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Network-aware support for mobile distributed teams

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ABSTRACT

An experiment evaluated network-aware support to increase understanding of the factors that are important for successful teamwork in mobile geographically dispersed teams of first responders. Participants performed a simulated search and rescue team task and were equipped with a digitized map and real-time situation updates on the location of other participants in a simulated disaster area. The connection to a server, however, was made deliberately error-prone, leading to occasional losses of network connections. Consequently, participants were not provided with real-time situation updates. To deal with this problem we equipped team members with a network-aware application that signaled network loss to them and adapted the graphical representation of the location of fellow team members accordingly to the quality of location information present. The experiment revealed that presenting complete and reliable geospatial information improves teamwork. Teams connected to a server over a fast and reliable link showed superior performance over teams with no network connection whatsoever to a server. The present study failed, however, to demonstrate the added value of network-aware support when teams had to collaborate in the presence of an unreliable communications infrastructure. Although participants indicated a slight preference for the network-aware application over a condition without support signaling network loss, no differences were observed in team process and outcome measures.

1. Introduction

In large-scale emergency situations or disasters, fielded first responders, such as firefighters, police officers, and medics, have to collaborate with each other as a team, quickly and in an effective and efficient way. Consequently, they need to act in concert and smooth communication is essential (Van der Kleij & Schraagen, 2006). Currently, coordination is carried out using walkie–talkies and first responders rely heavenly on the incident commander to provide high-level information (Wagner, Phelps, Guralnik, & VanRiper, 2004). The situation is often highly dynamic and chaotic and first responders must adapt their response as the situation unfolds, translating into high levels of cognitive load and suboptimal coordination between team members.

Given the complexity of large-scale emergency situations, information is needed to develop a proper understanding of the situation, often referred to as situation awareness. Some of the information needs are for geospatial information, such as digitized maps of the disaster area. Other information needs are for real-time information, such as reports from the incident commander, emergency services, and other parties involved in the emergency situation. This information together enables geographically dispersed teams of fielded first responders to get an accurate picture of what is happening, helping them to coordinate their collaborative efforts and fight the crisis effectively.

The knowledge of others' locations, or mutual location awareness, appears to be pertinent for social interactions (Nova, 2007). Johansson, Trnka, and Granlund (2007) found that teams using information systems combining real-time positioning of resources, fellow responders, and fire outbreaks outperformed teams using paper maps when extinguishing a simulated forest fire in terms of saved area. Moreover, communication volume was reduced between the geographically separated command module and ground chiefs in support teams. These teams exchanged significantly fewer messages via e-mail than teams using paper maps. Because these teams had an accurate picture of what was going on in the area of operations, there was less need for communication concerning one's own and others' position and the locations of the fires.

Mobile handheld computers may be employed to address the information needs of first responders and support situation assessment. By augmenting fielded first responders with wireless communication technology, these devices can become electronic communicators, capable of delivering real-time situation updates, providing information on resources, the location of fellow responders, and on the status of possible victims. Services that detect the

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locations of users and broadcast them to the others enable the members of a team to share context so that they can achieve their own actions more effectively. For example, through the use of global positioning satellite technology, automatic reporting of responders' locations can be achieved, reducing the communications workload of the responder (Gutwin & Greenberg, 2002; Nova, 2007).

Emergency services see a lot of potential in location-based services, the provision of real-time situation updates, and information on resources to make better decisions, faster, with a greater attention to detail, and with a near optimal utilization of teams and resources (Wagner et al., 2004). However, geographically distributed teams of fielded first responders sometimes have to work in the presence of an unreliable communications infrastructure, leading to information shortages and suboptimal coordination between team members. This paper presents a solution to this problem; namely to equip distributed teams with an intelligent network-aware application that signals network loss to the users and adapts the graphical presentations of the locations of fellow team members according to the quality of location information present. Moreover, this paper explores whether providing team members with this additional awareness information will help them to deal with the problems of group collaboration in the presence of an unreliable communications infrastructure (cf. Cheverst, Blair, Davies, & Friday, 1999).

1.1. The importance of intelligent adaptation

Characteristics of mobile computing are portability, mobility, and connectivity (Augustin, Yamin, Barbosa, & Resin Geyer, 2002). These characteristics insert constraints on portable systems. A portable computer is small, light and it requests sources of energy of little power. Consequently, portable computers have restrictions in the memory size, storage capacity, computational power, and user's interface. Furthermore, the portability increases the loss risk, or damage of the mobile device.

The wireless connection raises obstacles as well: intermittent communication (frequent disconnection, block signaling, and handoff), restricted and highly variable bandwidth, high latency, and high error rate. Another aspect to consider is the network connection. When in movement, the mobile device changes its location and possibly its network contact point. This implies the utilization of different networking technologies to maintain network connectivity while mobile (Cheverst et al., 1999). In general, a mobile computer may experience a wide range of network connections over time and rapid and massive fluctuations in the quality of service provided by the underlying communications infrastructure. Roughly, an application's network connection can be placed in one of three broad categories:

- Strongly connected. The client is fully connected to a server over a fast and reliable high-bandwidth link, such as Ethernet.
- Weakly connected. The client is connected to a server, but only over a slow and possibly error prone link, such as a modem connection (either wired or cellular), or a radio link.
- Disconnected. The client has no network connection whatsoever.

It is assumed that a mobile computer will experience each of these types of connection over some period of time.

Cheverst et al. (1999) argue that one of the key properties of mobile distributed groupware applications is the ability to perform intelligent adaptation; that is tailoring its behavior based on changes in the underlying communication infrastructure. In general, to be adaptive to a dynamic environment, an application needs to be context-aware. Context-aware applications are defined as applications that appropriately react to information sensed from the environment (Benerecetti, Bouquet, & Bonifacio, 2001). In an adaptive system the operator and tool work together as partners to maintain an optimal level of performance. Context is viewed as a collection of features of the physical environment that can affect the behavior of the application. The main advantage of context awareness, according to Benerecetti et al. (2001), is that it allows designers to create applications that can use information about contextual features to automatically adapt their behavior to a dynamic environment.

Special cases of applications that react to information sensed from the environment are *network-aware applications.* Network-aware applications adapt to changes in availability of network components, in particular the bandwidth (Augustin et al., 2002). The adaptation may involve data reduction, transformation, or filtering techniques for network transport. Adaptation may also involve the visualization of geospatial information uncertainty as a result of network loss, which we will discuss in the following section.

1.2. Visualization of geospatial information uncertainty

Traditional mobile distributed groupware applications tend to hide details concerning the state of the connection from users and also assume a constant level of communication (Cheverst et al., 1999). As mentioned, the quality of network connectivity may fluctuate considerably while being mobile. Hiding information about the status of an application's network connection from the user may lead to lead to suboptimal or even disastrous decisions. A solution to this problem is to make the user aware of relevant uncertainty in the data (Griethe & Schumann, 2005). For example, Baus, Krüger, and Wahlster (2002) describe a navigation system for pedestrians that adapts the graphical presentations according to the quality of location information present. The navigation system encodes positional information by the size of a dot, which represents the user's current position on the map. Decreasing quality of information about the location results in a bigger circle. The system also takes into account the user's current walking speed. If the user moves fast, the system presents a greater portion of the map to help the user to orientate. Once presented with this awareness, users should be able to intelligently adapt their collaboration patterns.

Presenting uncertainty and asking users to manage it more explicitly may also alleviate some of the feared impacts of increasing automation, such as deskilling and loss of situation awareness (Nicholls, Battino, Marti, & Pozzi, 2003). Further, there is general agreement that visualization of uncertainty is an important strategy to enable analysts, decision makers, and others to cope with uncertain information (MacEachren et al., 2005). Indeed, Antifakos, Schwaninger, and Schiele (2004) showed that human performance on a memory task was increased by explicitly displaying uncertainty information. In an experimental setting, participants were asked to remember numbers out of a list. The task was designed to be hard enough so that participants could only remember approximately half or even less of the numbers. Before the user was actually asked to enter the remembered numbers, the system provided a tip on what the numbers might have been. This memory aid was based on the observation that users are actually used to and highly successful in dealing with uncertain information throughout their daily lives. So, Antifakos et al. (2004) decided to display this uncertainty explicitly and leverage from the user's ability to choose the appropriate action. While varying the uncertainty of this tip and whether or not the uncertainty was displayed, Antifakos et al. measured participants' performance. The experiments clearly showed that displaying the degree of uncertainty affected performance. Hit rates increased substantially when uncertainty information was displayed, especially when tips of high quality were shown and when the task was difficult.

Most approaches to uncertainty visualization have treated uncertainty as a single and static attribute of data (MacEachren et al., 2005). These approaches generally include the use of visual variables such as size, color value, grain, and color hue to present uncertainty measures to the user. However, some researchers have explored the potential of dynamic signification in the form of animation to highlight aspects of uncertainty and as a method for understanding uncertainty. For example, Fisher (1993) applied animation to uncertainty representation in multivariate classification of the sort encountered when classifying soils and land cover. He gave certain parts of maps a stable color indicating relatively certain classifications, while at the same time he made uncertain regions change continuously, drawing user attention to them. This dynamic approach using animation seems to be especially effective for displaying uncertainty in space-time processes, including parameters like speed, duration, range, or extend of motion (Griethe, 2005).

1.3. Evaluation of mobile support in virtual environments

When designing novel mobile support concepts for complex and dynamic environments, iterative design and evaluation cycles are often required to come up with effective and usable systems. Various evaluation methodologies have been developed that can be used, each with its strengths and weaknesses (Streefkerk, Van Esch-Bussemakers, Neerincx, & Looije, 2008). Some are suited in initial development cycles focusing on requirement analysis, such as focus groups. Wizard of Oz experimentation, in which (part of) the new functionality is faked, can be used to select which of the various design alternatives should be build. To evaluate one or more designs in complex scenarios, real life settings provide the richness and complexity for proper testing, but also have some serious drawbacks. Field testing is expensive, can be dangerous or even impossible, and conducting controlled experiments is almost impossible due to the high number of variables that the experimenter must control. Experimentation in simulated environments is an alternative that is becoming increasingly popular due to the availability of low-cost yet realistic virtual task environments provided by modern game-engines. Experiments in virtual environments provide much more flexibility than Wizard of Oz experiments, are easily controllable, and data can easily be logged (Frey, Hartig, Ketzel, Zinkernagel, & Moosbrugger, 2007; Lewis & Jacobson, 2002; Te Brake, De Greef, Lindenberg, Rypkema, & Smets, 2006).

Game technology has been used before to simulate a crisis response domain. Unreal Triage (McGrath & McGrath, 2005) is an analysis and training tool for emergency responders using a synthetic task environment, created by the Unreal Tournament game engine. The player's objective is to perform primary triage. Players must locate and classify the casualties into one of four treatment categories. The player interviews each casualty to determine cognitive health and then examines the casualty for the status of the airway, breathing and circulation. Hazmat: Hotzone is a networked, multiplayer simulation, created at Carnegie Mellon University in cooperation with the New York Fire Department, which uses game technology to train first responders for chemical and hazardous materials emergencies. FiRSTE is a first responder training environment that focuses on training first responders with a high level of immersion and physical interfacing (Leu et al., 2003).

Two concepts are used to describe how realistic a simulator mimics a real-world task: fidelity and validity. *Fidelity* is the level of realism that a simulation presents to the user. When a simulator has 100% fidelity it represents the real world in a one-on-one matter. It is needless to say that this 100% fidelity does not occur and that the development of a simulator towards 100% fidelity is expensive. *Validity* indicates the degree to which the simulator reflects the underlying construct, that is, whether it simulates what it intends to simulate. The question validity addresses is: Did we design the right simulator? When a virtual environment is used to evaluate new concepts, validity of the environment must be high. It may not be required that the virtual world looks very realistic, but the characteristics of the task conducted by the participants in the virtual environment must resemble the situation in the real world.

1.4. The present study: The blob interface

In concordance with the pedestrian navigation system of Baus et al. (2002), we designed an application delivering real-time situation updates, providing information on the location of other responders, and providing information on possible victims on a digitized map of the area. The interface, which we call *the blob interface*, also involves two levels of uncertainty indicators. The first level is a simple static visual notification indicating that network connections are lost. Rounded semi-transparent blobs appear on the digitized maps of responders over the last-known locations of their teammates until connections are restored, hence the name blob interface. The second level adds animated detail about characteristics of the uncertainty, specifically the possible location of fellow team members during the period that network connections are lost. The blobs grow in size over time approximating the maximum movement speed of fellow responders until connections are restored. That is, the application adapts the graphical presentations of the locations of fellow first responders on the map according to the quality of location information present. This is hypothesized to assist mobile distributed first responders in making inferences about the possible location of fellow responders during losses of network connections, making collaboration and coordination less difficult.

Hence, when compared to an application that does not adapt to changes in availability of network components, we expect that the blob interface would improve coordination between interdependent distributed first responders, reduces cognitive load, requires less time for response, coordination and decision making, and eventually allows for more lives to be saved. Interestingly, the opposite may also be true. Presenting uncertainty may also overload the user with information (e.g., display clutter), leading to a higher mental workload, inefficient information exchange, and more stress (cf. Antifakos et al., 2004; Nicholls et al., 2003). In the latter view, there is a trade-off between the value of presenting additional awareness information and the display clutter and cognitive overload that may result from it.

2. Method

2.1. Participants and design

Forty-eight participants (20 male and 28 female), primarily students, were randomly allocated to 16 mixed-gender three-person teams. Their age ranged from 19 to 31 years ($M = 22.75$, $SD = 2.02$). Participants were paid €45 for their contribution in the experiment. Furthermore, the best performing team was held out the prospect of an extra team bonus of €60, to enhance motivation and stimulate teams to perform at their best. None of the team members knew each other prior to the experiment. The design was a one-factorial within-group design with four levels. The sequence of the levels was counterbalanced for all teams, but since order had no effects whatsoever it is not discussed further.

2.2. Task and apparatus

To explore the effects of network-aware support on teamwork, a virtual environment was created that required geographically distributed team members to collaborate with each other, using the Unreal Tournament 2004 game engine. Unreal Tournament is a so called ego-shooter game which offers a realistic 3D-virtual environment in which users can navigate and interact with other users or objects over a networked computer system (Frey et al., 2007). The game engine of Unreal Tournament has proven to be a well developed, flexible, and usable engine for research purposes (Lewis & Jacobson, 2002; McGrath & McGrath, 2005; Te Brake, Van der Kleij, & Cornelissen, 2008).

For this study, several characteristic elements of the Unreal Tournament 2004 user interface, like weapons and health points, were removed. Further, several other modifications were made to the environment to simulate a disaster area. The scenario involved an accident with a poisonous gas in an urban environment. Participants communicated through a radio connection, and had to save, as a team, as many victims as possible. Fig. 1 depicts the environment after the modifications were done.

Control of movement within the environment was restricted to forward, backward, and turning motions controlled by a Logitech dual-action game controller. Team members acted in separate rooms and were seated at a table behind a 19-in. Iiyama computer screen (1280 × 1024 pixels) and a Dell Optiplex GX270 Intel Pentium 4 computer equipped with Microsoft Windows XP service pack 2 and the Unreal Tournament program. The experimental set-up is depicted in Fig. 2.

During task performance, team members wore Sennheiser stereo neckband headsets with an integrated microphone; model PC 145 USB, to communicate with each other over a network computer system running Teamspeak2 software. Teamspeak2 is communication software using an internet protocol that allows users to speak on a chat channel with other users, much like a telephone conference call. Although there was a slight delay in communication, this was not perceived as a hindrance by the participants. The experimenter in the control room was also connected to this communication network to tell the participants when a scenario ended and when it was time for a break.

One virtual task environments was constructed using the Unreal Tournament 2004 level editor. In each experimental and training trial the starting position of the participants and the locations, type, and the timing of appearance of the victims differed (see also Table 1). The positions of 40 victims were randomly selected out of a total of 60 fixed positions. Their order of appearance, type, and timing were also randomly selected. Two training trials were used to familiarize participants with the user interface, game controller, support levels, task, and each other.

Fig. 1. The Unreal Tournament user interface.

Fig. 2. Picture showing the experimental setup for one of the participants (staged).

Table 1
Information about the four different types of victims.

Cat.	Description	Time (s)	Incidence	Points
1	Severely wounded, needs one rescuer	30	12 (30%)	10
2	Lightly wounded, needs one rescuer	60	16 (40%)	5
11	Severely wounded, needs two rescuers	30	4 (10%)	25
22	Lightly wounded, needs two rescuers	60	8 (20%)	15

Note. A total of 40 victims appeared in each trial.

2.3. Independent variables

To help the participants perform their task we presented them with a digitized map with the factual information about the location of their team members, and the location and status of the victims. The information was displayed on a 17-in. Iiyama Vision Master computer screen (1024 × 768 pixels) that was connected to a Dell Intel Core 2 laptop (CPU 2.00 GHz, T7200, 1.00 GB RAM) equipped with Microsoft Windows XP service pack 2. On the base of their own and their team members' location and the location and status of the victims, the participants had to think about, adjust, discuss, and implement the best and most optimal plan of action.

The reliability of the information was made dependent on network connections. As mentioned, mobile applications first responders use in the field may experience a wide range of network connections over time. An application's connection with a server can be placed in one of three broad categories: strongly connected, weakly connected, and disconnected. It is assumed that a mobile application will experience each of these types of connection over some period of time. Based on these types of connection, four experimental conditions were created including one condition running a network-aware application designed to aid geographically distributed first responders in the field. These conditions are described in more detail below:

1. Strongly connected. In this condition, participants were able to communicate through speech with their fellow responders. Participants were equipped with a digitized map of the disaster area showing their own location and a reliable link, delivering real-time situation updates, providing information on the location of other responders, and providing information on the victims (see Fig. 3).
2. Disconnected. Participants in this baseline condition were also able to communicate through speech with their fellow responders and were equipped with a digitized map of the disaster area

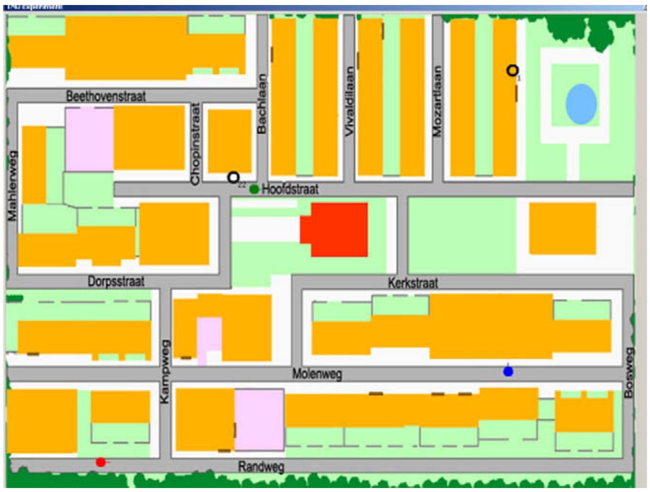

Fig. 3. Screen shot of the digitized map shown to the participants in the strongly connected condition. The colored points represent the three participants. The black circles represent victims. The number besides the victims indicates how many rescuers are needed at the scene and how much time there is for the rescue operation (see also Table 1).

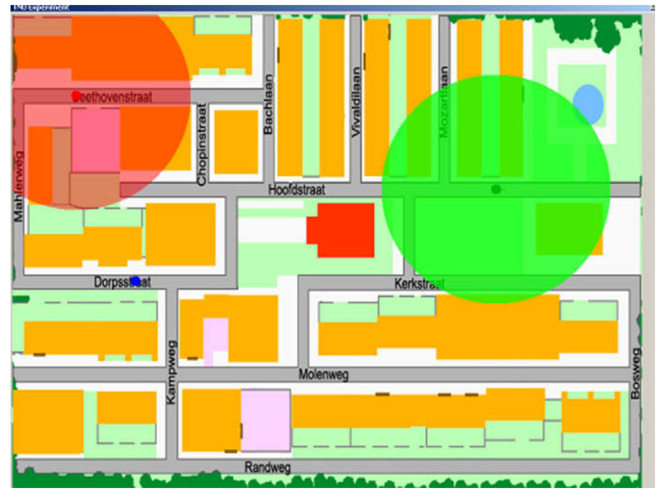

Fig. 4. Screen shot of the digitized map shown to the participants in the weakly connected, with network-aware application condition (i.e., the blobs condition). The rounded semi-transparent blobs of color indicate that network connections are lost. Moreover, the blobs indicate the possible location of fellow team members. The blobs grow in size approximating the maximum movement speed of fellow responders until connections are restored.

showing their own location. However, participants in this condition had no network connection whatsoever to a data server. Consequently, they were not provided with real-time situation updates. Thus, these teams had no information on the location of other responders and the victims.

3. Weakly connected, with network-aware support (i.e., the blob interface). Again, participants were able to communicate through speech and were equipped with a digitized map of the disaster area showing their own location. The connection to a server, however, was over an error prone link, leading to an occasional loss of network connections which varied between 10 and 30 s. The possible locations of fellow responders during such losses of network connections were shown as semi-transparent blobs. The blobs grew in size over time approximating the maximum movement speed of fellow responders until connections were restored (see Fig. 4).
4. Weakly connected, no support. Teams in this condition also were connected to an error prone link. However, losses of network connections were not signaled to the responders. Thus, real-time situation updates on the locations of fellow responders and victims was not available for the duration of the network loss. Consequently, the position of fellow responders and the status of the victims remained unchanged.

2.4. Dependent variables

2.4.1. Team performance

To objectively evaluate the team's performance, we calculated the overall team score. The overall team score was based on the total number of people saved. A total of 40 victims appeared during each trial. Some of these victims required only one rescuer at the scene to be saved. However, other victims required two rescuers at the scene, which made participants interdependent for successful performance on the task. To make things more complex, we introduced time pressure to the task. The lightly injured victims needed to be rescued within 60 s, the more severely injured victims needed to be rescued within 30 s. Thus, our task included a total of four different types of victims. Table 1 shows the victim categories, the total number of appearances in each scenario, the allotted time periods, and the game points awarded when rescued. Consequently, teams could earn a maximum of 420 points in each trial.

2.4.2. Participant ratings

Questionnaires on satisfaction, information exchange, and a rating scale on mental effort were administered at the end of each experimental trial. Furthermore, an interview was conducted at the end of the experiment to subjectively evaluate the support conditions and assess the strategies used by the participants. All questionnaires and the rating scale were pre-tested and found to be reliable, simple to administer and to take little time for participants to complete. All questionnaire items were measured on seven-point Likert scales in which a score of 1 corresponds to the most negative option and a score of 7 corresponds to the most positive option. Convergent validity and internal consistency reliability of the questionnaires were adequate with correlation coefficients ranging from .62 to .93 and Cronbach's α coefficients ranging from .75 to .85. The questionnaires, the rating scale, and the interview are discussed in more detail below.

2.4.2.1. Process satisfaction. Process satisfaction — the contentment with the interactions that occur while team members are devising decisions (Thompson & Coovert, 2003) — was assessed with an adapted version of the questionnaires used by Dennis (1996) and Green and Taber (1980). It contains the following two items: 'I am satisfied about the quality of the interaction within the team' and 'I am satisfied about the choices we made as a team' (two items, Cronbach's $\alpha = .75$).

2.4.2.2. Outcome satisfaction. Outcome satisfaction includes the approval of the final team decision (Thompson & Coovert, 2003). This questionnaire was adapted from Green and Taber (1980) and includes the following five items: 'I am satisfied with the final result we produced as a team', 'I am attached to the final results of our team', 'As a team we produced the best result conceivable', 'I am personal responsible for the final result our team produced', and 'My personal share is recognizable in the final result of our team' (five items, Cronbach's $\alpha = .77$).

2.4.2.3. Information exchange. The sharing of members' expertise and knowledge is important in groups (Stasser & Titus, 1985). It was found that the effectiveness of groups fluctuates as a function of what information is shared and the degree that information is shared (Stasser, Taylor, & Hanna, 1989). Information exchange was assessed with a questionnaire to assess the perceptions of the participants concerning the completeness, speed, and amount of information given and received in discussions while performing the task. The information exchange scale was adapted from Van der Kleij, Rasker, Lijkwan, and De Dreu (2006) and includes the following four items: 'We had enough opportunity to exchange information', 'During the task accomplishment I shared a lot of information with my team members', 'Information could be exchanged without unnecessary delay', and 'When things were unclear during the task we asked each other for explanation' (four items, Cronbach's $\alpha = .80$) (cf. Van der Kleij, Lijkwan, Rasker, & De Dreu, 2009).

2.4.2.4. Mental effort. To evaluate mental effort the Dutch Rating Scale Mental Effort (RSME) was administered once per test session directly after completion of the task. O'Donnell and Eggemeier (1986) define mental effort as the ratio between the task demands and the capacity of the operator working on the task. Mental workload is high when the difference between task demands and capacity is small. The RSME, originally developed by Zijlstra in 1993, is a one-dimensional scale with ratings between 0 and 150. The scale has nine descriptive indicators along its axis (e.g., 12 corresponds to *not effortful*, 58 to *rather effortful*, and 113 to *extremely effortful*). It is designed to minimize individual differences. We selected the RSME because it is simple to administer, is not intrusive, and at the same time it provides a good indication of the total mental workload (Veltman & Gaillard, 1996; see also Van der Kleij et al., 2006, 2009).

2.4.2.5. Subjective assessment of support conditions and strategies. At the end of the experiment, the participants were interviewed as a team to assess participants' subjective evaluation of the four different support conditions, in general, as well as strategies teams used to perform the task. With regard to overall subjective evaluation, participants were asked to specify which type of support they liked best, second best, third best, and which they liked least. With regard to work strategies, participants were asked to specify for each support condition the strategy the team used to perform the task.

2.5. Procedure

Upon arrival an informed consent was obtained and each participant was led to a separate room, each of which contained two computers with two monitors, a controller and a headset. Participants had an instruction sheet in front of them with facts about the different types of victims in the simulation (see also Table 1). When participants were seated, instructions about the task were given on paper. After clarifying the instructions, the first trial started. Each trial lasted 20 min. The simulation was run six times. The first two trials were training trials, which we told participants before they started working. The training trials were set up to familiarize participants with navigation through the Unreal Tournament environment, the task, the support conditions, and communicating through the headsets. During and after each training trial, the experimenter gave instructions and feedback. A Latin square design was applied to ensure that the four experimental conditions were equally divided across teams and order of appearance. After each experimental trial, the participants individually filled in a questionnaire that measured satisfaction and information exchange and a rating scale for mental effort. After the last game the participants were debriefed and interviewed together about the experiment.

3. Results

One-way repeated-measures ANOVA was used to analyze the data. In all cases, an α level of .05 was used to determine statistical significance. Analyses were performed at the team level to account for statistical interdependence (Kenny, Kashy, & Bolger, 1998). Table 2 summarizes the means and standard deviations for the dependent variables across conditions.

3.1. Demographic characteristics and experience with computer games

A baseline questionnaire was included at the beginning of the experiment that assessed basic demographic information, including age and gender, and participants' experience with working in teams, playing computer games, ego-shooter games, and Unreal Tournament. Participants had a reasonable amount of working experience in teams ($M = 4.96$, $SD = 1.52$), an average amount of playing with computer games ($M = 3.25$, $SD = 1.78$), a small amount of experience with playing with ego-shooter games ($M = 2.29$, $SD = 1.76$), and minor experience with playing Unreal Tournament ($M = 1.71$, $SD = 1.34$), all on a scale of 1–7. Since no differences were found between teams, it is not discussed further.

3.2. Team performance

There was a significant main effect of support condition on team performance, $F(3, 45) = 42.48$, $p = .00$, $\eta_p^2 = .74$. Post hoc analyses using Tukey's least significant difference (LSD) test revealed that teams in the connected, $F(1, 15) = 84.77$ ($M = 173.125$), weakly connected with network-aware support, $F(1, 15) = 105.21$ ($M = 172.50$), and the weakly connected *without* support, $F(1, 15) = 94.48$ ($M = 165.00$), conditions saved significant more victims than the teams in the disconnected condition ($M = 52.50$). However, contrary to expectations, the blob interface did not allow for more lives to be saved as compared to teams without support. Moreover, the strongly connected condition did not allow teams to rescue more victims

Table 2
Cell means (M) and standard deviations (SD) of the dependent variables by support condition.

Dependent variable	Support condition				Row
	Connected	Disconnected	Weakly connected, with blobs	Weakly connected, without blobs	
Team performance[a]	173.13 (50.76)	52.50 (10.65)	172.50 (49.63)	165.00 (48.41)	140.78 (29.86)
Process satisfaction[b]	5.93 (.37)	5.20 (.68)	5.53 (.51)	5.49 (.70)	5.54 (.38)
Outcome satisfaction[b]	5.54 (.36)	4.68 (.47)	5.27 (.33)	5.28 (.44)	5.19 (.24)
Information exchange[b]	5.63 (.38)	5.19 (.73)	5.38 (.45)	5.56 (.50)	5.44 (.41)
Mental effort[c]	61.92 (12.94)	43.13 (19.59)	61.60 (13.36)	60.60 (13.02)	56.81 (11.67)

Note. Values enclosed in parentheses represent standard deviations.
[a] The values represent mean team scores on the task. The maximum score is 420.
[b] The values represent mean scores on seven-point Likert scales.
[c] The values represent mean scores on a one-dimensional scale with ratings between 0 and 150. The scale has nine descriptive indicators along its axis (e.g., 12 corresponds to not effortful, 58 to rather effortful, and 113 to extremely effortful).

than teams that were weakly connected, regardless of whether these teams were equipped with the blob interface or not.

3.3. Participant ratings

3.3.1. Process satisfaction

A significant main effect of support condition was found for process satisfaction, $F(3, 45) = 5.50$, $p = .003$, $\eta_p^2 = .27$. Post hoc analyses revealed that process satisfaction was significantly lower in the disconnected, $F(1, 15) = 15.64$ ($M = 5.20$), weakly connected with network-aware support, $F(1, 15) = 5.94$ ($M = 5.53$), and weakly connected *without* support, $F(1, 15) = 4.93$ ($M = 5.49$), conditions than in the connected condition ($M = 5.93$). Moreover, process satisfaction in the disconnected condition was significant lower than in the weakly connected with network-aware support condition, $F(1, 15) = 4.71$ ($M = 5.53$). However, no differences were present between the weakly connected conditions.

3.3.2. Outcome satisfaction

There was a significant main effect of support condition on outcome satisfaction, $F(3, 45) = 14.96$, $p = .00$, $\eta_p^2 = .50$. Post hoc analyses showed that the outcome satisfaction in the disconnected, $F(1, 15) = 39.48$ ($M = 4.68$), condition was significant lower than in the connected condition ($M = 5.54$). Moreover, outcome satisfaction in the weakly connected condition with network-aware support, $F(1, 15) = 30.32$ ($M = 5.27$), and the weakly connected condition *without* support, $F(1, 15) = 16.68$ ($M = 5.28$), was significant higher than in the disconnected condition. Again, no differences were present between the condition with network-aware support and the condition *without* the blob interface.

3.3.3. Information exchange

There was a significant main effect of support condition on the quality of the exchange of information, $F(3, 45) = 4.06$, $p = .034$, $\eta_p^2 = .21$. Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of the conditions, $\chi^2(5) = 16.00$, $p = .007$. Therefore, degrees of freedom were corrected using the Greenhouse–Geisser estimates of sphericity ($\varepsilon = .59$). Post hoc analyses revealed that the quality of information exchange were significant higher in the connected condition, $F(1, 15) = 6.24$ ($M = 5.63$), and weakly connected without support condition, $F(1, 15) = 5.67$ ($M = 5.56$), than in the disconnected condition ($M = 5.19$). Further, it was also revealed that the quality of the exchange of information in the weakly connected condition with network-aware support, was significant lower than in the connected condition, $F(1, 15) = 5.85$ ($M = 5.38$). No differences were found between the weakly connected condition with network-aware support and the condition *without* support.

3.3.4. Mental effort

There was a significant main effect of support condition on the experience of mental effort, $F(3, 45) = 11.30$, $p = .001$, $\eta_p^2 = .43$. Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of the conditions, $\chi^2(5) = 26.45$, $p = .00$. Degrees of freedom were corrected using the Greenhouse–Geisser estimates of sphericity ($\varepsilon = .48$). Post hoc analyses showed that mental effort expenditure in the connected condition, $F(1, 15) = 17.09$ ($M = 61.92$), weakly connected with network-aware support condition, $F(1, 15) = 13.07$ ($M = 61.61$), and in the weakly connected *without* support condition, $F(1, 15) = 10.30$ ($M = 60.60$), were significant higher than in the disconnected condition ($M = 43.13$). This finding lends support for the view that presenting additional information may overload the user instead of reducing the cognitive load (cf. Janis & Mann, 1977; Schneider, 1987).

3.3.5. Subjective assessment of support conditions and strategies

As expected, with regard to overall subjective evaluation of the four different support conditions, all teams preferred the strongly connected condition, which delivered real-time situation updates, provided information on the location of other responders, and information on the victims. Interesting to note is that teams also reported that there was more interpersonal communication in this condition than in other conditions. Participants perceived the disconnected condition as the condition in which the lowest amount of communication had occurred, a perception which was confirmed by our observations. This was rather unexpected. We had hypothesized that additional information on the situation, the location of other responders, and information on the victims, would lower the need to communicate: Why communicate when you have all information to perform the task at your disposal? Apparently, the more information teams have, the more there is to communicate about. This explanation was acknowledged by our participants. Teams used information to coordinate their joint efforts. When there was no information at all, teams only communicated their own locations to each other to make sure that they covered as much of the disaster area as possible.

Most teams selected the weakly connected condition, with network-aware support as second best, although two teams selected this condition as being least preferred. Teams appreciated especially the notification function of the blobs, signaling that network connections were lost. Only three teams found the animations useful in assisting them in visualizing the possible location of fellow responders during loss of network connections. The two teams that preferred this condition least indicated that the blobs cluttered the screen, were distracting, and led to inertness. The completely disconnected condition and the weakly connected condition *without* support were selected by an equal amount of teams as being least preferred.

With regard to work strategies, most teams used a combination of two strategies. The first strategy, which was used in all four experimental conditions, was to work separately from three equally sized areas on the map until their joint efforts were needed. Another strategy teams used, except for teams in the disconnected condition, was to work with a self-selected dispatcher function coordinating the joint efforts of other members. Usually this function was fulfilled by the person who was the furthest away from the location of the victim that needed to be rescued.

4. Discussion

Teamwork is important. When we assign a task to a team rather than to an individual, there are several benefits, such as the ability to work in parallel and speed up work processes. Proximity is an important moderator to good teamwork. Proximity helps to initiate communication, conduct a conversation, and maintain awareness of the state of the environment, task, and team (Kiesler & Cummings, 2002; Kraut, Fussell, Brennan, & Siegel, 2002). Mobile distributed teams of fielded first responders lack physical proximity. This can constitute a major barrier to team effectiveness (for an overview, see Van der Kleij, 2007). For example, in distributed teams, it becomes more difficult to have an ongoing awareness of other team members' endeavors and to maintain a common picture of the problem at hand. Without some sort of knowledge of the progress of team tasks, what fellow workers are doing, who is communicating with whom, what equipment is out of order, and so forth, it becomes difficult, or even impossible, to engage in coordinated teamwork.

The present research was set up as a detailed empirical study to increase knowledge and understanding of the factors that are important for successful teamwork in mobile distributed teams of first responders. Information is critical to collaboration in mobile distributed teams. However, these teams sometimes have to work in the presence of an unreliable communications infrastructure, leading to information shortages and suboptimal coordination between team members. Our main goal was to conceive and test a solution to this problem; namely a mobile network-aware groupware application that signals network loss to the users and adapts the graphical presentations of the locations of fellow team members according to the quality of location information present. This application was hypothesized to assist mobile distributed first responders in making inferences about the possible location of fellow responders during losses of network connections, helping them to coordinate their collaborative efforts and fight the crisis effectively. To test the application and investigate the added value of signification of network loss and visualization of geospatial information uncertainty, we compared the network-aware application to three realistic situations: a situation in which participants had complete and reliable information (i.e., there was no need for signification of network loss); a baseline situation in which participants had almost no information at all; and a situation in which participants were connected to an error prone link, however, without a network-aware application signaling losses of network connections.

Below we discuss the main results. First, we discuss the importance of the real-time mapping of participants' positions on a representation of the environment in the form of a map. Second, we discuss the added value of network-aware support. It is important to note that the participants in this research were all students that had no considerable stake in the outcome of their interaction. Moreover, the task used in the experiment lacks the richness and complexity of real search and rescue tasks, stress is limited, and no life-threatening situations occur in the lab. Although the laboratory offers several advantages (see Driskell & Salas, 1992; Elmes, Kantowitz, & Roediger, 1992), it may also raise questions regarding the transfer of the research findings to the field. For example, university student may act differently than first responders. To minimize this risk, we have chosen a task for this study that does not require specific knowledge about search and rescue tasks, but focuses on the development of situation awareness and the use of uncertain information in planning and decision making. These are rather generic activities for which students can be used as participants. Thus, although the task environment provided by our experimentation platform had low fidelity, the validity of the simulation was high. This does not mean that experimentation in virtual task environments can completely replace field testing. However, this setting does allow us to eliminate mistakes and design flaws in an efficient and cost-effective manner before a new tool is brought to the field for more extensive testing.

In general, the results demonstrated the benefits of delivering accurate and real-time location-awareness information to distributed teams (cf. Nova, 2007). Teams connected to a server over a fast and reliable link showed superior performance over teams with no network connection whatsoever to a server. Providing accurate and real-time location-awareness information also increased the quality of information exchange in the team and the amount of satisfaction with team processes and outcomes. Interestingly, these benefits were accomplished at the costs of a higher mental workload. Participants apparently needed to accelerate their cognitive functioning to process the extra information (see also Van der Kleij, Paashuis, Langefeld, & Schraagen, 2004). In addition, we learned from the interviews at the end of the experiment that teams connected to a server over a fast and reliable link communicated more to coordinate their joint efforts. As mentioned, this was contrary to expectations. We hypothesized that the accurate presentation of partners' position in the environment would result in a simplification of communication; that is a decrease in the volume of communication. A likely explanation is that the increased availability of information increased the need for information exchange and communication, again increasing the expenditure of effort.

Participants indicated a preference for the blob interface over the condition without support signaling network loss. Teams appreciated especially the notification function of the blobs, signaling that network connections were lost. Animations visualizing the possible location of fellow responders during loss of network connections were not perceived as useful by the majority of our participants. The blob interface, however, did not reduce the cognitive load of team members, nor did it increase satisfaction or made information exchange between interdependent team members more efficient. More importantly, the blob interface did not help distributed teams to save more 'lives'. Thus, notwithstanding the theorized benefits of dynamic signaling of network loss and the preference for network-aware support of our participants, presenting uncertainty did not result in more optimal team work.

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