Emergent Team Coordination: From Fire Emergency Response Practice to a Non-Mimetic Simulation Game

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ABSTRACT

We take the work practices of fire emergency responders as the basis for developing simulations to teach team coordination. We introduce *non-mimetic simulation*: economic operational environments that represent human-centered components of practice, such as team structures and information flows, without mimicking concrete aspects of an environment. Emergent team coordination phenomena validate the non-mimetic simulation of fire emergency response.

We develop *non-mimetic simulation principles* through a game, focusing engagement on information distribution, roles, and the need for decisive real time action, while omitting concrete aspects. We describe the game design in detail, including rationale for design iterations. We take the non-mimetic simulation game design to participants for a series of play sessions, investigating how forms of information distribution affect game play. Participants coordinate as a team and, although they are not firefighters, begin to work together in ways that substantively reflect firefighting team coordination practice.

Categories and Subject Descriptors

H.5.2 [User Interfaces]: Evaluation.

General Terms

Design, Experimentation, Human Factors.

Keywords

Non-mimetic simulation, team coordination, games, work practice, emergency response.

1. INTRODUCTION

Fire emergency responders (FERs) operate in small teams dispersed throughout an incident, using team coordination skills to protect lives and property. These skills are learned on the job and through expensive, high fidelity simulations (Figure 1). We introduce *non-mimetic simulation*: economic operational environments that represent human-centered components of practice, such as team structures and information flows. Non-mimetic simulations focus resources on learning goals that are identified as most important from investigations of work practice.

The non-mimetic simulation form emerges through analysis of design implications that resulted from ethnographic investigation of fire emergency response practice: information differential, mixing communication modalities, and use of audible cues [25]. These implications address how distributed cognition [9] is practiced, without prescribing how to mimic fire, smoke, and other concrete characteristics of the environment. This paper develops non-mimetic simulation design principles for information distribution, roles, and the need for decisive real time action. Each of a team's four members has different pieces of an evolving real-time information puzzle. They must communicate and coordinate in order to succeed. Participant roles vary available actions, functioning as the axis along which information is distributed. Real-time constraints create stress so that participants must resolve information distribution efficiently. We report on the transformational stage of iterative design that operationalizes these principles through a non-mimetic simulation game.

We are engaged in a long-term study of how to teach team coordination with non-mimetic simulation games. We hypothesize that non-mimetic simulations will be transferable; i.e., a simulation based on data from fire emergency response may prove to teach team coordination to a wide range of people, not just FERs. We are also interested in the special affordances of location-aware games, specifically, that they enable players to stick together sometimes, and split-up at other times. We hypothesize that the affordances of this modality of HCI, which are crucial in leveraging information distribution, may prove to better simulate team coordination in fire emergency response. In order to test this hypothesis, we develop both stationary and location-aware games. This creates a 2x2 matrix of interesting conditions to investigate, involving FERs and non-FERs. Each of these conditions, in itself, is complex and involved.

The current research investigates a *stationary* non-mimetic simulation game with non-FERs. Its design is guided by prior research, ethnography of FER work, and pilot studies. We develop non-mimetic simulation principles. We report on our iterative design and the results of a user study. To validate the simulation, we gather qualitative data on player behaviors, investigating communication that mirrors FER work practice. Non-mimetic simulation game players, like FERs, engage in distributed cognition [9]. They share information and take decisive action to achieve goals and avoid threats.

2. BACKGROUND

The relevant background integrates cognition, emergency response practice, simulation, and game design. Distributed and team cognition theory are the basis from which we analyze fire emergency response work practice and integrate it into our design.

Figure 1. Students practice fighting fire in a night burn exercise.

GROUP'09, May 10–13, 2009, Sanibel Island, Florida, USA.

We develop a new form of simulation, and contrast it with prior forms and systems. Game design theory informs our approach.

2.1 Distributed and Team Cognition

Distributed cognition considers the role of representations in how information is jointly processed and shared among humans engaged in collaborative work [9]. Team members learn to transform information from one form, for example, a map, into another, such as the embodied experience of moving through a building. FERs engage in such transformations to coordinate their situated actions [23] at an emergency incident.

High-performance teams engage in *implicit coordination*, where participants get the information they need without asking for it, and so can synchronize action with minimal communication overhead [5]. *Communication overhead* is the cost of sharing information, in time and cognitive and technology bandwidth [13]. *Shared mental models* play a key role in team members' ability to work together safely and efficiently, as members can model the process and outcomes of work in their heads, without needing to communicate about it [2]. Anticipation ratio (AR) is a measure of implicit coordination [5]. AR compares number of reports an individual makes to the number of requests. The higher an individual's AR, the better he is at anticipating the needs of others while having his own needs met.

2.2 Emergency Response Practice

Other researchers examine emergency response practice. Landgren describes the temporal flows and communication of FER work in Sweden, showing the similarities to how it is carried out in the USA [12]. Landay's group explores the role and information artifacts of incident commanders, providing us with insights into the role [10]. The WearIT@Work project works with FERs to develop testbeds for wearable computing systems in support of emergency response [11]; through this process they uncover aspects of information flow that we refer to as *information distribution*. Denef's ethnographic work investigates the navigation and information-sharing practices of FERs in France, describing the importance of multi-channel sensory information and the way it flows up the command hierarchy [4]. Palen explores the role of technology in the aftermath of disasters [17].

2.3 Simulation

Non-mimetic simulation differs from prior simulation forms: live, virtual, and constructive [16] that seek to mimic concrete aspects of a working environment. In live simulations, such as burn training at the Emergency Services Training Institute (ESTI), participants rehearse using real equipment in the real world, an expensive and potentially hazardous endeavor (Figure 1). Virtual simulations attempt to realistically mimic a real-world situation through a virtual environment. In constructive simulations, such as the Distributed Dynamic Decision simulation [22] or C3Fire [6], participants make strategic decisions while managing virtual resources. Some prior research addresses building team skills through mimetic simulation [6][22]; the present research focuses resources on human-centered communication processes. It does not expend resources to model emergency environments directly.

2.4 Game Design

Salen and Zimmerman [19] frame game design in terms of rules and play. Rules are constraints defining how a game is executed by players; they describe available actions and their consequences, limiting the scope of play. Play is what people do when engaged with rules and representations. A key component of game design is the action-outcome cycle, in which representations indicate to players how their choices affect play. *Game mechanics* connect rules with play experiences. We adopt games for our simulation, because they are enjoyable and intrinsically motivating [14].

3. FROM ETHNOGRAPHY TO DESIGN

We previously developed design implications for teaching team coordination, distilled from ethnographic investigation of FER work practice [25]. Ongoing investigations are undertaken at ESTI Brayton Field, one of the world's largest firefighter training facilities [24]. They bring together experience reports from expert FERs, observation of burn training exercises (Figure 1), and participant observation of a National Incident Management System course [15].

On reflection, we noticed that these design implications do *not* state a need to model fire, but rather address engaging participants in real-time information flows through multiple communication modalities. The design implications led us to conceptualize the form of non-mimetic simulation, and now, in turn, to non-mimetic simulation principles for team coordination: designing information distribution to engage participants in distributed cognition, creating roles that direct information availability and possible actions, and enforcing real-time constraints on action.

The non-mimetic simulation principles represent aspects of team coordination practice without a mimesis of fire and smoke. *We hypothesize that a non-mimetic simulation of information flows in fire emergency response practice can effectively engage team coordination skills.*

3.1 Prior Design Implications

Prior design implications for systems teaching team coordination skills were based on work practice: information differential, mixing communication modalities, and audible cues [25].

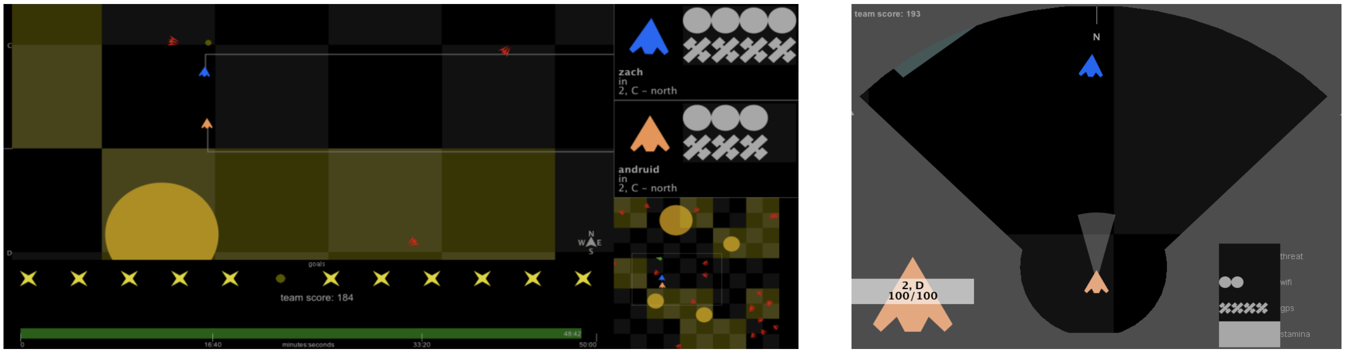
Because FERs work from different, changing vantages and because an emergency incident is unstable, we recommend the use of information differential in systems teaching team coordination. Information differential involves dividing up the information picture among team members, so that each has a different piece of the evolving information puzzle. Information should be constantly changing, and potentially uncertain.

A key choice in how FERs communicate is whether it is face-to-face or radio. Face-to-face is easier and richer, but sometimes FERs must split up to accomplish distributed tasks. When not co-located, FERs can communicate by radio; this modality is reliable, but limited and problematic. The affordances and constraints of the working environment and the information to be transmitted govern which will be most effective. Radio is more difficult to use due to noise and lag; only one person can speak (via push-to-talk) at a time. Face-to-face communication is vastly preferred, but radio is essential.

Sounds from the environment and FER equipment make audible the fireground and FER state. Cues can be overheard through the radio, contributing to shared mental models. FERs use audible cues to understand their local environment and remote environments over radio.

3.2 Information Distribution

Information in varied forms and content is available to different members of an FER team [25]. We call this division of critical information among team members and the need to share information and coordinate to succeed information distribution, revising our previous terminology, "information differential." Information distribution makes explicit the essential role of



a. excerpted coordinator view b. seeker view

Figure 2. Information distribution in coordinator and seeker views.

(a.) Coordinator view: seeker *zach* has just collected a goal, and is being followed by seeker *andruid*. All seekers are online. zach and andruid are in danger of being attacked by the approaching threat.

(b.) The alternative view, from andruid's perspective. The meters at the right indicate WiFi and GPS are strong and no nearby threats. The left indicates the seeker's grid location and full HP. A wall, invisible to the coordinator, can be seen just to the left of the other seeker.

distributed cognition [9] as team members assemble complementary pieces of the situated information puzzle that confronts them. Designing information distribution consists of supplying information to team members in such a way that members have alternative perspectives on the overall situation that are characterized by the modality of information (e.g., directly sensory, versus artifact-mediated), in addition to its content. Information distribution creates an environment where relevant data is dispersed among team members who gather, distill, and share it with one another to make sense of the whole incident. Simulation designers must create interdependencies, so that each individual's task requires communication from other team members.

3.3 Participant Roles

One effective way of creating information distribution is to reflect FER work roles. FERs use differentiated roles to accomplish specific tasks [10][15][25]. Firefighters search for victims and put out fires. An incident commander (IC) directs teams from a distant vantage, possibly consulting information artifacts. Each role carries access to a different piece of the information picture and enables a specific set of actions at the incident.

For every incident, one or more companies are deployed. An *officer* leads each company, which consists of at least two *firefighters*. The highest-ranking officer at an incident takes on the transient role of IC [25][28]. FERs characterize these roles by their duties; we alternatively classify them by their information access and communication capabilities.

Firefighters search for victims and put out fires. They are located in the fireground of an incident where they directly experience the environment, and perceive mainly what is local to them. The local perspective shifts as a firefighter changes vantage. Firefighters communicate with each other face-to-face while they are co-located, using radio to contact other teams and officers remotely. They act on their situated environment [23], improvising as necessary [4][25].

The IC, who coordinates companies around the fireground, is located at a distance, to observe the situation in context. The IC may have access to information artifacts that aid memory and planning [10][25]. The IC uses the radio to communicate with the companies, as they are his eyes and ears in the incident. If radios fail, runners substitute. The IC engages in processes of information translation, putting together reports from the fireground with his contextual overview, maps, etc. in order to make effective decisions.

Role and task at the incident drive the choice of communication modality. Because the IC is often far away from the fireground, she must use the radio to keep up with those in the fireground. Firefighters located near one another can communicate face-to-face.

3.4 Real-Time Constraints on Action

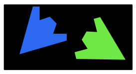
FERs work in dangerous environments that change continuously. There are hard limits on the amount of time that they can spend in and around a fireground. Not only must they consider dangers, but also air supply. Audible cues from the environment and equipment are one way in which FERs monitor their remaining time. Using sound effects helps create urgency in the real-time stress of the simulation environment. The real-time nature of firefighting also impacts the use of communication modality selection: some information must be communicated quickly, driving which modality is used.

4. NON-MIMETIC SIMULATION GAME

The present research develops non-mimetic simulation game designs with the goal of engaging participants in processes of gathering, distilling, and sharing information as in FER work practice, and motivating them to improve. We report on the *stationary* game design. The present design was developed iteratively through 17 games conducted over 18 months. Then a controlled user study was conducted. Future research will also develop location-aware designs. With the stationary game we anticipate some issues of location-aware games, and so imitate access to the necessary seamful [3] technologies: the global positioning system (GPS), to determine a player's location, and wireless networking (WiFi), to communicate it.

Effective teaching requires participation by the learner. In early games, communication was only one-way, because the game was easy enough to play without realizing the cost of communication. A single player controlled the entire team: all other players simply followed orders, without making decisions and without communicating themselves. Players knew enough to act on what they were told to do and did not take an active role in play (or learning). The design has been considerably iterated to increase the information distribution between roles, improving the need for

Table 1. Game entities, state, and hit points scoring rubric.

	entity (state)	summary
	seekers (**in**; **online**)	>0 HP; **can** collect goals; **tracked** in coordinator view; **+10 points/second**
	seeker (**safe**; in; online)	restores HP; **can** collect goals; immune to threats; **tracked** in coordinator view;
	seeker (**offline**; in)	**cannot** collect goals; immune to threats; **not tracked** in coordinator view;
	seeker (**out**) & threat	0 HP; **cannot** collect goals; **tracked** in coordinator view; **-10 points**
	1-seeker goal	collecting scores **+100 points**
	2-seeker goal	collecting scores **+200 points**
	3-seeker goal	collecting scores **+300 points**

team members to work together and share information. Game mechanics were modified to increase player engagement.

We present the stationary game design, describing its evolution, with a focus on player roles, communication, game mechanics, score, information distribution, and real-time stress. We anticipate differences between the present stationary game and the location-aware interactive game system throughout the section.

4.1 Player Roles

A team of players collaborates to achieve goals and avoid threats. Player roles are designed to reflect roles within FER teams in terms of information availability, possible actions, and communication modalities. From the firefighter and IC, we design two roles for the game: seeker and coordinator. A *seeker* consists of a player and an avatar. The *player* is a human who manipulates the *avatar* in the virtual world using a keyboard. In the later location aware game, the player will traverse real-world terrain and be tracked using GPS. The player's position will translate to a virtual world position for the seeker's avatar. Thus, a seeker is present concurrently in the real and virtual worlds. Seekers search for hidden objects (*goals*), while avoiding invisible *threats*.

To assist seekers in finding goals and avoiding threats, each team includes a *coordinator*. The coordinator observes and communicates with the seekers, like an IC. An interactive birds-eye view of the virtual world (Figure 2, a.), including the locations of seekers, threats, and regions containing goals provides the coordinator with a different perspective on the same virtual world.

4.2 Communication

FERs mix communication modalities, balancing the advantages and disadvantages of face-to-face and radio communication against the affordances and constraints of the environment, the information to be communicated, the details of the tasks at hand, and the relative locations of other FERs. When co-located, the seekers can speak to one another and use body language. When separate, or when talking to the coordinator, they use the radio. In the stationary game, we investigate two experimental conditions: one in which seekers are co-located, and another for separated.

For communication when separated, radios are interfaced to the PC using custom hardware, and integrated with a wireless headset (Figure 3). Each player activates their radio using a push-to-talk (PTT) button. These radios, like those used in emergency response work, are half-duplex, so when transmitting, a radio cannot receive. In addition to the problem of crosstalk, where two radio users transmit at the same time accidentally, there is also lag. Although PTT activates instantly, the receiving radios can take up to an entire second to connect to the sending radio. To help with this issue, a PTT indicator appears on the screen one second after a player presses the button.

We opt for radio over voice-over-IP (VOIP) for three reasons. First, radios, with all their problems, are used in actual emergency response work. The second anticipates working around the seams of the location-aware game: the radio will work even when WiFi is unavailable, enabling play through seams. Finally, using VOIP overly burdens the computers and network.

4.3 Game Mechanics

The objective of the game is to collect all goals before time runs out. Players earn points for their team by collecting goals. Seekers collect goals by finding a goal and moving to its location.

Pilot studies revealed limited, one-way communication in game play. The coordinator simply ordered the seekers around. Seekers acted like automatons, not like FERs, who perform situated, improvisational work [4][25]. We instituted a number of changes to increase information distribution and stimulate more balanced, active communication. One such change was the cooperative goal mechanic. Cooperative goals require the coordinated actions of multiple seekers to collect (Table 1).

As player roles are analogs for real-world emergency responder roles, other game elements map to practice as well. Threats are a loose simulation of fire, falling debris, and other dangers, representing a component of the fireground that must be overcome. Goals, which must be sought out in the dangerous environment, are like victims that must be rescued.

4.3.1 Seekers

Players move their avatars within the game's terrain, causing the avatars to transition between states (Table 1), which define what choices of action are available. In the location-aware game, players may walk anywhere within the game's boundaries, and will have to navigate real world terrain.

Anticipating the location aware game, the stationary game imitates the seamful design that has been found effective in location-aware games [1]. As long as a player's computer has access to both GPS and WiFi, that player's avatar is *online*. In the stationary game, the virtual world map includes regions of connectivity. Online seekers are tracked and appear in the coordinator's view. To seamfully incorporate states where a player has lost access to GPS or WiFi, a seeker drops *offline*. Offline seekers cannot collect goals, nor can the coordinator see them. Being offline can be advantageous, as offline seekers are immune to threats.

The game design has been iterated to include a hit point mechanic for seekers. Seekers have a set number of *hit points* (HP), which are reduced each time a threat contacts a seeker. A seeker can regain HP by visiting a *base*, an invisible region of the map where the seeker is immune to threats. While a seeker has any HP, that seeker is *in* and able to collect goals. When a seeker's HP are reduced to 0, that seeker is *out*, and unable to collect goals until some HP are restored.

Originally, contacting a threat instantly took a seeker out of the game. Players perceived this as random, since they can only detect the distance to nearby threats. The HP mechanic increases fairness to the seekers. Further, in the planned location-aware game, if a seeker's location is misreported by GPS (a common problem [1]) to coincide with that of a threat, the seeker has a chance to recover.

4.3.2 Threats

Threats use a variety of behaviors to prevent seekers from collecting goals. Due to the HP mechanic, groups of threats can be used to vary difficulty for players, without overwhelming them. While many threats slowly search the playing field for seekers, some exhibit other behaviors: patrolling the goals or protecting a single one. Threat starting locations are randomized at the start of each game.

4.3.3 Goals

Goals are what seekers must find in the game terrain. Seekers must stand near goals for a short period of time to collect them. This puts the seeker at risk, because she has little ability to move while collecting. If a seeker leaves a goal partially collected, the goal quickly returns to its original state.

Early designs used only single-seeker goals. Iteration developed cooperative goals. The cooperative goal mechanic requires that multiple seekers gather to collect certain goals. Goals that require fewer seekers can be collected more quickly when multiple seekers engage them. The iteration of the cooperative mechanic for goals encourages players to work together and better plan their moves. Play testers of both versions attested that cooperative goals greatly increased the need to stick together, and made the game more fun and interactive.

The number of seekers required for a cooperative goal can only be perceived by a seeker near the goal. The combination of adding cooperative goals and making the information available only to seekers makes the team more interdependent and less hierarchical. Coordinators need to know which goals require multiple seekers, in order to direct the team. The local information from the seekers essential to success. The role of seeker becomes more participatory, as the coordinator must rely on seekers to resolve uncertainties essential to engagement in game mechanics.

4.3.4 Terrain

Terrain affects how a seeker can move and where they can go. Seekers must circumvent impassable walls and discover bases where they can restore HP. While seekers can see nearby walls, the coordinator cannot; the coordinator can see bases, which are invisible to seekers (Figure 2).

We iterated the terrain design to encourage communication about the terrain within the team. Early terrain consisted primarily of open spaces, so seekers had no problem moving from one location to another; there was no need for seekers to provide the coordinator with any information about what they saw. The open maps offered little in terms of landmarks, which are essential in collaborative navigation [4]. The result was little communication about the terrain. Since seekers have most of the terrain information, this contributed to the problem of the coordinator doing all of the talking. The new maps require more navigation around obstacles, and are based on real-world maps of campus.

Anticipating the design of a location-aware game, the stationary game includes simulated access to the seamful technologies of WiFi and GPS. Game terrain includes regions of WiFi and GPS availability. These components are stable over time, as the game is short, and players may learn to leverage them during play, for example, going offline to get away from a threat.

4.3.5 Score

Score provides feedback and motivation, including a means to compare team performance over time and between groups [26]. Score serves as a "reward of glory" that players, in practice, often value, even though it does not directly impact the game through rules [19]. Scores are computed on a per-team, rather than per-player basis, to prioritize teamwork and deemphasize individual contributions.

Each player contributes a small amount of points to the score by staying in, online, and out of bases (taking a risk and remaining effective while doing so). In the event that the team collects all of the goals before time runs out, the team receives a bonus for the time remaining on the clock. Players are penalized for being captured by a threat. Goals provide most of the team's score, with cooperative goals being the most highly valued. Table 1 summarizes the events that affect score and their values.

Early designs did not include a score mechanic, so players could not determine their improvement over time. Score, as we shall see, is an essential motivator for players.

4.4 Developing Information Distribution

Information distribution, the way in which different pieces of the information picture are divided amongst players, is instantiated through carefully making visible aspects of the game state to the team roles. Seekers and the coordinator have access to different, but interrelated, information about the game state. Seekers experience the environment directly, and must respond to the terrain of the playing area. As they move, their vantages shift. Players see an overhead view of the seeker avatar's location, including impassable walls, nearby goals, and other nearby seeker avatars. A cone limits the view to what is in front (Figure 2, b). Panels display current status (HP, GPS satellites tracked, WiFi connectivity, nearby threat alert), location, and facing. In the location-aware version, each player will see a similar interface through a monocular head-mounted display.

The coordinator observes the virtual world from an overhead view (Figure 2, a). A main map shows the current locations of online seekers and the locations of any threats (Figure 2, a, upper-left). The map includes highlighted regions that contain goals for the seekers to find. A callout on the right shows information on each seeker: name, color, facing, map region, and status (online / offline, in / out). The bottom section shows an overview of goals and time remaining. A radar view [8] (Figure 2, a, lower-right) serves to orient the main map in the overall playing area. No terrain information is available to the coordinator, beside the bases where seekers are safe. Any information on walls or other obstacles must come from the seekers.

Of particular note in the information distribution design is the way goals are presented to each role. For the coordinator, goals are fuzzy regions of the map, which must be scouted by the seekers. Seekers, once they are close, can spot goals, and see how many seekers are necessary to collect the goal (indicated by a number of status rings around it, as in Table 1).

Originally, the design included less information distribution: coordinators were able to see precise locations of goals. In this design, seekers simply obeyed the coordinator, who would run down the list of seekers, rattling off directions for each to find a goal. There was no reason for seekers to say anything to the coordinator, or for the coordinator to ask for any information from the seekers. Changing the coordinator interface representation of goals to fuzzy regions resulted in richer communication among players.

Table 2. Study session ordering. Each team played 4 sessions of 2 games each. The role of coordinator rotates across sessions. Ordering of communication modality conditions alternates each session. Co-located seekers communicate face-to-face; distributed seekers use radio. Coordinator communication is always radio.

session	communication modality order	coordinator
1	tutorial, co-located, distributed	A
2	distributed, co-located	B
3	co-located, distributed	C
4	distributed, co-located	D

4.5 Creating Real-Time Stress

The game design creates real-time stress for players through time limits, goal mechanics, and threats. Game events are sonified, to increase player stress and enable use of audible cues.

Games run with a hard time limit (15 minutes, in the current iteration) in which players must seek out all of the goals. While players are not penalized for failing to collect all of the goals before time runs out, their scores will be considerably higher if they do succeed, due to a bonus based on the time remaining.

Threats exert the greatest time stress on players. Threats are guided to the goals in the game, so they often show up in places where the seekers need to be. Because collecting goals requires seekers to gather at a location for a period of time, threats pose serious danger to the seekers if they are not careful to avoid them. A seeker being taken out at a critical moment can cause the team to lose time, as that player will have to return to a base, then revisit the goal.

Goals provide another form of real-time stress. Goals are only collected while a seeker stands nearby, if the seeker moves away, the goal's status quickly degrades. This time requirement means that seekers must work together quickly and cannot operate independently when collecting cooperative goals.

Monitoring the environment, one's status, and the status of other FERs through sound is an important skill that keeps FERs safe. FERs can hear remote audio cues over the radio, providing context to a remote speaker's words. To enable participants to leverage these kinds of audible cues, changes in seeker state are sonified:

- **online / offline** – alert when connectivity changes.
- **low HP alarm** – beeping alert.
- **losing HP** –white noise, gets louder as HP decrease.
- **out** – alert sound when a seeker is reduced to 0 HP.
- **healing** –notes increase in pitch as the seeker regains HP.

Each sound effect is played for the individual seeker whose avatar's state is changing. Sounds are played through the radio connection (Figure 3), so that when a seeker transmits, any sounds that seeker is hearing are also transmitted to listening players, enabling overhearing of remote state.

5. USER STUDY DESIGN

To validate our non-mimetic simulation game design, we conducted a controlled user study using the stationary game. The hypothesis is that the game is a non-mimetic simulation of fire emergency response. If so, players will engage in team coordination, with multi-way flows of information through communication. Forty subjects, recruited from the university and community, were organized into 10 teams of four members each. When possible, we recruited groups of people who already knew each other. Participants were compensated: food was provided at

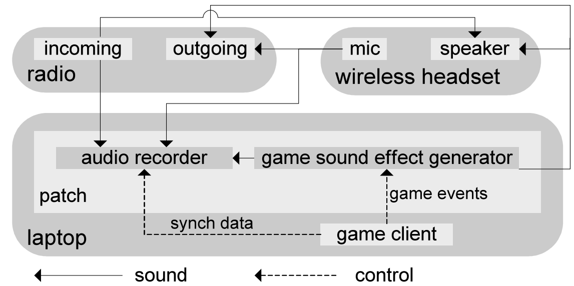


Figure 3. Diagram of audio system used for game studies showing a single player's setup. Arrows indicate flow of sound; dashed line indicates control signals.

each session, and each participant received a gift card (30USD) when their group completed four study sessions.

The study was conducted with two communication modalities: seekers co-located with coordinator isolated (co-located condition), and all players distributed (distributed condition). Players not co-located must use the radio to communicate. These conditions emulate FER practice, which requires mixing communication modalities. Relying on the radio is challenging, and thus FERs use face-to-face communication whenever possible. The varied conditions require the participants to practice with the radio, which they might otherwise avoid doing, because of its problems and limitations.

Each session consisted of two games, one in each condition, with order counterbalanced (Table 2) to minimize ordering effects[1]. Before and after each game within the session, participants were given time to reflect, share feedback with each other, and plan for their next game, which is important in forming effective strategies and discovering creative solutions to problems [7][20][21]. The coordinator role was rotated, to mimic the way in which FER education is carried out [Cary Roccaforte, personal communication]. Each participant played the coordinator role during one whole session.

5.1 Study Setup

The stationary game is played on 4 laptop computers, enabling dynamic re-configuration of the experimental setup for the 2 conditions. Each laptop is equipped with a radio, connected using custom hardware, and a Bluetooth headset. The coordinator's laptop is also equipped with a mouse, so that player can more easily manipulate the map interface.

The game client consists of a Java application, launched from a web study application, integrated with a Pure Data [18] signal-processing patch, which handles audio mixing, game sounds, and data recording (Figure 3).

For the co-located condition, the three seekers are located around a table, so that they are facing one another; the coordinator's computer is located in a separate room. Thus, the seekers need the radio to communicate with the coordinator, but not with each other. For the distributed condition, each player is in a separate room, and the radio, with its inherent limitations and challenges, is always required for communication.

For the study, we created a game terrain map using part of the university campus as the basis. The game terrain map was held constant for the games, although the locations of goals and threats were randomized for each game. Each of the two games within the

[1] Due to the cumbersome nature of re-arranging the laptops for the conditions, we followed the same order for each group (Table 2).

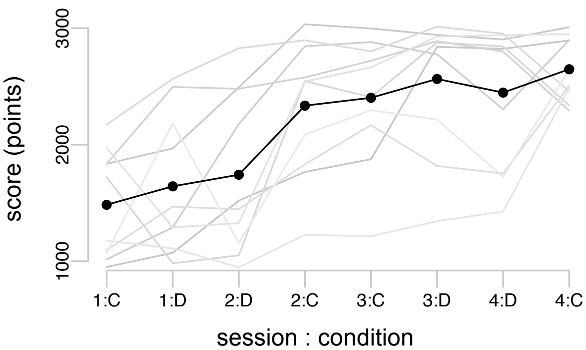


Figure 4. Team scores over time. Heavy black line indicates average score for all teams. Light gray lines indicate scores of individual teams. Teams improved from game to game with few exceptions; most decreases occurred when a session began with the distributed condition. The maximum score is 3,100 points.

session was 15 minutes, with 12 goals (5 1-seeker, 4 2-seeker, 3 3-seeker) and 20 threats.

5.2 Sessions

Each teams' four sessions were scheduled one week apart, to provide time for incubation [21], but sometimes it was necessary to adjust to accommodate participants' schedules. Table 2 indicates the differences between the sessions. Sessions were organized as follows (components of the first session only are indicated with the open bullet (○)):

○ Informed consent obtained from participants.

○ Participants fill out a pre-questionnaire, establishing prior experience with teams, sports, and video games, as well as demographic information.

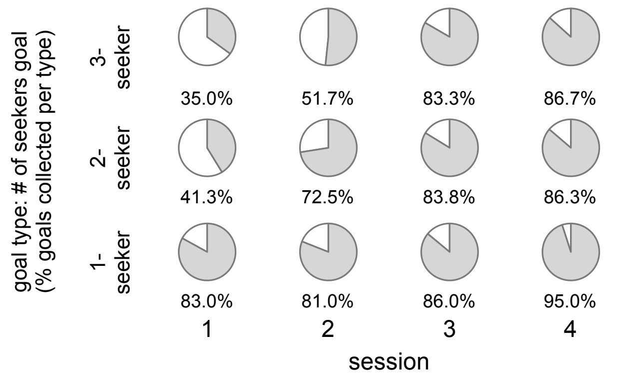
○ Participants play a tutorial game, in which they are presented with the seeker and coordinator interfaces side-by-side, and given a series of instructions on how to perform both roles. The side-by-side design enables understanding information distribution. Early prototypes indicated this was necessary, as players were confused about what one another could see and would spend time discussing the interfaces or arguing about ground truth in the game world.

- The team is informed of the coordinator's identity for the session and given a minimum of 10 minutes reflection time, where it is suggested they discuss strategy and make plans before the first game of the session.
- Participants play the first game of the session (see Table 2 for condition ordering), and answer a short questionnaire about the experience.
- Players are given a minimum of 10 minutes reflection time, where it is suggested they discuss strategy and make plans for their second game.
- The team plays the final game of the session, in the opposite condition, and follows up with a questionnaire about the game itself, and the session as a whole. The final session includes extra questions reflecting on the study as a whole.
- The team is given a minimum of 10 minutes to reflect.

5.3 Data Collection

Data is collected from multiple sources during each session. In addition to self-report data from the questionnaires, we captured game play logs, audio recordings of each individual and radio communication, and the reflection meetings of the teams. Game play logs were recorded on the server, in XML, to determine score information and play back game events.

Table 3. Average goals collected by all groups in each session. Each pie represents all of the goals of a certain type available; shaded regions represent the percentage collected. Note the increase in cooperative goals collected over time, and the high percentage of 1-seeker goals collected early relative to the others.



Each individual's computer records a 4-track wave file of audio during the game. One track records all utterances made by the player into the headset microphone and a second records all incoming radio communication. The third track records the sound effects played to the participant during the game. Because each frame of game state is numbered, we use track 4 as a synchronization track, recording the current game state. The synchronization track is used to put all of the four wave files (one from each participant) together, creating a comprehensive audio file. This file is then used to listen to the player utterances, and determine what was said to co-located seekers, and what was said over the radio.

Finally, a studio boom microphone is used to record player reflection periods before and after games. These meetings are revealing: players discuss strategy and evaluate their previous performance together.

6. RESULTS

Audio with game logs serves as the primary source of data. Each player's audio was coded according to a scheme devised from FER work and a broader scheme to compute anticipation ratio (AR) for each player [13]. Analysis identified instances of strategy, team coordination, and problems. Most significant results are observed through qualitative data. Teams are referenced by the letter "T" followed by an identifier; identifiers are assigned in the order that individuals volunteered for the study.

6.1 Teamwork – Improvement in Play

All teams' scores improved both in terms of overall points (Figure 4), and the number of cooperative (2- and 3-seeker) goals they collected (Table 3). The average team score for the first game is 1,484 points, by the final game, the average increases to 2,647 points. Table 3 shows the percentage of the different types of goals collected in each game session. In early sessions, players collect mostly single-player goals (83% 1-seeker, 41% 2-seeker, 35% 3-seeker), which do not require coordination. In late games, players collect more cooperative goals, which require them to work together (95% 1-seeker, 86% 2-seeker, 87% 3-seeker). Seven of ten groups collected half or fewer of the possible cooperative goals in their first session, while every group collected more than half of the available single-player goals.

6.2 Strategy – Emergent Roles

Some teams appointed a *seeker leader* to direct others by monitoring the local environment and incorporating strategy and information from the coordinator. Although no formal seeker leader role was specified in our design, T5, T6, T8, and T10 did, during at least one game, adopt a seeker to lead the team.

Seeker leaders are helpful, because they allow the coordinator to delegate responsibility and give the seekers independence to act on local information and improvise strategy. In the following anecdote [T8], the coordinator directed the seekers to a base. The seeker leader spontaneously overrides with an augmented plan based on local conditions.

Coordinator (radio): Everybody go east together. Directly east.

Seeker Leader (r): OK, we have walls to the east. We are going to move around the walls and move east.

C (r): Go around the walls, go north, and...go north around the walls, and then to the east.

SL (r): Negative, we're going to head south, there's a goal directly beneath the base.

C (r): OK, good, go there.

SL (face-to-face): OK, follow me.

Similar to the emergent role of seeker leader was the adoption of a *CAPCOM*[2] who filters all communication to the coordinator from the group of seekers. This role is only effective in the co-located condition, as seekers can rapidly communicate with each other, and the CAPCOM can relay important information and requests to the coordinator. T4 and T10 adopted this strategy; T2 discussed using it, but never implemented it.

6.3 Strategy – Co-location in Game

As teams played together and reflected, players eventually adopted a strategy of seekers sticking together. Early in the study, each seeker played independently, losing the rest of the group, and then needing to be re-united in order to collect any cooperative goals.

In later games, teams evolved strategies. Rather than splitting up, they would use a *2 collectors and 1 scout* (2+1) or *all-together* strategy. In the 2+1 strategy [T1, T3, T4, T5], two seekers pair up to collect cooperative goals, while the third seeker runs ahead to scout the terrain. The scout's job is to collect single-player goals, and locate the cooperative goals for the pair.

In the all-together strategy [T1, T2, T3, T4, T5, T6, T7, T8], all seekers move around the map as a team. In this way, they are able to help each other find invisible bases and almost always able to collect any goal found. If the goal requires fewer than three players, the remainder of the group is back-up, in case someone is captured by a threat at the last minute. The disadvantage of the all-together strategy is that it is an all-or-nothing proposition: once a threat captures one player, the rest are often also captured.

6.4 Team Coordination

During play, instances of team coordination were observed. These instances took the form of players responding to requests with action, rather than communication (implicit coordination) [T3] and leveraging audible cues.

Implicit coordination was observed through correlation between higher scores and both a reduction in overall communication and an increase in the coordinator's anticipation ratio. This is consistent with [13], which indicates that higher performance teams reduce their communication overhead by improving implicit coordination. Coordinator AR in the distributed condition is positively correlated with score (.6944 Spearman correlation). Total communication within the team is negatively correlated with score in the distributed condition (-.6247 Spearman correlation).

Reports by participants after study sessions indicate that they believe their own teamwork is improving. Members of T2 remarked that playing the game together would improve their skill at team sports. After one game, a team chided one of their members for "trying to be a hero" [T5], while another discussed how the coordinator should monitor and anticipate the needs of the seekers [T4]. One team member noted "what's genius to me is the idea that each of you has an incomplete set of information, you *must* communicate, it's not like games where they try to get people to communicate but there's no real reason to" [T4].

6.5 Competition – Motivating Improvement

Many participants expressed an intense interest in not only improving their scores, but improving them relative to the other teams in the study [T2, T4, T6, T7, T9, T10]. Although we did not formally make a leaderboard available to the participants, we did field their questions about other teams' performance. This prompted them to strive harder in successive games.

Upon obtaining a record score in the third session, T2 members remarked that, rather than be compensated they would prefer a trophy indicating that they were "Number 1". On hearing about this, T6 members bested T2 in their next session, mentioning that they would be happy to provide the T2 members *with a trophy for 2nd place*. In their final session, T2 gathered all the goals in less than 7 minutes, a record that has yet to be broken.

Of note is the fact that players were at first uninterested in their total score, but more interested in the number of goals collected. Once the team succeeded at collecting all of the goals, they turned to reducing their play time. Both aspects of achievement are included in our scoring rubric.

7. DISCUSSION

The findings validate the stationary game as a non-mimetic simulation of fire emergency response. We hypothesized that a non-mimetic simulation of information flows in fire emergency response practice can effectively engage team coordination skills. Through the simulation design principles of information distribution, participant roles that limit available action and information, and real-time stress, participants engage in implicit coordination while improving play. Emergent play reflects FER practice. Participants improve team coordination skills by engaging with distributed information; they work together to coordinate diverse perspectives and collect cooperative goals. New roles and strategies emerge, similar to those of FERs. Score motivates play. While higher scores, in themselves, cannot be seen as evidence of learning, we examine how the game stimulates players to improve in team coordination.

7.1 Improving Coordination with Play

As participants improve their scores, we observe a concomitant decrease in communication overhead (-.6247 Spearman correlation, distributed condition) and an increase in coordinator anticipation ratio (.6944 Spearman correlation, distributed condition). Participants in different roles, with distributed information, must integrate and communicate with each other, but economize communication as they improve [13]. Coordinators start to provide seekers with the information they need without being asked. The evidence indicates an increase in implicit

[2] T4 used the term "CAPCOM", which is a role at NASA, responsible for communicating with spacecraft [29].

coordination among team members [5]. They learn to work as a high-performance team in the context of the game.

7.2 Collecting Cooperative Goals

As they play, participants shift from primarily gathering individual goals to gathering cooperative goals. Table 3 indicates that few cooperative goals are collected in early games, but in later ones, nearly all such goals are collected. Improving the number of collected cooperative goals is indicative of an improvement in team members' ability to coordinate action and share information effectively. Real-time constraints on goal collection, in the form of the time required to collect the goal and incoming threats, make cooperative goals difficult to collect. To collect a cooperative goal, seekers gather in the same location at the same time while threatened. They either move together, which endangers them all, or gather at a location from diverse positions. Players resolve information distribution by communicating about the goal: its location and type (number of seekers required), the safety of the area (nearby bases, seams, and threats), their locations, and their status.

The cooperative goal mechanic was designed to increase teamwork among players. Originally, all goals required only a single seeker, so players operated independently. We made the design decision that the coordinator would not see how many seekers a goal required, which increased information distribution and multi-way communication, making the simulation better reflect fire emergency response practice.

7.3 Parallels to Work Practice

Participants' practice emulates work practice through emergent leadership positions and the use of co-location strategies for the seekers. While player roles substantively reflect FER roles, players add their own roles that strengthen the connection.

The advantage of a seeker leader, like a company officer in FER work practice, is that it reduces the burden on the coordinator. Rather than handle each seeker individually, the coordinator can focus on a single player, who enacts strategy and delegates responsibility. This formalization creates a chain of command within the team that is not formally specified, but that clearly parallels FER work practice [4][28][Cary Roccaforte, pers. comm.].

The game was initially designed such that the coordinator was like the IC, with the three seekers mirroring firefighters. As we increased information distribution, with cooperative goals and fuzzy representations in the coordinator's view, the seekers grew more autonomous. FERs also act autonomously, working with a general strategy from outside the fireground [4][25][Cary Roccaforte, pers. comm.]. They must be free to improvise as the situation warrants, because each has unique, valuable, distributed information, which contributes to distributed cognition.

The emergence of additional roles and strategies validates the design of the simulation. The coordinator functions more directly as an IC, the seeker leader or CAPCOM is like a company officer, and the remaining two seekers are like firefighters. Furthermore, the emergence of a leader among the seekers enables them to operate more autonomously. T4 mentions this specifically in one of their reflective periods, noting to the coordinator that they do not need to be micro-managed. T5 demonstrates its importance, as the group of seekers works together to collect a 3-seeker goal near an offline region ("dead zone") by walking backwards:

C (r): That point seems to be a bit better defended...

Seeker 1 (f2f): I couldn't take it because I was in the dead zone.

S2 (f2f): Whoa, that is close...

S1 (f2f): It's important the direction we go to it because one direction is too close [to the offline region of the map].

S3 (f2f): No, no. Back up, go towards it backward. That we can [back over it]...

S1 (f2f): Exactly, that's what we should do.

Sometimes the coordinator can identify patterns that the seekers cannot. While trying to collect the final goal of the game [T3]:

C (r): [S1], can you take them back around the way you just came? If you guys run out of that dead zone, you might be able to get to [the goal] before the threats.

The 2+1 and all-together strategies lend themselves to having a seeker leader, who makes group decisions in the field. As in fire emergency response work, there is safety in numbers. It is necessary for firefighters to stick together [25][28]. A downed firefighter can be pulled out by a teammate, just as a backup seeker can collect a goal when another falls. Multiple firefighters can accomplish more than an individual: their combined strength is necessary to direct a powerful fire hose or lift heavy debris. This synergy of coordination is captured in the simulation by the design of cooperative goals.

7.4 Score Motivates Coordination

Score and competition between teams is a powerful motivator for participation and improvement. Team members repeatedly expressed concerns about their ability to perform relative to other teams and were eager to play the game to improve their scores. The extra points for cooperative goals motivated players attempt more difficult goals by working together; this, in turn, required them to coordinate to succeed.

Leaderboards, requested extensively by participants, are a future design iteration that will enable participants to quickly compare their scores with others. The effectiveness of leaderboards is seen historically. High-score lists, once common in arcades and maintained by official referees for world records [27], have seen resurgence through globally networked home entertainment. In Microsoft's Xbox Live, an online gaming community, players earn a cumulative *Gamerscore* for accomplishments in games. Sony's Playstation Network includes *Trophies*, a similar concept. Score enables comparison between players and against a single player over time.

8. CONCLUSION AND FUTURE WORK

We have presented the iterative design and evaluation of a non-mimetic simulation game for teaching team coordination skills based on work practices of fire emergency responders. Because our prior design implications [25] do not specify a need to model fire and smoke, we omit these, developing non-mimetic simulation principles: information distribution, participant roles, and real-time stress.

We design information distribution to create a distributed cognition environment, wherein team members are reliant on each other for rapidly-changing information. Roles define available actions and information. Participants are under real-time stress to perform. The result is a simulation that successfully captures the human-centered aspects of fire emergency response, engaging participants in the intense team coordination of FERs. Non-FER participants develop emergent strategies that match those in fire emergency response work practice.

While mimetic simulation has tremendous value, we emphasize human-centered aspects of practice that are overlooked, providing a new teaching tool that can be integrated with existing methods. The game format enhances the value of non-mimetic simulation, as learners can engage with it during down time, enhancing skills while having fun; competition between teams motivates improvement. The derivation of the simulation from grounded data of practice is essential to its validity.

Our principles for non-mimetic simulation focus on human-centered aspects of practice. Fire emergency response work is carried out safely and efficiently by sharing and integrating rich, multi-way flows of information. Information access is an essential difference in the roles of firefighters and ICs. Real-time stress impacts the way that FERs select and share information. In capturing these aspects of work practice, we develop a simulation in which non-FERs learn to coordinate effectively. Their emerging practices reflect the long-standing work practices of expert responders.

Future work will take the stationary game to ESTI, for use by FER students and experts. A pilot study with FER students supports our hypothesis. The students cited clear analogs between the game and burn training. They expressed excitement that they would have an edge in upcoming mimetic simulations, as they now had practice using radios to share information and better understood some of the advantages and frustrations of the modality.

We will continue to iterate the design, and construct a location-aware gaming platform to compare with the existing stationary game. Moving to location-aware interaction opens new doors for interactivity. In the stationary game, participants are unable to physically move around, they are locked in either the face-to-face or distributed communication modality. They are not afforded choice of modality that will best help them in their situated context of goals and threats. We hypothesize that a location-aware game will result in richer information distribution and improved team coordination. Further experimentation will be required to determine if the location-aware modality will be more effective. The present research establishes the emergence of team coordination in the stationary non-mimetic simulation game.

9. ACKNOWLEDGMENTS

Special thanks to Fire Chief Cary Roccaforte, for advising on work practice. This project funded by NSF grants IIS-0803854 and IIS-0905594.

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