Zero-Fidelity Simulation of Fire Emergency Response: Improving Team Coordination Learning

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ABSTRACT
Fire emergency responders rely on team coordination to survive and succeed in high-stress environments, but traditional education does not directly teach these essential skills. Prior simulations seek the highest possible fidelity, employing resources to capture concrete characteristics of operating environments. We take a different tack, hypothesizing that a *zero*-fidelity approach, focusing on human-centered aspects of work practice, will improve team coordination learning. Such an approach promotes simulation focus by developing an *alternative environment* that stimulates participants to *engage in distributed cognition*. The costs of simulation development are reduced.

To supplement preparation for burn training exercises, 28 fire emergency response students played the *Teaching Team Coordination game* (T^2eC), a zero-fidelity simulation of the distributed cognition of fire emergency response work practice. To test our hypothesis, we develop quantitative evaluation methods for impact on team coordination learning through measures of communication efficiency and cooperative activity. Results show that participants improve cooperation, become more efficient communicators, differentiate team roles through communication, and leverage multiple communication modalities. Given the context of the study amidst the educational process, qualitative data from the students and their expert instructor supports the ecological validity of the contribution of the T^2eC zero-fidelity simulation to fire emergency response education.

Author Keywords
Zero-fidelity simulation, distributed cognition, implicit coordination, education, games, emergency response

ACM Classification Keywords
H.5.3 Information Interfaces: Group and Organization Interfaces—*Computer Supported Cooperative* [*Play & Learning*]

General Terms
Experimentation, Human Factors

INTRODUCTION
For the sake of argument and as an antidote to the fever for glitzy, high-fidelity sweeping the simulation field, we introduce a new *zero*-fidelity approach to simulating fire emergency response to teach team coordination. Prior approaches to simulation have assumed that increasing fidelity means better simulation [1]. The result is increasingly immersive, but literal, representations. They have addressed the physical conditions of fire emergency response, but not how team members work together. Team coordination saves lives in emergency response scenarios, but traditional education techniques direct limited resources at urgent needs, such as the basics of firefighting. The present research reduces the cost of simulation, with the potential to increase the scope of educational applicability, by focusing on human-centered characteristics of situated distributed and team cognition.

Our long-term goal is to develop human-centered education systems derived from work practice that are transferable across domains. The present research establishes zero-fidelity simulation as an effective method for teaching team coordination to fire emergency responders (FERs) without diminishing the value of existing simulations. Prior work developed design implications to teach team coordination from fire emergency response work practice [28] and established design implications for non-mimetic simulation by testing with non-FERs [30].

Our *principal hypothesis* is that by playing zero-fidelity simulation games, fire emergency responders will learn team coordination skills. We develop measures of team coordination based on communication efficiency and cooperative effectiveness. Communication efficiency is evaluated through a new speech/action coding scheme that quantifies the content of team communication and in-game action. Cooperative effectiveness is calculated directly from game log data.

We present an ecologically valid user study in which students at the Texas Engineering Extension Service's (TEEX) Emergency Services Training Institute Firefighter Training Academy (FTA) play the Teaching Team Coordination Game (T^2eC, pronounced "tech"). Students find the game motivating. They improve at cooperative tasks and become more efficient communicators, indicating improvement in their team coordination skills. The study validates our design implications for teaching team coordination and designing *non-mimetic* simulations, which we now call *zero-fidelity*, situating the work in the simulation literature. Depending on players' roles in T^2eC, they communicate differently. Participants employ multimodal communication to efficiently work together. They and their instructor articulate how the simulation contributes to their performance on the fireground.

Throughout this paper, we bring in the voice of expert and practitioner, Fire Chief Cary Roccaforte, Program Coordinator of the FTA. Roccaforte has spent over 20 years as a program coordinator, instructor, and/or training officer; he has 12 years of experience as a firefighter prior to that. Roccaforte works closely with his students; throughout the user studies, he provided his own observations and insights into the impact of the game on their education.

BACKGROUND: TEAM COORDINATION

The present research develops educational systems for team coordination from fire emergency response work practice. Distributed cognition forms the basis for an information-centric understanding of teams, while team cognition contributes understanding of how team members work together and share information. We provide an overview of team coordination in fire emergency response work practice to understand the roles of workers and how they communicate.

A central construct in both distributed and team cognition is the *mental model*. Mental models are the way in which individuals maintain and manipulate a representation of the functioning of an object or process in their heads [8]. The model is a form of internal simulation based on experience, enabling high-level problem solving and prediction.

Distributed Cognition

Distributed cognition holistically analyzes working environments, describing cognitive processes spread among mutual interactions of humans and artifacts over time [12]. Task-relevant information is stored in multiple forms: mental models, embedded in the environment, and derived via formulae. Those working in a distributed cognition environment move components from an original to other, workable forms, applying new forms to the situation. Workable forms are communicated through a variety of media, enabling cooperation.

Team Cognition

Team cognition theory posits implicit coordination as an efficient mode for teams. In an *explicit coordination* mode, team members communicate frequently. Wide-area communication bandwidth is limited by single-channel, half-duplex[1] radios. Further, those receiving communication expend time and cognitive effort to listen and understand. The bandwidth, cognition, and time costs of communicating are *overhead* [17, 25]. High-performance teams reduce communication overhead through *implicit coordination*: they speak less and act more [5]. Implicitly coordinating team members *share* mental models, enabling them to predict and account for each other's work [2, 19]. As team members maintain *situation awareness*, they monitor the environment and predict its future states [4]. Shared mental models combine with situation awareness, supporting implicit coordination. The present research develops the implicit coordination skills of FERs.

Emergency Response Work Practice

Fire emergency response work practice involves intense team coordination in a distributed cognition environment. It is carried out by companies (teams) of *firefighters* directed by an *incident commander* (IC) [13, 15, 21, 28]; collectively, these are FERs. Companies operate at an *incident*, where they gather, integrate, and share information to rescue victims and fight fire. The IC observes from a distance, and combines information from artifacts and deployed responders to direct the action. The communicative role of IC is an instance of situated distributed cognition.

Communication is essential in emergency response. FERs prefer face-to-face communication because it is fast and easily understood [28]. However, half-duplex radios reach all FERs at an incident. Radio is problematic because it is slow and because crosstalk, a situation in which two radio operators transmit simultaneously, results in information loss.

ZERO-FIDELITY SIMULATION

We develop and validate a new theory of *zero-fidelity simulation*: learning environments that emphasize distributed cognition instead of mimicking concrete characteristics [30]. Prior simulations aspire to *high-fidelity*, capturing as much of a real-life environment as possible. There is a widely held belief that higher fidelity automatically translates to more effective learning [1, 11, 27]. Low-fidelity simulations have been shown to be effective for educating [1], but capture aspects of the real-world working environment. Some lower-fidelity simulations have addressed coordination of resources among team members without addressing the human-centered aspects of work practice [9, 14, 31]. Others take a high-fidelity approach to team education [26].

We take an alternative tack. Gagné suggests that training devices might be constructed to teach specific skills *without* a complete simulation [7]. According to Hays and Singer [11], much simulation research ignores these findings. Lave and Wenger [16] suggest that learning must be situated socially and operationally to be effective, but Reder and Klatzky [22] refute this claim in studying skill transfer. Through an extensive review of existing literature, they conclude that fully situated learning is frequently *un*necessary. They note, however, that situated learning *is* valuable in social environments. The present research develops a social context in which participants learn team coordination by engaging in distributed cognition like that of the source environment.

The present zero-fidelity simulation addresses not the concrete environment, but, instead, distributed cognition characteristics, abstracting alternative means by which participants can learn to perform tasks. Learned abilities are applied back in the target domain; prior work [7, 22] and performance studies' concept of restored behavior [24] support that this transfer of skills will be successful.

We discussed the need for zero-fidelity simulation education during a think tank with four response experts with the TEEX Urban Search and Rescue (US&R). Combined, these professionals possess over 100 years of experience in disaster response and recovery in the USA and EU. The experts were involved in the response to Hurricanes Katrina (2005), Rita (2005), and Ike (2008); the Oklahoma City Bombing (1995) and 9/11 (2001); all of the Provisional Irish Republican Army bombings in London, and the 7/7 bombings (2005). Two of the experts had played T^2eC; they cited its value for US&R operatives. The group mandated that zero-fidelity simulation's focus on how people communicate and cooperate under stress provides urgently needed educational experience, because the current practice in training fails to directly address team coordination. Meanwhile, they informed us, breakdowns in communication, not in equipment or people's understanding of how it works, are the primary source of failures in emergency response. The US&R experts indicated

[1] A *half-duplex* device switches between send or receive mode, but cannot do both simultaneously.

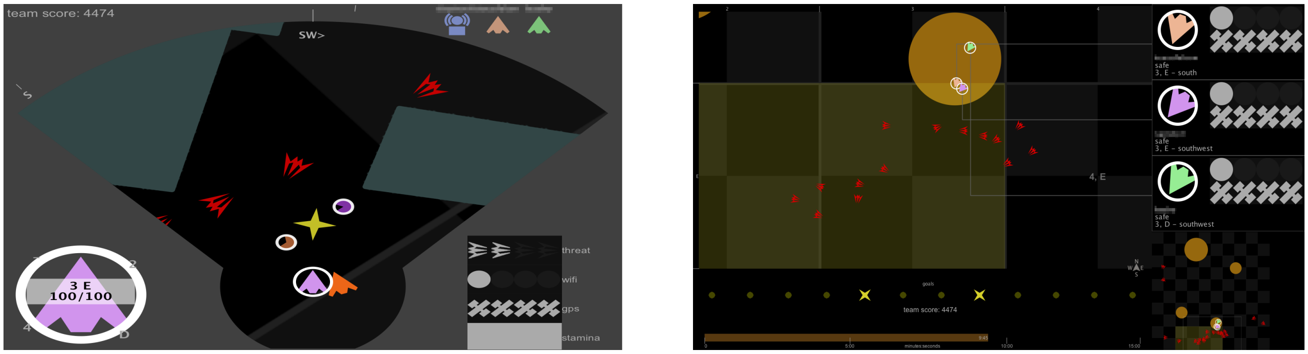


Figure 1. Screenshots from the T^{2}eC zero-fidelity simulation (Team 5, game 8, 5'15"). Purple and orange seekers collect a cooperative goal from a base. **Seeker View (left):** The white shield around the purple avatar indicates safe status; purple cannot detect information about orange's status. Threats are nearby. **Coordinator View (right):** The main view shows the terrain with all entities; highlighted regions contain goals. Walls (visible to seekers) cannot be seen. The right column shows the status of each seeker; a mini-map is on bottom. Below the main view is the goal list (two are un-collected) and remaining time.

that T^{2}eC fulfills a strategic hole in education that existing, expensive simulations do not, by capturing the human-centered components of practice.

Both the think tank and Chief Roccaforte discussed use of educational exercises to teach teams to cooperate. The think tank described tabletop exercises for command personnel, but indicated that the lack of stress limited their value. Similarly, Roccaforte described classroom exercises in which students practice using the radio; his concerns echoed those of the think tank. These low-fidelity simulations of team cooperation are ineffective for real world practice.

Effective zero-fidelity simulations are grounded in practice: practiced skills are based on those in real-life work. Practical grounding is essential for learning skills [22]. Zero-fidelity simulations take a place side-by-side with other forms of simulation training, such as the high-fidelity burn training simulations used in the FTA, fulfilling a complementary role.

Advantages of Zero-Fidelity Simulation

Zero-fidelity simulations have two main advantages over high-fidelity simulations: economy and focus. Zero-fidelity simulations are *economical* in that they are simpler to produce by abstracting out details that would be expensive to replicate. The present research investigates *focus* by showing the effectiveness of zero-fidelity simulations for teaching the distributed cognition of team coordination. As a point of comparison, FTA students undertake *burn training*, a high-fidelity simulation of firefighting in actual burning buildings.

Zero-fidelity simulations omit actual reality for conceptual learning. Cost is a consideration in simulators that leads designers to reduce simulation fidelity [7, 11]; zero-fidelity simulations are more economical. For example, to simulate the fire emergency response environment, we would need algorithms for and visualizations of fire and smoke, and more expensive and power-hungry processors. Instead, the present research runs with minimal system requirements. The monetary costs of running T^{2}eC are negligible, while burn training costs over 125USD per student per term.

Focusing simulation resources on distributed cognition focuses learning. High-fidelity simulations capture as much as possible about working conditions. The characteristics addressed by zero-fidelity simulations are based on the educational program. In burn training, participants *might* engage in team coordination, but the focus is maneuvering in closed environments, manipulating equipment, and predicting fire. According to Roccaforte, the FTA extended burn exercises to provide an opportunity for students to practice communicating with the radio under stress. The FTA includes radio practice in the classroom, but the value is limited because there is neither stress nor consequences for failure.

Because there is a need for team coordination education, the present research targets the *distributed cognition* of work practice. Essential characteristics of the original environment must be incorporated, such as those that are not a part of the classroom radio exercises. For example, in fire emergency response, participants must make quick decisions while under stress, so this is a requirement for a zero-fidelity simulation.

Games as Zero-Fidelity Simulation

Games function as a form of simulation [3, 23] in which physical and social processes are carried out. Narayanasamy et al. [20] classify games and simulators: games are not primarily designed to teach skills and simulations are not intended to be fun. Zero-fidelity simulation games bridge the gap, teaching skills while entertaining, so that players are encouraged to learn, providing intrinsic motivation [18, 23]. Gagné suggests that metrics within training devices can encourage cooperation or competition [7], adding external motivation. Framing zero-fidelity simulation as a game encourages players to compete and cooperate with each other.

Salen and Zimmerman [23] describe games as consisting of rules and play. Rules restrict action, while play is freedom to move within the rules; the rules make play meaningful. They identify the *core mechanics* of a game as the set of rule-constrained actions that players take repeatedly to play.

TEACHING TEAM COORDINATION GAME

The present research studies our game design for teaching team coordination [29, 30]. Game mechanics in the virtual world are instantiated through *entities* that operate in *terrain*. Entities include seekers' *avatars*, *goals* that seekers collect, and *threats* that hunt avatars to prevent collecting goals.

Participant Roles

Because teams operate in distributed cognition environments, we identified the design implication of *distributing information* between team members to encourage communication

[28, 29, 30]. By apportioning parts of an emerging information puzzle to team members, they rely on one another to accomplish shared goals. *Participant roles* are the axis along which information is distributed, and each role has a different subset of game mechanics [30]. Information distribution is instantiated by only making some terrain components and entities visible in certain interfaces. In T^2eC, players on a human team take on one of two roles that are analogous to FER roles: seeker and coordinator.

Seeker players (three per team) each move an avatar in a virtual world, finding and collecting goals while avoiding threats. Seekers observe a local, high-detail perspective on the virtual world with a limited scope (Figure 1, left). The present game design differs from the design previously studied [30]: the location of threats is distributed to seekers, in addition to the coordinator; previously, only the coordinator could see threats. This change was made because information that changes quickly in a zero-fidelity simulation should be readily accessible to players, since communication is too slow to account for it. In spite of the high detail, locations where seekers are safe, *bases*, are only visible to the coordinator. Seekers are analogous to firefighters, who move through an incident to gather information and act on the environment.

The *coordinator* player (one per team) is physically isolated from the seekers and observes a limited overview of the game (Figure 1, right). The coordinator's view shows the locations of seekers' avatars and threats, as well as the general locations of goals. Some details of the virtual world can only be observed by seekers, such as walls that prevent seeker movement. The coordinator cannot directly interact with the virtual world; like an IC, she observes and communicates.

Virtual World Entities & Terrain

Seekers drive avatars in the virtual world to find and collect goals while avoiding threats. Seekers move through the terrain, circumnavigating walls and collecting and sharing information about the local environment. Threats move in the virtual world and take the seekers' avatars out of play. Once a seeker is *taken out*, reaching a *base* allows her to *come in*.

The team of T^2eC players collects goals to win the game. Goals are spread throughout the virtual world, and each goal requires one, two, or three seekers to collect. Cooperative goals are more difficult to collect than single-seeker goals, because players must coordinate action in the virtual world, including avoiding threats.

Virtual world terrain includes features that hinder or benefit seekers. Bases allow the seeker to rejoin the game after a threat attack. Walls impede movement.

Mixing Communication Modalities

Because the design implications for teaching team coordination recommend enabling players to dynamically mix communication modalities [28], T^2eC is designed to be a seamful mixed reality game. The present work, like [30], is not a mixed reality, but simulates regions in which seekers are offline. To enable mixing communication modalities, we use co-located and distributed study conditions (Figure 2).

In the *co-located condition*, seeker players sit around a table and communicate with each other face-to-face. In this condition, the coordinator is isolated and can be reached by radio.

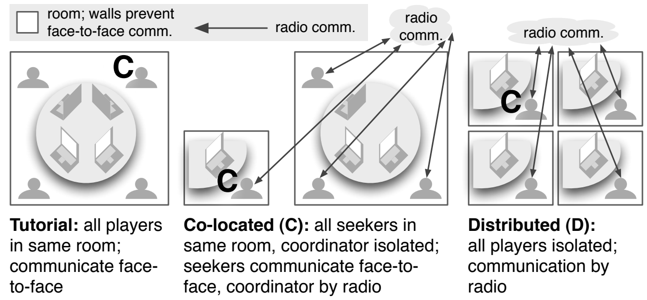


Figure 2. T^2eC study conditions. The coordinator is identified by a label "C". Walls indicate where face-to-face communication cannot be used.

In the *distributed condition*, all players are isolated and must communicate by radio. Because information is distributed among the players, they must communicate constantly to integrate and share it. *Communication is a core mechanic*.

TEAM COORDINATION MEASURES

We develop measures to detect changes in a team's coordination performance, as members combine communication and cooperative activity. A speech/action coding scheme, applied by researchers to assess player communication and game action, integrates communication with play. We combine the scheme with computed cooperation measures based on task performance data.

We apply the measures to audio recordings of players' communication, synchronized with game logs. For each player, we capture all speech from that player and all radio communication she hears. The audio record stores a synchronization track that links each moment of audio to a state in the game log. Game logs store all game state: locations and status of all entities and terrain. The logs allow researchers to play back game events and analyze player activity.

We employ the Coordinated Log + Audio Playback System (CLAPS) [10] to analyze data, observing game play while simultaneously listening to players' speech. The ability to synchronize multiple streams of data is essential, as the meaning of speech/action codes can only be disambiguated in the context of play. CLAPS re-creates a complete view of the gameplay experience, enabling researchers to discover critical incidents of effective team coordination.

Communication Performance: Speech and Action

Communication within a team offers insight into its ability to coordinate effectively [17]. To analyze team communication, we developed a protocol analysis coding scheme [6], grounded in prior findings of FERs' work practice and the team cognition literature. We classify each utterance as a particular type based on content and action taken in the game (Table 1). The result is a count of the number of times each player used a particular speech/action code in each game. In addition to recording content of communication, we record the modality the participant used and success or failure (crosstalk, radio interference).

The speech/action coding scheme is grounded in our prior work with FERs [28] and based on the established *anticipation ratio* measure of implicit coordination [5, 17]. The codes are analogs to observed FER practice, applied to the game. By observing game play, we discovered that some utterances overlapped multiple audio codes, showing especially efficient

code	AR	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."
metacommunication	–	communication about communication, including indicating a message was heard and understood and asking for clarification	"Repeat please."
metagame	–	communication about the game itself	"How do I run?"

Table 1. Speech/action coding scheme for analyzing T^{2}eC user study data. Each code is accompanied by its abbreviation, used throughout the Results and Analysis sections. The AR column indicates whether the code is a push, pull, or none when calculating anticipation ratio.

communication. For these, we used *hybrid codes* to mark a single utterance with two or more base codes.

Codes were applied by three researchers, so that each game was coded twice. Inter-rater reliability was calculated as the coder pairwise Pearson correlation coefficient. The average, for all coders on all codes was 0.87.

Data Subsets

In our analysis, we work with subsets of the data. For each of the five speech/action codes, the subscript $_p$ indicates a code utterance count is normalized against all the utterances by a *player*, measuring the *composition of a player's communication*. Player communication composition indicates how players are focusing the information they supply or request in play; it is how they are playing the game. The subscript $_t$ indicates that the code is normalized against the amount of *time* in a game. This allows measurement of the aggregate communication of teams, supporting *comparisons across teams*. The measure UT_t counts the total utterances for the team, normalized for the time in the game (Table 4). When a subset of the data comes from a single role, this is indicated with a bracketed subscript: $_{[S]}$ for seekers, $_{[C]}$ for coordinators.

Anticipation Ratio

Anticipation ratio (AR) measures communication efficiency in a range of teams; an improvement in communication efficiency indicates a shift toward implicit coordination [5, 17]. The implicit coordination mode reduces unnecessary communication overhead because team members become more effective at predicting each others' actions through shared mental models. Intuitively, what AR measures is that the less one needs to speak to get one's information needs met, the lower the load on cognition and communication channels.

AR measures the amount of information team members provide against that requested. *Pulling* information functions as a form of noise in the limited communication channel, burdening the team with cognitive load and reduced access to the communication channel. AR places value on *pushing* information out to the team. The function for computing AR is $push/(pull + push)$. 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.

Each speech/action code is classified as a push, a pull, or none of the above (Table 1). 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 4. Because hybrid codes are more efficient, only the $push$ component of each was counted (so a $pull$ component did not penalize AR); if a hybrid was multiple $push$'s, the $push$'s were counted multiple times. The higher a team's AR, the better team members are anticipating each other's information needs. An increase in AR indicates an improvement in communication efficiency and, thus, implicit coordination.

variable	description
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 $cycRem$

Table 2. Measures of team task performance.

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 3. Independent variables for teams and individual players.

variable	description
$AR_{C:S(rd)}$	anticipation ratio of coordinator reports to seeker requests over the radio ($RPGS_{t[C]} + RPS_{t[C]} + RQA_{t[C]} : RQGS_{t[S]} + RQS_{t[S]}$)
UT_t	total utterances for the team, normalized for $cycRem$ ($RQGS_t + RQS_t + RPGS_t + RPS_t + RQA_t$)

Table 4. Audio data variables building on Table 1.

Team Task Performance

We directly calculate metrics of team task performance, measuring the team's ability to efficiently complete cooperative activity in T^{2}eC. Team task performance measures are summarized on Table 2.

We calculate how many of each type of goal the seekers collect (GC_{xS}). Goals that require more seekers to cooperate ($x > 1$) are more difficult, but single-seeker goals require significant coordination. Because the game ends early when all goals are collected, the measure $cycRem$ represents time remaining; it is used to normalize other measures. We combine GC_{xS} and $cycRem$ into the unified $gamePerf$ measure.

Inspired by emergent player strategies informally observed in [30], we investigate how players band together in the virtual world. *Seeker bands* occur when one or more seekers can see each other in the virtual world. The measure $band_{xS}$ counts the amount of time x seekers were moving together in the virtual world, normalized for $cycRem$.

Burn Training Observation

Burn training exercises are qualitatively evaluated by instructors at the FTA. The exercises are commonly run with different combinations of students over two weeks. Instructors provide feedback to the students in an after-action review. For the present study, Chief Roccaforte observed the burn training exercises of participating and non-participating students, providing a qualitative account of how playing T^{2}eC impacted their performance, supporting ecological validity.

EVALUATION METHODOLOGY

The purpose of the present study is evaluate the effectiveness of T^{2}eC for teaching team coordination to FERs, so we work with students from the Emergency Services Training Institute Firefighter Training Academy (FTA). The FTA is an intense program in which students attend nine weeks of full-time (8+ hours per day) classes, then perform two weeks of burn training, followed by a week of exams. Many students hold outside employment while attending the school.

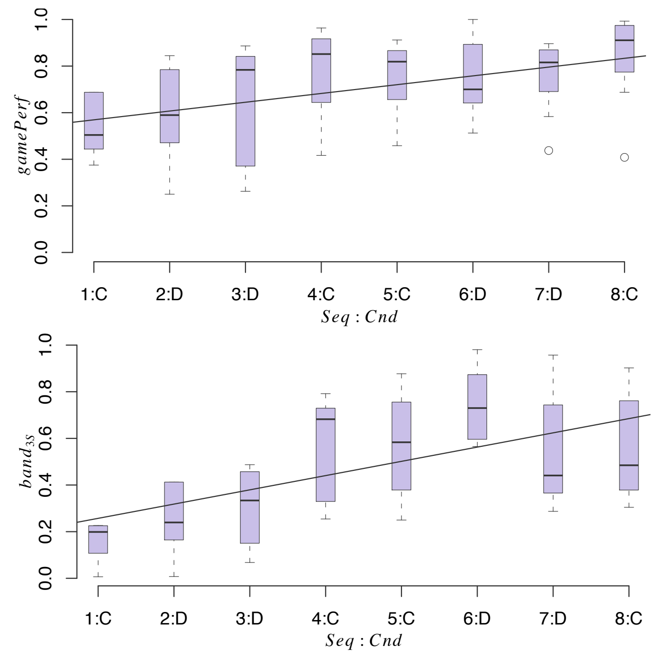
A total of 28 students participated in the user study, forming seven teams (three from spring and four from summer 2009). Studies were conducted prior to participants beginning burn training exercises. A self-report instrument indicated that the subject population was 14% female and that highest education was high-school or lower for 85%. The instrument also asked for years of experience in team-based situations; 46% had less than one year's experience and another 29% had 1–5 years experience. Team members selected pseudonyms for the study[2], and optionally created a team name. The teams that did select names were called calTEXANADA, Team Firestorm, Team Rainmen, and FoxtrotAndCo.

Experiment Design

We build on established experimental methods to observe team coordination in T^{2}eC [30], using an iterated game design. We deploy the user study after-hours with the FTA students, so they engage with it as a leisure activity outside of class. This develops ecological validity, confirmed through qualitative data. T^{2}eC supplements the course material as an enjoyable education opportunity.

Teams join for four sessions, at one-week intervals. During a session, team members play the two game conditions: co-located and distributed (Figure 2). In the first session,

[2]We refer to players by their pseudonyms unless that identifies them; otherwise, we use a code: <P-*teamNumber-playerNumber*>. We also identify team name, if any.



a.	$gamePerf \sim seq : m = 3.29, R^2 = 0.17, p < 0.005$
b.	$cycRem \sim seq : m = 6.97, R^2 = 0.07, p < 0.06$
c.	$gamePerf \sim cnd : p > 0.4$
d.	$band_{3S} \sim seq : m = 4.43, R^2 = 0.26, p < 0.001$ $band_{2S} \sim seq : m = -2.02, R^2 = 0.07, p < 0.05$ $band_{1S} \sim seq : m = -4.47, R^2 = 0.27, p < 0.001$
e.	$band_{3S} \sim cnd : p > 0.9$ $band_{2S} \sim cnd : p > 0.8$

Figure 3. Team task performance results. Teams collect goals quicker in later games (top plot) while banding together more (middle plot).

the team plays a tutorial, in which every team member acts as seeker, but simultaneously observes the coordinator's interface. The tutorial explains game play and controls and demonstrates information distribution. For the tutorial game, all players are co-located and can speak to each other face-to-face. It is followed by the two normal conditions.

Quantitative Analysis Methods

The dependent variables in the evaluation are team coordination measures. Independent variables (Table 3) are derived from the experiment and game designs: seq is index of the game sequence across sessions, measuring time; cnd is the condition for a game, either co-located $[C]$ or distributed $[D]$; rl is a player's role, either seeker $[S]$ or coordinator $[C]$.

We use several quantitative analysis methods for analyzing the resulting data. The first method is a linear model of how a 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 the fitness of the line. A positive slope indicates a direct relationship, while a negative slope indicates an inverse one. Where we call attention to an insignificant result, we omit the m and R^2 values and report p as greater-than.

The second analysis method is Welch's t test [32]. 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.

RESULTS

We report results from T²eC user studies with FER students using speech/action code and team task performance measures. Team task performance compares variables derived from game logs that describe cooperative performance. Using the speech/action coding and post-study interview data, we discover changes in player communication. We compare communication data across participant roles, noting different communication styles. Finally, we discuss the ways players use different modalities to communicate with each other.

Team Task Performance

Players improved their ability to play T²eC as a team through repeated sessions. They collected more goals in a shorter time (Figure 3, bottom, a.). Teams completed the game faster as they played more (Figure 3, bottom, b.). Game condition did not significantly impact performance (Figure 3, bottom, c.). Figure 3 (top) plots game performance over time, showing the increasing trend. *Cooperative task performance* improves.

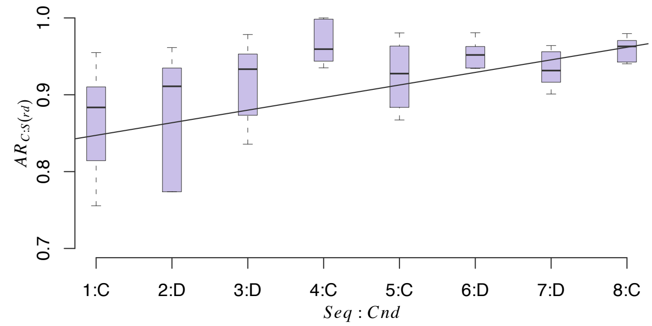
Seeker band variables indicate the percentage of time during which seekers banded together. Game sequence strongly influenced the amount of time seekers banded together (Figure 3, bottom, d.). Game condition did not strongly impact seeker band formation (Figure 3, bottom, e.). Figure 3 (middle) charts the change in $band_{3S}$ over game sequence. *Seeker banding* occurs more frequently in later games.

Improved Communication Efficiency

Analysis of the data resulting from team coordination measures shows that playing T²eC improved participants' communication efficiency. Increases in team anticipation ratios were observed. From the coded audio data, we computed $AR_{C:S(rd)}$: coordinator's pushes to seekers ($RPGS_{t[C]}$, $RPS_{t[C]}$, $RQA_{t[C]}$) against seekers' pulls over radio ($RQGS_{t[S]}$, $RQS_{t[S]}$). A one-tailed t test compared $AR_{C:S(rd)}$ for the first and last sessions, the result indicates an increase in AR (Figure 4, bottom, a.). Further analysis with a linear model revealed an overall increase in AR over repeated sessions (Figure 4, bottom, b. and top plot). Condition did not impact AR (Figure 4, bottom, c.). We observe that *anticipation ratio improves* through play.

Ecological Validity

Qualitative results establish the ecological validity of the quantitative findings. Participants completed the user study prior to beginning burn training. When subsequently interviewed, they noted that burn training ICs who played T²eC used the radio more effectively: they were "...short, sweet, and to the point" [Boomhower] over the limited radio bandwidth. This qualitative data supports the ecological validity of the findings. According to participants, engagement in zero-fidelity simulation resulted in *increased communication efficiency* in the high-fidelity burn training simulation.



a.	$AR_{C:S(rd)}, seq = \{\{1,2\},\{7,8\}\} : t(12) = -2.03, p < 0.04$
b.	$AR_{C:S(rd)} \sim seq : m = 2.32, R^2 = 0.09, p < 0.03$
c.	$AR_{C:S(rd)} \sim cnd : p > 0.2$

Figure 4. Changes in anticipation ratio (top plots 4, b.). Coordinators get better at anticipating the needs of seekers, while seekers request less. Team members communicate more efficiently over time, improving anticipation ratio; game condition does not impact communication efficiency.

Chief Roccaforte concurred, he observed an improvement in game-playing students' ability to coordinate. According to Roccaforte, students who had played demonstrated an increased confidence in their ability to direct other FERs. They were more articulate with the radio, specifying needs more clearly than other students. Further, they demonstrated a significant capacity to organize teams, instantiating an assistant role to help track deployed firefighters, improving accountability in the field.

Differences Across Roles

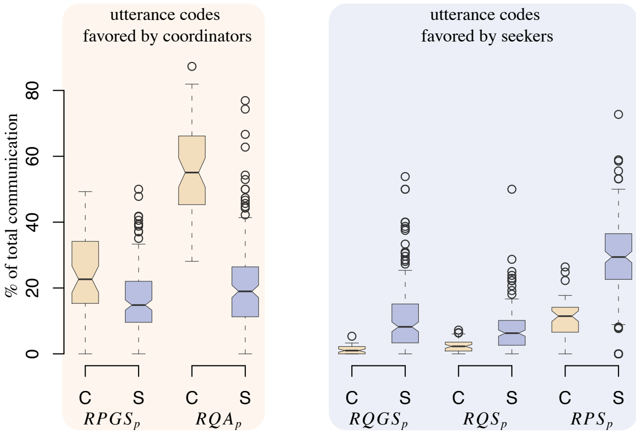
The roles players took on in game (rl) impacted the composition of their utterances to other players. A one-tailed t test was performed for each type of player communication (Table 1: $RQGS_p$, RQS_p, $RPGS_p$, RPS_p, RQA_p), comparing the composition of communication by rl. Figure 5 (top) plots the percentages, clearly showing a difference in communication types favored by roles. Seekers requested game state and status more than coordinators while reporting status more (Figure 5, bottom, a.). Coordinators reported on game state and request action more than seekers (Figure 5, bottom, b.). *Communication composition is dependent on role*.

Communication Modality Use

Condition impacted total communication by seekers; a one-tailed t test showed that *seekers* communicated more in the co-located condition ($UT_{t[S]}, cnd = \{C, D\} : t(107) = 13.05, p < 0.001$). Condition did not impact total communication by coordinators ($UT_{t[C]}, cnd = \{C, D\} : p > 0.4$). *Seekers speak more when face-to-face than by radio.*

ANALYSIS

The present research establishes the value of zero-fidelity simulation for team coordination learning. The design implications of information distribution, roles for engaging participants in alternative communicative tasks, and employing multi-modal communication are validated. In the T²eC user studies, we see the FER students improve their team coordination by shifting to implicit coordination. Players employ different communication styles when operating as coordinator or seeker. Rich, multimodal communication emerges through game play. Participants and instructors connect game play to practice, motivating ecological validity.



a. $RQGS_p, rl = \{S, C\} : t(172) = 11.47, p < 0.001$
$RQS_p, rl = \{S, C\} : t(213) = 7.99, p < 0.001$
$RPS_p, rl = \{S, C\} : t(197) = 14.88, p < 0.001$

b. $RPGS_p, rl = \{S, C\} : t(80) = -4.27, p < 0.001$
$RQA_p, rl = \{S, C\} : t(97) = -16.29, p < 0.001$

Figure 5. Impact of role on communication. Plot: Within each pair, coordinator data points are on left, seeker are on right. Each point represents one instance of a player in a game. Table: Positive *t-values* indicate that seekers favor a communication code, while negative values indicate that coordinators do.

Shift to Implicit Coordination

Through play in T^2eC, we observe an improvement in team coordination through concurrent improvement in cooperative task performance and communication efficiency.

Cooperative Task Performance

Players improve their *cooperative task performance* over time by practicing collaborative action. The design of cooperative goals in T^2eC requires that players work together to succeed [29]. The team's performance depends on seekers gathering at goal locations, while avoiding threats. Even single-seeker goals require coordination, such as scouts or decoys to distract threats. In spite of the difficulty of banding together, players succeed at collecting more goals in less time.

Seekers learn to *band together* in the virtual world and successfully collect more cooperative goals. There are two mechanisms for collecting goals: moving together or meeting up. The data indicate that seekers find it more effective to move together. According to Boomhower "[Team Firestorm]... learned pretty quick that if all three people stayed together... that was the easiest way to get it done." An alternative strategy, less often employed, was to locate a cooperative goal, then meet up. Moving together is difficult because the seeker view only shows what is ahead and not, for example, that a companion is following behind. Banding together means that seekers are frequently in more danger, as threats can attack the whole group.

Improving Anticipation Ratio

We find that team anticipation ratio improves through play. *A high AR indicates a shift to implicit coordination* [5]; team members actively share information while their own information needs are fulfilled. *The observed increase in participants' AR shows they learn to implicitly coordinate.* Teams reduced their communication overhead, increasing the amount of communication that informs and directs, rather than requests.

We find that one player strategy to improve AR is that team members respond with action, rather than communication. In connecting to practice, participants noted that it was essential to communicate less and that their communication efficiency increases. Ryan [Team Firestorm] noted that while responding to communication with action was essential, the game design allowed the coordinator to observe activity that an IC might not. This suggests an interesting new line of research, in which we manipulate information distribution to provide the coordinator with even less information.

Stepping into Game Roles

Prior work suggests that participant roles are an effective way to distribute information and build team coordination in zero-fidelity simulation [30]. In our study, *communication composition was dependent on role*, demonstrating that this mechanism of information distribution is effective in structuring team communication. Coordinators, who can only influence game play through radio communication, *direct* and *inform*. Seekers, who need information about the world outside of their scope, receive it from the coordinator. They *request* what they need to know. They supply one another and the coordinator with information about their own *status*.

In FER work practice, alternative perspectives and positions at the emergency incident enable different sets of action and communication. The IC has access to information through information artifacts; these enable tracking status of firefighters, like the coordinator's interface. Radio communication is available to both the IC and the firefighters. The IC directs the team, as the coordinator does. Firefighters, at the fireground, have direct access to the situation, like seekers. They know and communicate about the state of their environment and their bodies, like reporting game state and status.

We also see that seekers, but not coordinators, communicate more frequently in co-located games. These games offer more expressive power than distributed games because players communicate face-to-face, instead of only by radio. The coordinator, like the IC, cannot communicate face-to-face. This demonstrates *employing multi-modal communication*.

Multi-Modal Communication

We develop the design implication of mixing communication modalities in systems to teach team coordination, reflecting the FER practice of using face-to-face communication when possible and radio when necessary [28]. The present user study was configured to require radio for speaking to the coordinator, while seekers have the option to speak face-to-face when co-located. Throughout the user study, we observe participants using both face-to-face and radio communication.

When T^2eC is played co-located, seekers have the ability to speak to each other face-to-face. We observe them taking advantage of the communication modality this condition affords them. In co-located games, seekers use face-to-face communication because it is more effective and convenient, but contact the coordinator when necessary.

Multimodal communication is an instance of distributed cognition. Participants select the form of communication that best fits the situated affordances and constraints. In emergency response practice, this is critical. Participants must consider how to best share information while minding the limitations of the communication channel. Participants suggested a future line of research might go so far as to simulate even more entities vying for the limited bandwidth. Real-time stress plays an essential role in the decision-making process; information must always be shared quickly because the situation changes rapidly.

Value to Practice

Based on qualitative data gathered from interviews with FER T^2eC players and Roccaforte, we found that students connect T^2eC play with practice. Participants reported that "the rules of using a radio" were the same in T^2eC and in FER practice [Jack, Team Firestorm]. According to participant Ryan [Team Firestorm], "The key to the game was (almost) less communication, and it's the same on the fireground, too." <P-1-3> [calTEXANADA] 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 that:

> It's the learning of communication... its 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. [Wilson0803[3], calTEXANADA]

The T^2eC study served to reinforce team learning in the FTA. During a reflective session, calTEXANADA appointed one of their seekers to "task force leader"[4]. The leader would direct the other two seekers on the team during the next game. Chief Roccaforte overheard the exchange; he was surprised that the team successfully applied course knowledge to organize themselves.

CONCLUSION

The present research supports the method of zero-fidelity simulation learning by evaluating the Teaching Team Coordination Game with fire emergency response students. The novel method of zero-fidelity simulation eschews the popular method of capturing the physical environment with the highest possible fidelity. While such simulations have value, the zero-fidelity approach *reduces the cost and increases the focus of education*, avoiding the need for complex algorithms and hardware to model concrete reality. Instead of capturing *all* of the target environment directly, zero-fidelity simulation design begins with understanding and re-situating distributed cognition task components in an alternative context. The results of the present study support our principal hypothesis: *by playing zero-fidelity simulation games, fire emergency responders learn team coordination skills*, indicating that zero-fidelity simulation is an effective approach to education.

In processes of distributed cognition, such as those undertaken by FERs, team members transform information, taking it from original forms into representations that facilitate sharing, displaying, speaking about, and otherwise communicating to co-located and distributed partners [12]. In distributing information, it is thus essential to vary form (embodied in the environment, a gauge, a map) as well as function (health status, waypoints) [28, 30]. Participant roles restrict the choices in the zero-fidelity simulation game; they situate players amidst the core game mechanics. Game mechanics, such as speaking to team members or moving in the virtual world, are the means through which players transform and share information. In the present research, we observe participants engaging in processes of information transformation. For example, to communicate with each other about their locations, players use the block-and-grid coordinate system shown in the interface [29]. Other information, such as plans held in the mind, must also be communicated; participants use gesture, block-and-grid coordinates, and the game's vocabulary to communicate plans and associated understanding, contributing to shared mental model formation [2, 19], and thus to situation awareness [4].

Participant students apply what they learn to their work as firefighters, supporting the ecological validity of the study. They and Roccaforte note that ICs who have played are more effective, they economize the limited communication channel, reducing communication overhead [17, 25]. Roccaforte cited improved organizational skill, clarity of radio use, and confidence in coordinating in ICs who had played. The skills of operating in a distributed cognition environment, one in which valuable information is apportioned among team members, is essential to the job. Knowledge of what to communicate, when, and how saves lives in the field.

We show that the interface design implications of information distribution, participant roles, and mixing communication modalities function as design *principles*. Information distribution and action capabilities characterize roles and drive learning. Players use information available to them, sharing it to coordinate. Players mix communication modalities based on information available, who needs the information, and the affordances of the environment. The mixing of communication modalities *leads to implicit coordination*. The teams become more effective, then apply what they learn to their work. Roles are an effective axis on which to distribute information and mechanics; participants use their roles to guide choices about communication modality. Researchers and practitioners can use these principles to develop their own zero-fidelity simulations and games.

We present experimental methods for measuring the impact of collaborative virtual worlds on team coordination. These measures may be applied to other situated contexts in which users communicate. By examining and coding communication content, we gain insight into how well a team performs. Directly computed measures can be evaluated using performance logs that track cooperative tasks in the environment.

Zero-fidelity simulations have the potential to transfer across domains. We hypothesize that a zero-fidelity simulation of the intense team coordination of fire emergency response may be effective in other contexts. This opens doors to exciting new forms of hands-on education in which participants learn human-human interaction skills essential to a number of domains. As abstracted socio-technical systems, zero-fidelity simulations educate participants in distributed cognition tasks. Future work will investigate transferability by testing T^2eC and other zero-fidelity simulations across domains, from diverse emergency responders to programming teams.

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[3] Wilson0803 is an outlier among the novice students, having had over 10 years experience in military teamwork.

[4] *task force*: "Any combination of [personnel or equipment used in an operation] assembled to support a specific mission..." [21]

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