. Later iterations of the apparatus use a functionally equivalent network-based audio simulation of communication channels. Each machine is equipped with a headset that allows participants to communicate via the simulated communication channel.

Studies are run through an in-browser sequence of questionnaires and automated game launches. Participants use laptop keyboards to interact with the game. Coordinators are also provided with a mouse, which simplifies the task of controlling the coordinator interface. Depending on the experiment condition, participants are either colocated, sitting around a table facing each other, or are assigned to separate, sound-isolated rooms. Figure 8 diagrams the conditions.

5.2. Method

Teams of four participants were asked to play TeC over a period of four weeks. Teams played eight games over four sessions. Sessions were spaced a week apart to allow time for incubation, which has been show to help people develop new ideas and strategies for approaching a task [Smith 1994]. During each session, teams played two 15-minute games, one each of the two conditions: collocated and distributed. Conditions were counterbalanced across the sessions to avoid ordering effects. Before and after each game, participants were given a qualitative questionnaire. Participants were aware that the purpose of the game is to improve team coordination, but not what data is used to assess team coordination.

Prior to each game and after the final game of a session, participants engaged in a 10-minute team reflection session. Team reflection sessions enable players to discuss their performance in past games and develop strategies for future ones. Such reflection

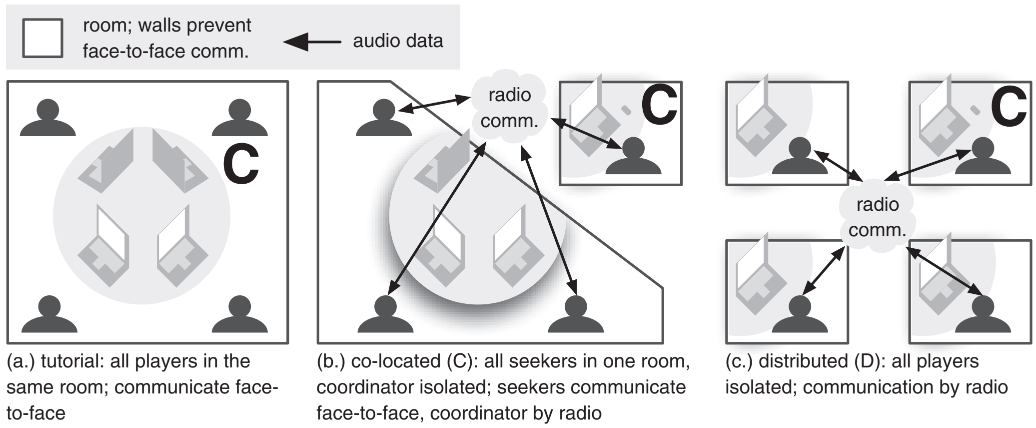

Fig. 8. Condition setups for TeC experiments. [Toups et al. 2011]

sessions have been shown to help aid problem-solving, support shared mental model formation, and build trust [Schön 1984; Gurtner et al. 2007].

Before the beginning of the first session, participants played a tutorial game, where they were presented with both the coordinator and seeker interfaces while learning the basics of playing TeC. This facilitates cross-training across the TeC roles, which has been shown to have positive effects on team performance [Cannon-Bowers et al. 1998; Marks et al. 2002; Volpe et al. 1996].

5.3. Data Collection

During user studies, we collect data from game logs, player communication, and questionnaires, deriving a combination of quantitative and qualitative data. Game logs sample the internal state of the game at 10Hz. They include the map, states and locations of seekers, threats, and goals. During game play, we record each participant's voice, incoming audio signal, and game sounds. A synchronization track enables combining this data with the game logs to replay it (Section 6.1).

A multipart questionnaire was administered across segments of the study. The questionnaire initially gathers background information about the participants, including demographics and education, game, and team coordination history. Throughout the study, it requested information about players' perceptions of their team during game play, both positive and negative.

The team reflection sessions were audio recorded. These serve as a rich source of data on how each team is playing and perceiving the game. In TeC studies with FER students, we interviewed a teacher and expert practitioner, TEEX FTA program coordinator Chief Roccaforte, for his insight into players' burn training performance with regard to TeC game play.

6. MIXED DATA ANALYSIS

We developed a new mixed methods approach [Frechtling and Sharp 1997] for zero-fidelity simulation evaluation, analyzing quantitative and qualitative data from multiple sources. We developed quantitative measures for analyzing team coordination. A new protocol analysis *speech/action coding scheme* enables us to quantify the patterns of communication within teams based on recorded audio data, examining team efficiency from the perspective of implicit coordination (Section 2.3). TeC game metrics are derived from logs and address cooperative task activity. These game performance measures contribute to analyzing cooperative task performance components of team

Table II. Speech/Action Coding Scheme for Analyzing TeC User Study Data [Toups et al. 2011]

Code	AR Code	Description	Example
game state request (*RQGS*)	*pull*	player asks for information about the virtual world (entities, terrain), but not other players	"Where is the next goal?"
game state report (*RPGS*)	*push*	player supplies information about the virtual world (entities, terrain), but not other players	"There are threats here!"
status request (*RQS*)	*pull*	player asks for information about another player (including seeker status)	"Where are you?"
status report (*RPS*)	*push*	player supplies information about him/herself or another player, including progression toward an objective	"I'm out right now."
action request (*RQA*)	*push*	player asks another player to do something	"Let me know where to go next."
meta-communication	–	communication about communication, including acknowledgement and asking for clarification	"Repeat please."
metagame	–	communication about the game itself	"How do I run?"

Note: Each code is accompanied by its abbreviation, used throughout. The AR code column indicates whether the code falls into the AR substrate of push, pull, or none for calculating anticipation ratio.

coordination. Qualitative data sources, audio recordings, and questionnaires, enable unpacking participant perceptions of the game and observing how they restore learned behaviors in practice.

6.1. Reviewing Data: Coordinated Log + Audio Playback System

To analyze experimental game records, we constructed the Coordinated Log + Audio Playback System (CLAPS) to synchronize individual audio records and game logs, reconstructing a multiperspective playback of recorded games [Hamilton et al. 2009]. Using CLAPS, we observe and analyze complex multimodal communication and coordination between players.

The multichannel synchronized audio and game play visualization exposes what each player saw, said, and heard. With this high-fidelity recreation of each team's zero-fidelity simulation record, we can examine TeC game play experiences. The channels of audio and visualization serve as the basis for analysis of team communication through a speech/action coding scheme. This enables assessment of communication efficiency and differences between player roles. Using CLAPS, we also gather qualitative instances of distinctive team coordination.

6.2. Speech/Action Coding Scheme

Communication within a team offers insight into its members' ability to coordinate effectively [MacMillan et al. 2004]. To analyze team communication, we developed a protocol analysis coding scheme [Ericsson and Simon 1992], grounded in prior findings of FER work practices and the implicit coordination literature (Section 2.3). For each utterance, we classify and log communication content (Table II), the speaker's action within the game, the modality the participant used, and success or failure (crosstalk, radio interference) [Toups et al. 2011]. The result is a count of the number of times each player used a particular speech/action code in each game, which is then analyzed to determine the pattern of communication in the team and its communication efficiency.

We engaged a grounded theory method of constant comparison [Charmaz 2006] to derive this speech/action coding scheme (Table II). The source data collection began with observation of FER students in burn training and interviews with expert responders [Toups and Kerne 2007]. It is simultaneously built on a substrate of the established anticipation ratio measure of implicit coordination (see Section 6.2.1). The codes are analogs to observed FER practice, applied to the game. We created an initial coding scheme for Study A with non-FERs. On reflection of game and work practice, we evolved the coding scheme to better match work practice for Study B with FER students. Throughout the development of the coding scheme, we constantly compared our schemes with our source ethnographic records. We also asked FER students how they would describe their communication, and if they thought that their communication was adequately captured by our codes. By observing game play, we discovered that some utterances overlapped multiple audio codes, showing especially efficient communication. To better capture the nature of these utterances, we developed hybrid codes to mark a single utterance with two or more base codes. [Toups et al. 2011]

6.2.1. Anticipation Ratio. Anticipation ratio (AR) is a metric for measuring the communication efficiency of teams [Entin and Serfaty 1999; MacMillan et al. 2004]. An improvement in communication efficiency indicates a shift toward implicit coordination (Section 2.3). The implicit coordination mode reduces unnecessary communication overhead because team members have become more effective at predicting each others' actions through shared mental models. Intuitively, AR measures that the less one needs to speak to get one's information needs met, the lower the load on cognition and communication channels. [Toups et al. 2011]

AR measures the amount of information team members provide compared to that requested. Pulling information functions as noise in the limited communication channel, burdening the team with cognitive load and reduced access to the channel.

$$Anticipation\ Ratio = \frac{push}{pull + push}. \tag{1}$$

The function for computing AR (Equation (1)) places value on pushing information out to the team. Where *push* is the number of utterances pushing information by part of the team and *pull* is the number of utterances pulling information by part of the team. Other utterances are excluded. [Toups et al. 2011]

Each speech/action code is classified as a push, a pull, or none of the above (Table II). In practice, AR is customized using different combinations of team members, based on the team being studied. In the present research, coordinator pushes are compared with seeker pulls from the coordinator over the limited bandwidth of the radio, as described in Table IV. Because hybrid codes are more efficient, and we are seeking to measure efficiency, only the push component of each was counted (so a pull component did not penalize AR); if a hybrid was multiple pushes, the pushes were counted multiple times. The higher a team's AR, the better the team members are anticipating each other's information needs. An increase in AR indicates improvement in communication efficiency and thus, implicit coordination. [Toups et al. 2011]

6.3. Data Analysis

We synthesized techniques to analyze the data. We manipulated several independent variables, and developed methods to derive dependent measures of cooperative task performance from game logs. We developed quantitative analysis techniques and notation to describe and depict the relationships between the independent variables, the cooperation measures, and the speech/action codes described earlier.

6.3.1. Independent Variables. We base observations of change in team coordination, consisting of cooperative task performance and efficient communication, on a set of independent variables. Game sequence measures time across sessions as an index among the 8 games that each team played.[6] Condition indicates whether the game was

[6] We never include tutorial games in the count, because they are intended to be exploratory for participants.

Table III. Independent Variables for Teams and Individual Players [Toups et al. 2011]

Var.	Description	Range
seq	ordinal value indicating the game in the sequence	1–8
cnd	game condition	$\{C, D\}$
rl	player role in game	$\{S, D\}$

Table IV. Measures of Team Communication Efficiency and Task Performance [Toups et al. 2011]

Variable	Description
$AR_{C:S(rd)}$	anticipation ratio of coordinator reports to seeker requests over the radio ($RPGS_{t[C]} + RPS_{t[C]} + RQA_{t[C]} : RQGS_{t[S]} + RQS_{t[S]}$)
GC_{xS}	number of x-seeker goals collected in game, normalized against number of that type available
cycRem	game cycles remaining when all goals have been collected, normalized against the performance of all teams (if the team fails to collect all goals, this value is 0)
gamePerf	$GC_{1S} + GC_{2S} + GC_{3S} + cycRem$; *gamePerf* directly captures the set of performance measures used in determining the end of the game, weighting the total collected goals and cycles remaining evenly
$band_{1S}$	% time all seekers alone, normalized for *cycRem*
$band_{2S}$	% time two seekers banded together (one isolated), normalized for *cycRem*
$band_{3S}$	% time all seekers banded together, normalized for *cycRem*

co-located (C) or distributed (D). Finally, role indicates whether the player was a seeker (S) or a coordinator (C). Table III describes the independent variables.

6.3.2. Cooperative Task Performance. We developed metrics for cooperative task performance, grounded in the TeC game design. Collecting goals places colocated seekers in danger. The process of goal collection requires information acquired from multiple game interfaces and perspectives. Performing goal collection efficiently is captured by combining the goal collection measures (GC_{xS}) with teams' game end bonus time (*cycRem*); the combination is game performance (*gamePerf*). Table IV describes the measures.

We aggregate the time seekers spend with their avatars colocated in the virtual environment. This *banding* metric corresponds to working together in disaster response: it simplifies coordination, improving chances for team success. By *banded together*, we mean that one or more seekers can see another. For each game log sample, we identify whether all seekers are isolated ($band_{1S}$), two are together with one apart ($band_{2S}$), or all three together ($band_{3S}$). Table IV summarizes the measures.

6.3.3. Quantitative Analysis Techniques and Notation. We employed several quantitative analysis methods for analyzing the resulting data. The first method is a linear model of how each team coordination measure changes with an independent variable. Results are presented as ([*dependentVariable*] $\sim$ [*independentVariable*] : m = [*value*], R^2 = [*value*], $p <$ [*value*]), where m is the slope of the regression line and R^2 is its fitness. Positive slope indicates a direct relationship, while negative slope indicates an inverse one. Where we call attention to an insignificant result, we omit m and R^2 values and report p as greater-than [Toups et al. 2011].

The second analysis method is Welch's [1947] t test. The t test compares the mean value of a set of samples in a pair of conditions of possibly unequal variances for a statistically significant difference between them. We report t test results as ([*variable*], [*conditionVariable*] = {[*1stConditionValue*], [*2ndConditionValue*]} : $t(df)$ = [*value*], $p <$ [*value*]), where t is the t statistic and df is the number of degrees of freedom of the data. In this section, we use one-tailed t tests, which determine if one condition is greater (positive t) or less (negative t) than the other. [Toups et al. 2011]

7. RESULTS

In this section, we synthesize the results from three TeC zero-fidelity simulation studies, including an interview with a panel of experts. The quantitative findings demonstrate that study participants become better at coordinating, as operationalized through improved performance on cooperative team tasks and increased communication efficiency. Qualitative data address the ways in which FER students connect TeC gameplay to practice. Findings from expert responders show that TeC addresses a need for stressful team coordination education. Informal strategies employed by players constitute team coordination activity.

7.1. Participants and Study Details

Long-Term Study A involved students and local community members but not the fire school, initiating investigation of how TeC 1.0 (Table I) impacts team coordination. Study B invoked TeC 2.0 in the TEEX Fire Training Academy with FER students. Preliminary Study C was a significant step toward deploying TeC in TEEX DPR curricula.[7] It began with a panel of expert DPR responders, and continued with a pilot deployment in which DPR responders played a series of short sessions.

To identify teams and team members, we use the notation of [*studyIdentifier*]/[*teamIdentifier*].[*participantIdentifier*]. [*participantIdentifier*] is omitted when discussing the team as a whole. For example, the first player in the sixth team in Study B would be B/6.1. Multiple teams may be denoted using a comma-separated list (e.g., Study A, teams 1 through 4 is A/1,2,3,4). In Study B, participants have team names so we use them instead of numbers. Panelists in Study C are treated as their own team (C/panel). Note that quantitative data tables use their own unrelated number scheme.

7.1.1. Study A: Non-FERs. The first formal user study of the TeC zero-fidelity simulation game in 2008 engaged local students and community members to examine whether or not non-FERs improved in a game designed from fire emergency response work practice [Toups et al. 2009]. We did not want to engage FER students until we had some evidence that TeC is effective. This study ran a total of 72 games with nine 4-player teams; it played a key formative role in the iterative design process.

Results from the study showed that players improved their team task performance, developed new roles within teams, and connected the game with improved team coordination skills. Audio with game logs served as the primary source of data. Each player's audio was coded according to an early version of the speech/action coding scheme that was later iterated (Section 6.2); data from Study A heavily influenced the iteration. Analysis identified instances of strategy, team coordination, and problems. Most significant results were observed through qualitative data.

Thirty-six subjects, recruited from Texas A&M University and the nearby community, were organized into nine teams of four members each. Few had extensive prior experience performing teamwork (Table V). Participants were compensated: food was provided at each session, and each participant received a gift card (30USD) on completion.

7.1.2. Study B: FER Students. Based on the formative results of Study A, we iterated the TeC zero-fidelity simulation design to increase predictability and improve information distribution. The participants in Study B were FER students at the FTA. The FTA requires over 40 hours of coursework a week and some students hold simultaneous outside employment. For this study, we ran a total of 56 games with seven 4-player

[7] http://www.teex.org/dpr/.

Table V. Prior Team Experience in Studies A (Non-FERs) and B (FER Students)

Years of team experience*	# participants (% of study) Study A	Study B
no response	8 (22.2%)	0 (0.0%)
0	12 (33.3%)	6 (21.4%)
<1	7 (19.4%)	7 (25.0%)
1–5	8 (22.2%)	8 (28.5%)
6–10	0 (0.0%)	5 (17.8%)
10–20	1 (2.78%)	2 (7.14%)

Note: Most Study A participants had little to no experience or chose not to respond; FER students in Study B show substantially more experience than non-FERs.
*Based on the multiple-choice question: "Do you have any experience with team-based situations, such as (but not limited to) firefighting, community activism, military service, or police service? If so, how much?"

Table VI. Study B Team Names (FER Students)

Spring (RC 128)	Summer (RC 129)
calTEXANADA (B/1)	Foxtrot and Company (B/4)
Team Firestorm (B/2)	B/5
Team Rainmen (B/3)	B/6
	B/7

teams (28 participants) who volunteered to play in their off time (details can be found in Toups et al. [2011]).

Subjects volunteered from the 2009 Recruit Class (RC) 128 (spring) and RC 129 (summer). Each team had participated in the FTA for at least five weeks. Studies were completed prior to burn training exercises. The FER student teams had a higher level of prior team experience than the non-FER teams in study A (Table V). Each participant was compensated with food at each session and a gift card worth 30 USD on completion of the study. Teams, as a whole, were allowed to select a name (Table VI).

In addition to gathering audio and game log data, we interviewed the students' teacher and program coordinator, Chief Cary Roccaforte. Roccaforte is a veteran FER with over 30 years experience in the field and in educating the next generation of FERs. As part of the study, he observed the students when they later performed burn training. His voice adds qualitative evidence of how TeC impacted student performance.

7.1.3. Study C: Disaster Preparedness and Response Experts. We interviewed a panel of expert crisis responders in January 2011, then piloted a study of TeC with responders at TEEX Disaster Preparedness and Response (DPR)[8] in February 2011. While this study is less methodologically rigorous, it attains high ecological validity, because the participants are not students, but deployed emergency responders, most of whom possess formidable experience and expertise. The panel gathered four experts in disaster response, including urban search and rescue and wildland firefighting, representing a diverse sample of crisis responders. Together, the four represented over 100 years of experience in the emergency response domain (Table VII), including extensive experience in historic natural and human disasters (Table VIII). Two of the four had played TeC prior to the panel: C/panel.1 and C/panel.2.

The panel and pilot deployment gathered qualitative data about the need for games in disaster response education. They show, from the perspective of experts in the field, how TeC fulfills a need for better team coordination education. The experts connect TeC to work practice, and find it effectively exercises communication and cooperation for crisis response.

[8]TEEX DPR is a leading organization engaged in on-going education of emergency responders worldwide.

Table VII. Experience Levels of Responders in the TeC Panel and Study C (DPR Pilot Deployment)

Id	Years of team experience	Domain
C/panel.1	20–30	operating coordination center for elite TX-TF1, small industrial plant emergency response teams
C/panel.2	>30	civil air patrol, urban search and rescue, disaster logistics
C/panel.3	>30	fire emergency response, wildland firefighting, structural collapse, urban search and rescue
C/panel.4	>30	fire emergency response and rescue
C/1.1 (C/panel.3)	>30	<see previous>
C/1.2	20–30	
C/1.3	6–10	
C/1.4	>30	communications leader for federal disaster response
C/2.1 (C/panel.1)	20–30	<see previous>
C/2.2	<1	
C/2.3	<1	
C/2.4	>30	fire emergency response, urban search and rescue

Table VIII. Sample of Notable Historic Disasters in Which Panelists Were Involved

Id	Disasters
C/panel.1	all major deployments in Texas since 2004, including hurricanes
C/panel.2	Hurricane Katrina, Hurricane Rita, Hurricane Ike
C/panel.3	wildland fires in LA county; all hurricanes since Iniki (1992); Oklahoma City Bombing; 9/11
C/panel.4	London Fire Brigade; all IRA bombings in London; 7/7 Bombings

Based on the findings of the panel of experts, and the pilot deployment, the DPR leadership has decided to deploy TeC as a learning module in a growing set of curricula and deployment scenarios. This functional endorsement, itself, serves to validate TeC as a simulation of emergency response practice across domains.

We conducted the pilot deployment during Superbowl weekend 2011 (February 5–6) at DPR's Gateway Facility, then the location of the coordination center and headquarters for the elite Texas Task Force 1 (TX-TF1) regional Federal Emergency Management Agency (FEMA) response team. For this particular weekend, DPR personnel were posted to the coordination center in case of a disaster at the Superbowl sporting event, for which they were prepared to dispatch and coordinate teams in the field. As this was a real crisis-prevention scenario, we needed to work around standard operations. Participants joined the study in the time between shifts. Given the resulting constraints, the study was run differently from the other two in that the game time limits were shorter and there were fewer games. All games were played in the distributed condition, and in a single session. The coordinator role was cycled as normal. The first game was a tutorial. C/1 only completed two games, due to time constraints; C/2 played all four games.

The pilot deployment gathered qualitative data to find out how the team of expert responders experienced TeC, and represented a transfer beyond the original domain of fire emergency response. Questionnaires asked them to report on what they learned about communicating by playing and how play connected to practice. The study participants, whose experience is summarized in Table VII, were primarily experts. Some are involved in supervising and running the TEEX DPR curricula. This study served for these participants as a pilot for incorporation of the TeC Game into these curricula.

7.2. Synthesized Results Across Studies

7.2.1. Improving Team Task Performance. Collecting goals, the team task in TeC, engages players in cooperation. As players progressed through Studies A and B, they improved team task performance by collecting more goals in less time (Table IX: A.1., A.2., B.1., B.2.; Figure 9). Study C lacked sufficient data to examine performance over time.

Table IX. Team Task Performance Results for Studies A (Non-FERs) and B (FER Students [Toups et al. 2011])

Study	Id	Result
Study A	1.	$gamePerf \sim seq : m = 6.51, R^2 = 0.35, p < 0.0001$
	2.	$cycRem \sim seq : m = 4.12, R^2 = 0.17, p < 0.0001$
	3.	$gamePerf \sim cnd : p > 0.6$
Study B	1.	$gamePerf \sim seq : m = 3.29, R^2 = 0.17, p < 0.005$
	2.	$cycRem \sim seq : m = 6.97, R^2 = 0.07, p < 0.06$
	3.	$gamePerf \sim cnd : p > 0.4$
	4.	$band_{3S} \sim seq : m = 4.43, R^2 = 0.26, p < 0.001$
		$band_{2S} \sim seq : m = -2.02, R^2 = 0.07, p < 0.05$
		$band_{1S} \sim seq : m = -4.47, R^2 = 0.27, p < 0.001$
	5.	$band_{3S} \sim cnd : p > 0.9$
		$band_{2S} \sim cnd : p > 0.8$

Note: In both studies, teams collected goals quicker in later games. In Study B, they banded together more. Condition did not significantly impact game performance.

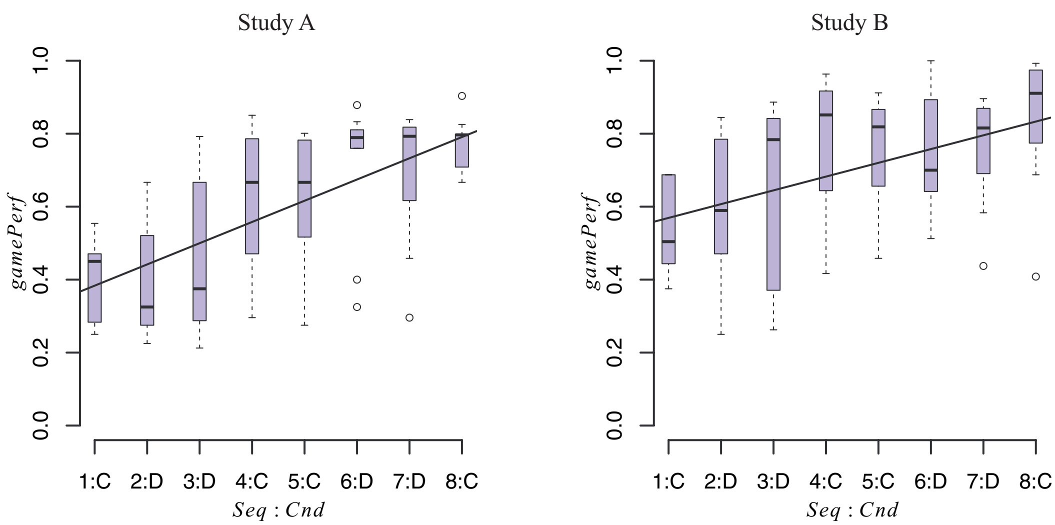

Fig. 9. Plot of team task performance results; Left: Study A (non-FERs, Table IX: A.1.); right: Study B (FER students, Table IX: B.1.) [Toups et al. 2011].

In Studies A and B, team members employed various strategies to band the seekers' avatars in the virtual environment (Section 6.3.2). In Study A, we observed qualitative evidence through CLAPS as well as team discussions. In early games, seekers frequently headed in different directions and got lost [Toups et al. 2009]. In many cases, the coordinator micromanaged the seekers into formation. In later games, after reflection, teams would develop a two-collectors-and-one-scout (2 + 1) strategy or an all-together strategy. In the 2 + 1 banding strategy [A/1,3,4,5], two seekers would stay together at all times and work independently of the third, who would scout. Each group was responsible for collecting any goals they could, and the two parts of the team would reunite for the others that were discovered. Using an all-together strategy [A/1,2,3,4,5,6,7,8] enabled seekers to move together as a team, and reduced the burden on the coordinator.

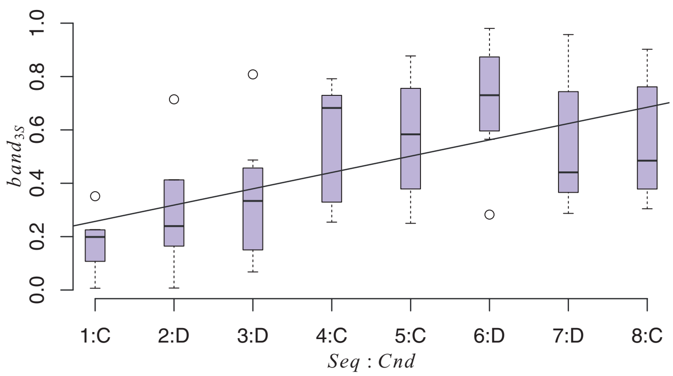

Fig. 10. Study B plot of banding results for 3-seeker bands (FER students, Table IX: B.4.) [Toups et al. 2011].

Based on Study A observations, we developed a banding metric for Study B, to quantify the amount of time seekers banded together. Over time, teams banded together more [Toups et al. 2011]. Table IX (B.4.) and Figure 10 show that the amount of 3-seeker bands increased over time, while fully isolated and $2 + 1$ decreased.

In all cases, gameplay condition had no significant impact on cooperative goal collection (Table IX: A.3., B.3.) or banding (Table IX: B.5.).

7.2.2. Emergent Role Strategies. Players developed new roles within their teams as part of play, delegating responsibilities that were not otherwise controlled by the designed roles [Toups et al. 2009]. Roles emerged during the reflective periods between games as players sought to deal with the scarcity of radio communication. One strategy, employed by A/4 and discussed (but not implemented) by A/2, was that teams would select a seeker who would perform all communication for the seekers on the team. Another role, developed independently in A/5, A/6, and A/8, was to have a seeker leader: the other two seekers would attempt to follow the leader, while providing information. Some Study B participants took a similar strategy and developed "task forces," restricting who within the team could use the radio [Toups et al. 2011]. It should be noted that the students intentionally invoked the term "task force," which refers to a configuration of resources in the Incident Command System [U.S. Department of Homeland Security 2008].

7.2.3. Competition Motivates Improvement. TeC teams were given a team score during and after play. While we recorded the scores in Study A, we did not make them available to the players. However, the players were extremely interested in their scores and their progress over time [A/2,4,6,7,9]. Players frequently asked about their scores relative to other teams. We found that competition between teams is intense, despite the teams having no contact with each other. In Study B, we made scores publicly available. FER student participants reported a number of anecdotes of competition between teams during class periods.

7.2.4. Implicit Coordination. FER student TeC teams in Study B became more efficient communicators as they played [Toups et al. 2011]. We employed the second version of the audio coding scheme to classify utterances, using CLAPS. In this study, each game was examined by two of three researchers. Inter-rater reliability, calculated as the pairwise Pearson correlation for each code on each game, was high (mean overall 0.87). The coding scheme can be used to calculate the implicit coordination metric of anticipation ratio (AR). We calculated AR for the TeC teams in Study B from team

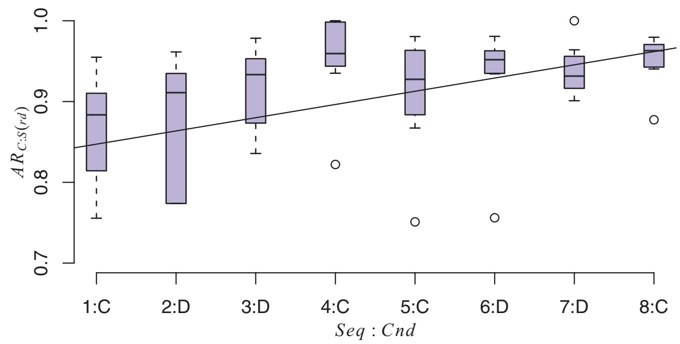

Fig. 11. Study B plot of anticipation ratio (FER students); as participants play more, they shift to implicit coordination (Table X) [Toups et al. 2011].

Table X. Changes in Communication Results for FER Students in Study B [Toups et al. 2011]

1.	$AR_{C:S(rd)}, ses = \{1, 4\} : t(12) = -2.03, p < 0.04$
2.	$AR_{C:S(rd)} \sim seq : m = 2.32, R^2 = 0.09, p < 0.03$
3.	$AR_{C:S(rd)} \sim cnd : p > 0.2$

Note: Team members communicate more efficiently over time, improving anticipation ratio; game condition does not impact communication efficiency.

Table XI. Study B Differences in Utterance Code Use Across Roles (FER Students) [Toups et al. 2011]

1.	$RQGS_p, rl = \{S, C\} : t(172) = 11.47, p < 0.001$
	$RQS_p, rl = \{S, C\} : t(213) = 7.99, p < 0.001$
	$RPS_p, rl = \{S, C\} : t(197) = 14.88, p < 0.001$
2.	$RPGS_p, rl = \{S, C\} : t(80) = -4.27, p < 0.001$
	$RQA_p, rl = \{S, C\} : t(97) = -16.29, p < 0.001$

Note: Positive *t-values* indicate that seekers favor a communication code; negative values indicate that coordinators do.

radio communication: reports from the coordinator compared with requests from the seekers. Over time, teams significantly reduced communication overhead by implicitly coordinating, as shown in Table X (B.1., B.2.) and Figure 11 [Toups et al. 2011]. As before, condition did not significantly impact communication efficiency Table X (B.3.).

7.2.5. Roles Impact Communication. In Study B, we analyzed communication composition by role. Team members employed information to which they had access, using it to aid their teammates [Toups et al. 2011]. Player role, seeker or coordinator, significantly impacted the types of utterances that players employed. Coordinators reported on the global game state and requested action (Table XI: B.1.). Seeker communications reported on the status of seekers, requested game state that was out-of-scope, and requested the status of other seekers (Table XI: B.2.).

From Study B qualitative data, we observed the emergence of hierarchy inversion in game play, mirroring FER work practice [Toups and Kerne 2007]. While seekers took orders from the coordinator and executed strategy, they also had valuable information and needed to take situated action in response to immediate stimuli. Seekers employed the information distributed to them and sometimes countermanded orders from the coordinator when the situation demanded it [B/Team Firestorm, B/5].

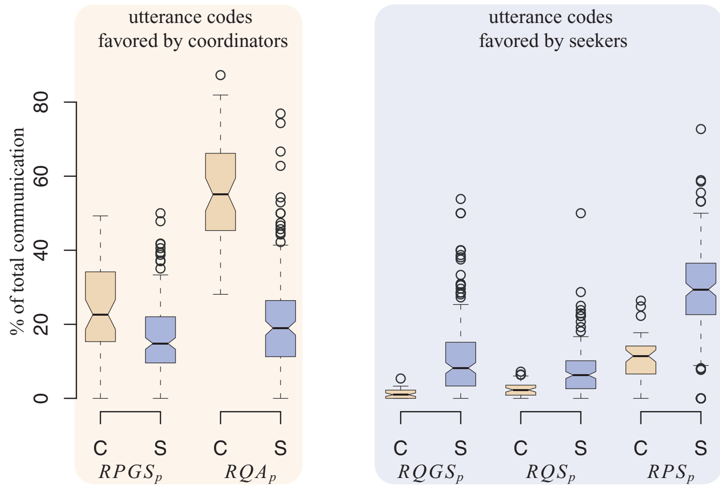

Fig. 12. Study B differences in communication across roles. Coordinators (C, orange, left in each column) prefer communication that informs about global game state and that directs seekers; seekers (S, blue, right in each column) prefer communication that informs about status and that requests information about the game state. (Table XI: B.1., B.2.). [Toups et al. 2011]

7.2.6. Identifying and Improving Communication. Study B team members identify the essential role of communication in game play, and reflect on how difficult it can be to use the radio under stress. Questionnaire responses indicate some of the early difficulties players faced. For example, in their second set of games, B/calTEXANADA attempted to restructure their team. According to the coordinator in that game, B/calTEXANADA.3, "... we tried to make the coordinator the only person to talk. This... did not work because the information needs to be two-way... " As in FER work practice, there is a need for all members of the team to communicate; sharing data from different perspectives is essential to success.

Indicating the need for cooperation, B/calTEXANADA.3 explained, "the only time teammates were hurtful... is when they got separated and went off on their own free lanc[ing]." B/calTEXANADA.3 was referencing, through the game, the dangerous practice of freelancing, where an FER operates completely independently, without considering the other teams at an incident [Toups and Kerne 2007]. Others made similar connections [B/calTEXANADA.4; B/Team Rainmen.1].

7.2.7. Applying TeC Learning to Practice. FER students in Study B used what they learned in TeC in later burn training to improve IC performance [Toups et al. 2011]. According to members of Team Firestorm, burn training ICs who had played TeC were "short, sweet, and to the point," while others were verbose and consumed radio bandwidth.

Chief Roccaforte cited TeC as teaching good communication and organizational skills. He reflected on his experiences as an educator, comparing students who had played TeC to those who had not in these and prior classes. Roccaforte noted that ICs who had played tended to create an intermediary coordination role, assigning one of the FERs as an aide. This reflects the process of expanding staff at the incident command post for a complex incident. He cited TeC players as being more articulate on the radio: they knew what to ask for and when to ask for it. As a specific example, he noted that many students, when requesting more resources, fail to indicate how many more responders are needed or where they should go; TeC players did not suffer from this problem.

In a group interview, B/Team Firestorm reported that "the rules of using a radio" were the same in TeC and in FER practice. According to participant B/Team Firestorm.4, "The key to the game was (almost) less communication, and it's the same on the fireground, too." B/calTEXANADA.3, noted that "on the fireground, there's only one radio frequency, so you have to really... key in on when they're talking to you... it really helped being able to listen for that." Another player noted the following.

> "It's the learning of communication... it's blanketed, it is not just with the game or with the fire service, once you learn how to communicate with a team, it just comes natural to start communicating like that. [B/calTEXANADA.4[9]] [Toups et al. 2011]"

7.2.8. Fulfilling the Need for Team Coordination Education with TeC. The panelists in Study C unanimously identified a need for team coordination education in disaster management. C/panel.3 and C/panel.4 specifically identified communication as the primary failure in the USA and the EU, mostly due to lack of training. We were told that it is difficult to be the "eyes of the IC" if you do not have practice carefully selecting, synthesizing, and communicating information [C/panel.1]. In many cases, we were told, responders do not understand what the IC needs from them [C/panel.3]. This perspective on the role of information in disaster response echoes the description we found in our prior work interviewing expert FERs [Toups and Kerne 2007].

According to C/panel.2, the technology for disaster communication is no longer the principal barrier to response; rather, social skills are lacking: responders do not know how to communicate effectively. The group cited a lack of training, specifically training in which participants communicate under stress. While incident command exercises, such as annual "tabletop" incident think tanks, may cause participants to work together, these exercises do not induce stress [C/panel.3]. A similar theme arose with Chief Roccaforte: classroom exercises do not produce stress and are thus ineffective at creating the kinds of information distribution demands that a team needs to experience to become effective at team coordination practice. TeC, we were told, does exactly this.

7.2.9. Experience of TeC. Based on questionnaire responses from Study C pilot participants and observations of their team reflection periods, the group of professional, expert responders found TeC to be a worthwhile team experience. They were eager to see the game deployed as part of a curriculum for emergency response.

Interestingly, C/2.4's game experience echoed C/panel.3's comment on experiences with failed communication, "Communications can be unique to each individual; the message transmitted is not necessarily the message received." When asked how the gameplay related back to practice, C/2.4 noted "This game requires teamwork and reliance upon others." During the post interview, C/panel.1 compared the game to a recent training exercise, observing the following.

> "What kept going through my mind on this was when we... [ran this group[10]]... through last week in the cottage,[11] in the dark, in the smoke, and all I could hear was... [C/panel.4]... saying "Talk! Talk! Communicate! Communicate! Communicate! Communicate! Where are you? Where's your team?" literally. But that's what [TeC] is!"

8. ANALYSIS AND FINDINGS: HYPOTHESIS VALIDATION

In this section, we synthesize the results to apply them to our principal hypothesis: crisis responders will experience zero-fidelity simulation as effective simulation of team

[9]B/calTEXANADA.4 is an outlier among the students (Table V), with over 10 years experience in military teamwork.
[10]Name withheld for confidentiality.
[11]One of TEEX DPR's training prop buildings.

coordination. To build this argument, we first show that participants engage with and improve team coordination skills. We take team coordination to be a combination of successful, cooperative action and efficient communication. To connect the zero-fidelity simulation to practice, we show how TeC communication and activity fundamentally resembles that of crisis response teams. We depict participants' reflections on the need for effective team coordination in TeC.

8.1. Improving Cooperative Task Completion

Participants in Studies A and B improved at difficult, cooperative tasks, quickly gathering cooperative goals while under threat (Section 7.2.1). Doing so is a combination of locating the goals in the hostile virtual environment, identifying them, and successfully gathering the team together in one place without being attacked. The cooperative task requires high interdependence, requiring sharing information across roles. Seekers attempted to band together, which is difficult due to limited scope.

The value of this kind of cooperation in team coordination derives from crisis response, where multiple teams of responders work together toward a concerted goal. Freelancing, or operating completely independently, is dangerous (Section 7.2.6, [Toups and Kerne 2007]). The fire emergency response domain, requires that responders work closely with one another NFPA respectively 2001; Toups and Kerne 2007].

8.2. Improving Communication Efficiency: Shift to Implicit Coordination

Communication overhead negatively impacts team performance, expending scarce cycles of sensing and thinking, time, and communication channel bandwidth [Entin and Serfaty 1999; MacMillan et al. 2004]. The radio's limited bandwidth creates particular challenges: not only is it inherently constrained, further, there is no feedback while communicating to indicate that teammates need to usurp the channel. Implicit coordination equals more effective team coordination.

Teams that played TeC reduced their communication overhead, operationalized through increased anticipation ratio. After playing, FER students become "short, sweet, and to the point" (Section 7.2.7). In early games, we observed several instances where players (normally coordinators) continuously communicated, preventing others from sharing valuable information. In Study C, C/2.4 noted, "When I focused on listening, not responding, I performed better," indicating that monitoring communication between others improved performance. In Study B, team anticipation ratio increased over time (Section 7.2.4). The observed improvement indicates a shift from explicit to implicit coordination [Cannon-Bowers and Salas 1998; Entin and Serfaty 1999]. As expected, in all studies, participants' engagement in team reflection sessions [Schön 1984; Gurtner et al. 2007] supported them in developing new strategies and improving team skills.

According to FER students and their instructor in Study B, implicit coordination carried over to burn training (Section 7.2.7). Participants reported that during burn training, people who had played the game were more efficient in their communication and were able to coordinate more effectively. Chief Roccaforte indicated that players were more "at ease" during intense burn sessions. This suggests that game players learned to restore learned behaviors of communication and stress management in an alternative environment, remixing and repurposing them.

8.3. Multiway Communication: Like Crisis Response

Distributed cognition across roles and vantages characterizes crisis response. The TeC game design abstracts these roles and vantages through information distribution to achieve a high level of multiway communication. In Study B, players made use of their unique perspectives on the virtual environment (Section 7.2.5). Players took advantage of the information they were given to improve team performance. In the interface, we made some information invisible, forcing players to rely on one another. The result was multiway communication derived from emergency response.

8.4. Zero-Fidelity Simulation Recognized as Emergency Response Simulation

FER students, Chief Roccaforte, and DPR experts experienced the game as a simulation of emergency response work practice. TeC engages players in stress and requires them to communicate and depend on each other. It provides an opportunity to learn the flexibility of the emergency response hierarchy. This exposure to the abstracted distributed cognition environment of the simulation promotes learning a set of behavioral skills, that, as in Schechner's [1985] film-strip-like segments of ritual, can later be restored in practice, as sequences of action.

A common theme from DPR personnel and Chief Roccaforte was the need for educational environments in which participants communicate under stress. Classroom and tabletop exercises without consequences do not create experiences in which participants practice necessary skills. Participants do not experience them as relevant simulations. At the other end of the spectrum, the expensive, high-fidelity simulation of burn training exercises provides stress, but limited attention to team coordination education. Participants learn a suite of interrelated skills, but do not focus on effective team distributed cognition.

In contrast to low-fidelity classroom exercises, we see that TeC players did experience stress. They reacted to the game with excitement; they got upset when they lost; elated when they won. The zero-fidelity simulation goes beyond the high-fidelity burn training exercises in its focus on team coordination; study participants and Chief Roccaforte identified the need to communicate effectively in play.

We observed transfer from the game into real-life, supporting our hypothesis that TeC is a simulation. The FER students reported on the value of the simulation and saw it boost their performance in burn training (Section 7.2.7). Chief Roccaforte identified TeC players as more effective communicators. When they were ICs, they employed organizational strategies to better track their firefighters.

Study A and B participants developed new roles within their team to delegate responsibility (Section 7.2.2). These emergent, informal roles within the team are important components of crisis response [U.S. Dept. Homeland Security 2008]. Chief Roccaforte observed that these emergent roles carried over to burn training: ICs who played TeC effectively delegated coordination responsibility to other FERs. Further evidence came from FER students who cited communication breakdowns as the main source of frustration and failure in play; these comments directly echoed our expert panel, who identified communication failure as the worst problem in crisis response. We see restored behavior at work: participants developed new roles in game play and carried them into FER practice. Flexible delegation of responsibility is frequently required in crisis response.

9. DISCUSSION: IMPLICATIONS FOR DESIGN

We derive implications for the process of designing zero-fidelity simulations. We begin with the principle of abstracting from practice, addressing how to let go of the concrete environment to focus on human-human interaction and information transformation; simulating the process of distributed cognition, without the concrete environment. We then identify methods for deriving information distribution from practice and connecting it to performance and using game rules to constrain action and provoke learning.

9.1. Abstracting from Practice

The paradigm of zero-fidelity simulation derives from human- and information-centered components of practice. Abstraction of human tasks is a primary design principle of zero-fidelity simulation. This is contrary to the design of mimetic simulations in which faithful recreation of the concrete world is central. Unlike traditional simulations, in which the goal is to reproduce the real-world environment at a high level of detail, zero-fidelity simulations use abstraction of reality as a guiding design principle. In this section, we look at how TeC employs abstractions derived from the target domain and motivates their transformations. Abstraction requires an initial grounding in practice.

9.1.1. Grounding in Practice. Zero-fidelity simulation designers must begin by deeply examining practice, and engage in constant comparison throughout iterative design processes. Derivation from practice involves evaluating what must be practiced unchanged, what can be transformed, and what characteristics can be eliminated from the source domain. What is the fundamental target task? What aspects of the environment are not essential to performing it? What components can be transformed without losing their essential natures? Deep knowledge not only of the domain, but also of educational goals, are necessary to answer these questions.

Responders gather, synthesize, filter, and transform information from diverse perspectives in dynamically changing, life-threatening circumstances. To teach team coordination, we see no need to recreate fire and smoke. The need to limit the visibility of information components and create real-time stress is essential. In the case of using the half-duplex radio, the quirks of its operation are relevant. This communication modality's half-duplex nature, the fact that two people hitting PTT at the same time results in squelch, is valuable to simulate because it functions as a limiting factor in communication, and so in team coordination. Further, PTT+squelch simulation provokes participants to be sensitive to each other's needs to use the channel.

9.1.2. Provoke Learning with Constraints. The radio and stress constrain players' actions and provoke learning. Players need to communicate with each other to synchronize remote collaboration. By remote, we do not just mean physically in the real world, but also in the virtual. Limited remote communication bandwidth constrains [Norman 2002] players, so that participants are forced to be mindful about what information they share and when. As we learned from FER practice, workers must be concise when using the radio. TeC is a success because playing resulted in students learning to be "short, sweet, and to the point" (B/Team Firestorm.1). We saw that effective use of the radio was learned playing TeC, then recalled, as restored behavior, on the fireground in burn training.

Real-time stress is an essential component across crisis response and so in its zero-fidelity simulation. Game play is exciting for players, and experienced as stressful. Panel participants and Chief Roccaforte identified the need for meaningful stress in communication and coordination education. Games create meaningful play by constraining action through rules [Salen and Zimmerman 2004b]. By constructing real-time constrained environments, using game rules, designers can inflict the stress critical to simulating the human-centered aspects of crisis response practice. The present research shows the value of zero-fidelity simulation as a tool for inflicting stress during education. Simulation of the concrete aspects of the source environment is not necessary. Participants in Study B even began to relate to the threats in TeC as fire, despite the clear, purposeful difference in behavior (B/5). This agains shows how participants can experience zero-fidelity as a simulation of their particular work practice.

9.2. Information Distribution: How-To

Many disasters are too complex and large-scale for a single person or even a single team to comprehend. The nature of crisis response demands that coordinators make top-down plans about strategy. In the field, responders take situated action to put those strategies into play, based on local, observed information and remote, communicated information.

We first identified information distribution as an essential component of emergency response work practice by observing FERs [Toups and Kerne 2007].[12] Through the iterative design and evaluation of TeC [Toups et al. 2009, 2009a, 2011], including engagement with the expert TEEX DPR personnel, the importance of information distribution to communication in team contexts grows even clearer. Disaster response team members operate with different perspectives about which they must communicate to aid each other in building shared mental models and developing situation awareness.

Information distribution designers must take into account the speed at which information changes. Very fast information should be directly accessible to players so as not to disrupt action-outcome sequences and eliminate meaningful play [Salen and Zimmerman 2004b]. Fast, unavailable information can have the deleterious effect of requiring micro-management [Toups and Kerne 2007], making players mutually dependent for their immediate reactions to their environment, instead of for formulating strategic responses. In designing the TeC game to be stimulating and to eliminate the experience of random outcomes, we made the most rapidly changing information immediately accessible. This does not eliminate the need to discuss it with teammates, but removes the chance that players will "die" without warning. The resulting principle is to blend making predictable and making invisible to provoke participants to collaborate to form strategy, not to function physically.

This section continues by developing the importance of information distribution in team coordination, the role of predictability, and the need for cross-training when employing information distribution. We show how predictability and cross-training contribute to shared mental models and situation awareness, and develop mechanisms for deriving participants' interdependence.

9.2.1. Information Distribution as the basis of Team Coordination. FERs leverage different perspectives. Each deployed unit has valuable information that needs to be shared with others, especially the IC. The IC needs to communicate strategy, as well as her global perspective.

In TeC 2.0 with FER students, information distribution impacted communication composition. The roles of seeker and coordinator demanded different communication styles. Each role required information from the others to succeed. Players leveraged the information available to them using it to aid their team. What's more, team members demonstrated knowledge of what other players could see, indicating the use of shared mental models and situation awareness. Shared mental models and situation awareness support teams in effective crisis response.

Our panel and DPR pilot deployment provided useful insight into the role and value of information distribution. C/panel.1 echoed our experiences with the FERs, describing how the IC is located remotely and needs responders to be his/her eyes on the scene. He further explained that the process of selecting and communicating information is difficult and largely untrained. C/panel.3 described a need for education to support responders in learning what information to provide, and when; he explained that rarely do responders know what is needed by other team members, but they need to communicate anyway. In playing TeC, C/2.2 learned that "My teammates' feedback was as important to me as the info[rmation] I could provide."

[12]Originally, we referred to this as information *differential*, but shifted the term to emphasize the operationalization of distributed cognition in the form of components.

9.2.2. Enable Cross-Training in Education. We developed a cross-training tutorial in TeC, based on FER education practice. In order for players to make use of information distribution, they need to be aware that it is in play. In early prototype games (Table I), players assumed that others could see what they did. There was a need to develop information distribution education. The cross-training tutorial prepares players not only to be ready to take on one role, but further, to develop shared mental models of what the other role players simultaneously experience. This aids them in communicating with one another effectively. Players must be cross-trained so they mutually understand how information is distributed among them.

9.2.3. Support Situation Awareness. Making predictable contributes to shared mental models [Gentner and Stevens 1983], and thus, to situation awareness [Endsley 2000]. At their core, situation awareness and mental models give responders the ability to plan ahead based on the trajectory of the environment. The cross-training of the TeC tutorial informs players about the experiences of their teammates, so they can form mental models later, when they are separated. When communicated and/or overheard, such mental models become shared, supporting the team in reducing their communication overhead by predicting. This enables players to mentally simulate the future and make meaningful choices [Salen and Zimmerman 2004b] about how to act.

9.2.4. Derive Interdependence. The roles of teams in crisis impact what data they gather and how it is used. Team members frequently need to take action based on information gathered by others. The key to information distribution is deriving this interdependence among teams and/or team members. TeC develops several mechanisms. Successfully collecting a cooperative goal may entail the coordinator identifying a region with the goal in it while monitoring the status of threats in that area. Seekers then must travel to the area and stay together and safe while locating the goal. The coordinator may help to keep seekers mindful of threats, but cannot see the walls that seekers may need to maneuver around. Seekers must communicate to synchronize quickly, collecting a found goal while avoiding threats. When a seeker is attacked, the coordinator may need to guide her back to safety. In deriving interdependence, actions to be undertaken in the simulation must rely on information from other participants.

10. CONCLUSION

We eschew the race to build the most realistic, highest-fidelity simulations. Not only do we find that zero-fidelity simulation is effective in the intense distributed cognition context of disaster response, but also that disaster responders from multiple disciplines experience the TeC game as a simulation that engages team coordination skills. They clearly note the need to cooperate and communicate efficiently while playing. Crisis responders learn to become more efficient and discover the problems inherent in crisis response communication.

We resituate the distributed cognition processes of crisis responders into a game based not on concrete fire or smoke, but rather on abstract game play derived from human-centered components of practice. A primary set of decisions in the game, the core mechanism, centers around, which information to share with teammates, and how. The design of information access is driven by the goal of stimulating multiway communication like crisis response. The core components, taken together, are cooperative, requiring that players carefully synchronize their actions, or fail. The threat of failure, and its opposite, a high score motivates players, providing meaningful stress and simulating crisis. By making success hinge on real-time communication, collaborative decision making, and interdependent action, TeC inflicts high levels of stress, addressing a vital need in crisis response education.

Previous classroom exercises have not simulated team coordination. The practice of composing a problem on a board or tabletop, and asking an incident coordination team to quickly reflect on it and solve it, or even communicating with other students over a radio to accomplish a cooperative task, are convenient rhetorical exercises, but lack essential stress. They do not engage players in the kind of coordination that they will experience in the field and lack direct consequences for action. Unfortunately, this is the extant state of previous team coordination education.

The TeC zero-fidelity simulation game demonstrates evidence of improving team coordination capabilities of responders. We show that participants engage with the information to which they have access and employ it in ways that substantively match crisis response practice. Other essential information, held by teammates, must be acquired by selecting an appropriate communication modality: face-to-face or radio. Importantly, participants identify the value of the simulation: they see the need to communicate and they improve, they identify the learning value of TeC, they employ what they learn in practice.

10.1. Zero-Fidelity Hypothesis

When we discuss fidelity, we refer to the way a simulation mimics the physical, functional, and psychological characteristics of its target environment [Beaubien and Parker 2004; Kozlowski and DeShon 2004; Rehmann et al. 1995]. Low-fidelity simulations, at a minimum, seek to capture the psychological aspects of a task; their goal is still to make participants believe they are acting out practice. Our approach goes beyond even low-fidelity, in that we abstract out all of these concrete components, even the psychological: participants are not intended to believe that they are performing their real-world tasks. We retain available communication modalities because they possess characteristics and challenges that participants must comprehend and overcome, and moreover, because communication is essential to team coordination.

Our principal hypothesis is that crisis responders will experience zero-fidelity simulation as effective simulation of team coordination. Earlier high-fidelity approaches have been based on the assumption that participants will experience simulation of the environment, and that, like reality, the simulation will be effective. These simulations focus on concrete mimesis, expending resources to accurately capture as much of the real world as possible. Such simulations may produce visceral results without directly addressing team coordination. We have demonstrated evidence for the two components of our hypothesis: that participants will experience zero-fidelity as simulation, and that they will learn to coordinate through play.

TeC is designed from practice to engage the same human-centered, human-human, and human-information processes that FERs and other crisis responders experience. We work to improve team coordination ability. We further decompose team coordination into successful completion of cooperative tasks and increased efficiency in communication. We observed both through quantitative measures. Players become adept at completing cooperative goal collection in spite of sparse information and threats, and they do so faster. Players learn to reduce the amount of communication that does not support the team. We measure this through a novel coding scheme derived from work practice. Participants apply what they learn to their work; on the fire ground, they restore behaviors learned from game play.

To validate the function of TeC as a simulation, we see that participants identify the learning goals of play. They concern themselves with communication within a team. They cite breakdowns in play that result from team members not meeting their information needs. We observe emergent behaviors across studies. These behaviors, as articulated by Chief Roccaforte's observation, are components of effective and flexible team coordination. The DPR panel of experts also experienced TeC as simulation.

They advocate the widespread deployment of zero-fidelity simulation to teach team coordination for crisis response. We observe that behaviors learned in game play are restored in contexts of response practice.

10.2. Transferability Hypothesis

Even though it was derived from fire emergency response practice, because TeC abstracts the concrete to address team communication and cooperation, we hypothesize that it will prove valuable in other domains. The next step, for example, into crisis response in general, is supported by the data.

> "In almost all emergency response applications, there are some common threads. . . . most of the time, time is an issue; so efficiency in communications is really important. Another thing that frequently happens is that you don't know very well the people that you're having to work very closely with. . . in a very stressful situation. . . The more efficient we can make them is a big win, and so by helping them to communicate better with each other in a stressful short-fuse situation is really critical (C/panel.2)."

We see that a diverse group of crisis responders find TeC to be a valuable simulation of team coordination in emergency response. In moving forward deploying TeC in DPR curricula, we will gather further data to support this hypothesis. We hypothesize that it is possible to abstract even more, that the need for implicit coordination in teams does not stop with crisis response. Teams of programmers, for example, who use different communication modalities (face-to-face, telephone, chat, email), face similar problems of integrating distributed information. We will investigate how suitable the present game is for teaching team coordination in alternate contexts, and also how such situated contexts can inform the design of new information distribution game mechanics.

10.3. Summary

The present research has shown how a zero-fidelity approach based on work practice led to the design of efficacious team coordination education for crisis responders. There is no need for glitzy high-fidelity, instead, a simple set of laptop computers, game software, communication equipment, and a physical space arrangement that distributes players is effective. The human-centered TeC design focuses on the human-human interaction and the need to gather, integrate, and communicate information within a team. Our panel of experts informs us that the TeC game is the most direct simulation of team coordination they have ever experienced, and that they expect it to play a vital role in improving the efficacy and safety of future crisis response teams. They are backing this us up with a mandate to deeply integrate zero-fidelity simulation into the curricula of TEEX Disaster Preparedness and Response. One planned use case is to help previously unfamiliar responders quickly gathered to face a large scale crisis learn to work with each other. We are committed to working with DPR to realize this potential for zero-fidelity simulation to beneficially transform crisis response.

ACKNOWLEDGMENTS

Special thanks to Cary Roccaforte and the instructors at TEEX for supporting this research.

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Received March 2011; revised July 2011; accepted September 2011