The Effect of Geographical Information Systems on a Collaborative Command and Control Task

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ABSTRACT

This paper tests the claimed benefits of using geographical information systems (GIS) in emergency response operations. An experimental study comparing command teams using GIS and paper-based maps is presented. The study utilized a combined approach using microworld simulations together with physical artefacts. Participants in the experiment took the role of command teams, facing the task of extinguishing a simulated forest fire. A total of 132 persons, forming 22 teams, participated in the study. In eleven of the teams, the participants were given access to GIS with positioning of fire-brigades as well as sensor data about the fire outbreak. In the other eleven teams, the participants were using paper-based maps. The result shows that teams using GIS performed significantly better than teams with paper-based maps in terms of saved area. Communication volume was considerably reduced in the case of GIS teams. Implications of these results on GIS are discussed as well as methodological considerations for future research.

Keywords

Geographical information systems, command and control, emergency response, microworld simulations, communication, performance.

INTRODUCTION

In the last two decades, many organizations working with emergency management (EM) have made extensive investments in various information and communication technologies (ICT), such as geographical information systems (GIS), advanced databases, and mobile applications, with the goal of increasing performance and control in their work. This includes management of everyday accidents and emergencies, as well as response to crises and disasters. Various powerful, easy to use – and understandable – computer-based decision support and information management systems have been proposed to assist EM participants to achieve a higher level of sophistication in information support during emergency response efforts (for example Fedra, 1998; Iakovou and Douligeris, 2001).

At the same time, the impacts of modern ICT on real-life work practice have received attention from the scientific community. Fields like computer supported cooperative work (Schmidt and Bannon, 1992), distributed cognition (Hutchins, 1995) and cognitive systems engineering (Hollnagel and Woods, 2005) have all emphasized the importance of studying actual use of new systems in practice, rather than to draw conclusions from hypothetical gains of new technology.

In this research, the aim is to test whether the use of GIS leads to performance improvements in emergency response. Low-fidelity simulations, so called microworlds (Brehmer and Dörner, 1992; Brehmer 2004), were used in order to investigate the effects of GIS on a collaborative command and control task. The effects were examined both in terms of performance implications as well as impacts on process with respect to communication.

Background

Geographical information systems (GIS) are computer-based systems, which integrate different technologies for spatial visualization, data management, decision modeling, and planning, and provide a common organizational framework for heterogeneous multidimensional data (Laurini and Thompson, 1996; Bernhardsen, 1999; Maguire et al., 1991). In EM, most of the initiatives to use and integrate GIS within the work of EM organizations have arisen in the last two decades (Dash, 1997; Zerger and Smith, 2003). GIS have been used to support emergency response operations during the World Trade Center terrorist attacks (Thomas et al., 2002; Kevany, 2003), the hurricane Fran (Dymon, 1999) and Katrina (Roper et al., 2006) response and recovery, and many others.

Present GIS for command and control applications are designed to support tasks such as real-time assessment of the responded events, access to operational data about the target area and the operational resources, and, not the least, data exchange between commanding officers. Such support GIS offers may influence the way that commanding officers give orders to their subordinates, for example in form of mission tactics (extinguish fires north east of city X), or direct control (go to position x, y), and consequently how well command teams perform. For example, the mimetic representation of reality that GIS provides to its users may encourage such direct control (Johansson et al., 2001). Thus, the communication is likely to be different with GIS compared to the traditional data exchange using paper-based maps.

At the same time, the handling of systems, such as GIS, is becoming increasingly complex, requiring much attention from the users under a high level of stress. In many EM organizations, commanding officers do not work with GIS on a daily basis. These commanding officers have often problems to fully exploit the functionality as well as to understand and interpret the presented data in GIS. Many EM organizations working with GIS may thus encounter significant problems in using these systems when they are challenged by extraordinary situations that demand use beyond the 'normal' operations. In such situations, for example large flooding, forest fires and storms, it happens that GIS is abandoned for less sophisticated equipment, especially in communication intensive phases (Johansson and Persson, 2002). This development is worrying since ICT, and particularly GIS, are becoming an indispensable part of modern emergency response operations (Mendonça et al., 2001). Most command and control systems are also becoming more and more coupled, meaning that it soon will be impossible to perform important tasks without using the equipment (Johansson and Persson, 2002). There is thus a risk that GIS-based command and control applications meant to improve efficiency may actually become a bottleneck for performance.

The issue of performance and communication in emergency operations when using GIS has not been investigated in this context earlier. Aldaijy (2004) examines GIS effectiveness in EM, however between different GIS solutions and by using a survey. From general GIS and organizational research, studies systematically evaluating performance, efficiency and effectiveness are also limited (Budic, 1994; Gillespie, 2000). From studies investigating the benefits of introducing GIS in terms of productivity, Buckley can be mentioned. Buckley (1998) suggests that there is a rather unusual productivity curve related to GIS implementation, something that indicates that GIS may even potentially hamper performance, at least if the involved personnel does not work with GIS on a daily basis. Studies by Johansson et al. (2003) or Uran and Janssen (2003) have also suggested that the gain of introducing GIS is far from self-evident.

RESEARCH AIM

By utilizing a combined approach using microworld simulations together with physical artefacts, in this case paper-based maps, this research aims to test GIS and its effects on the command and control task in terms of performance and communication. No simple straightforward hypothesis is formulated since there are two possible assumptions. First, command teams using GIS can perform better due to faster and more accurate data access and sharing provided by GIS. At the same time, the GIS teams can perform worse than command teams using paper-based maps. The GIS team members have received only short introductory GIS training and may thus experience difficulties in handling the GIS technology.

The research questions are therefore set as follows:

- Will command teams using GIS perform differently than command teams using paper-based maps in extinguishing a simulated forest-fire and in what way?

- Will the communication volume of command teams using GIS be changed compared to command teams using paper-based maps and how?

METHOD

The method used is controlled experiments using a microworld simulation. Microworlds are low-fidelity computer simulations, providing a computer-generated task environment that has complex, dynamic and opaque characteristics (Svenmarck and Brehmer, 1991; Brehmer and Dörner, 1993; Granlund, 1997; Granlund, 2002). Many of the characteristics in the microworlds are similar to the characteristics of tasks that people normally encounter in real-life situations, allowing controlled studies of decision-making, both by individuals and teams of decision-makers (Brehmer and Dörner, 1993; Granlund, 1997; Rolo and Diaz-Cabrera, 2001; Granlund et al., 2001; Gonzalez et al., 2005). The experimental sessions are usually rather short, between 20-30 minutes per session; at the same time, larger sets of sessions are commonly run. As the simulation is fully computer-based advanced monitoring tools can be used, and data on wide range of parameters can be gathered (Granlund et al., 2001).

Microworld simulations have been used in a number of studies on team decision-making and performance (Svenmarck and Brehmer, 1991; Howie and Vicente, 1998; Granlund, 2002, 2003; Granlund and Johansson, 2003; Jobidon et al., 2006). Microworlds have also been used to study cultural differences in teamwork (Lindgren and Smith, 2006a, 2006b), as well as to test new ideas and effects concerning ICT in command and control (Johansson et al., 2000, 2005). For an elaborated discussion about the use of microworlds in research, please see (Brehmer and Dörner, 1993; Brehmer, 2004).

In this study, the C3Fire microworld (Granlund, 1997; Granlund, 2002; Granlund and Johansson, 2004), specifically designed for command and control studies, was used. The C3Fire microworld simulates forest fire-fighting. In the C3Fire microworld participants, participants' organization and communication structures can be set up in accordance with the research goal. The user interfaces and communication tools can be individually set-up for all participants. The “world” in C3Fire is comprised of a number of quadratic cells, which, apart from representing different types of terrain, can take different states (not burning, burning, closed out, burned out). These states are generally used as a measure of performance in the microworlds simulating fire-fighting tasks (Lövborg and Brehmer, 1991; Svenmarck and Brehmer, 1991).

For this study, a new GIS module with advanced GIS capabilities corresponding to present GIS in command and control applications was developed. This GIS module includes modifications in three areas compared to previous applications of the C3Fire microworld: GI visualization, GIS functionality and map input. From the visualization perspective, it possible to use different map views and layers. The module also makes it possible for the participants to swap between various types of map layers in a single map window. Map layers provided to the participants in the map windows are traditional cartographic products, such as topographical, orthophoto, and land use maps.

Experimental Design

The study is a between groups design with one factor: (a) command teams using GIS combined with direct update of fire-brigade positions and fire outbreak sensor capacity, and (b) command teams using paper-based maps. The difference between the two conditions is thus the support the participants obtain in terms of visualization and data sources. At the same time all the teams face the same scenarios.

Eleven teams were tested in each condition, meaning a total of 22 teams consisting of six persons, summing up to 132 participants. The participants were university students. Optimally, real fire-fighters should have participated in the study in order to increase the ecological validity of the findings. Rogalski (1999) has, for example, found differences in the way experts and novices act in EM tasks. Johansson et al. (2005) have also suggested professional participants as a way to increase the ecological validity of microworld simulations. However, considering the length of this study, and the high number of participants needed (132 in total) we decided to use university students, since it would be too difficult to use real fire-fighters.

Each team consisted of six participants; three working as commanding officers and three as ground chiefs controlling three fire-brigades each (see Fig. 1 and 3 below).

Every team performed five trials, lasting for 20 minutes each. The teams were also given an introduction to the simulation for about 20 minutes. An earlier study by Svenmarck and Brehmer (1991), also using forest fire simulations, has shown that the performance curve stabilizes between the third and the fifth trial. Therefore we chose to limit the study to five trials per team, partly for practical reasons, but also because of the above mentioned indication that performance stabilizes at that level. To engage the participants for more than three-four hours may also lead to undesired fatigue, which could have unwanted effects on the outcome of the simulations.

The GIS Condition

Command teams using GIS have precise and accurate real-time data available from the GIS, but face the problem of managing the technology (see Fig. 1). Just like in many real-world situations, this is not a system the participants would work with on a daily basis.

The participants acting as commanding officers have access to three computer terminals. One terminal is equipped with GIS, providing access to three different digital map layers – topographical map (1:50 000), road map (1:100 000), and orthophoto (black & white, 5m resolution) – with possibility to swap between the map layers (see Fig. 2). The other two terminals are designed for communication purposes between the commanding officers and ground chiefs.

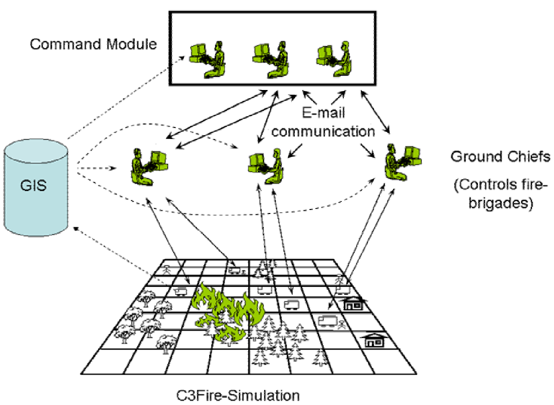

Figure 1. The commanding officers have access to different map layers, exact position of the fire-brigades and location of the fires via the GIS module.

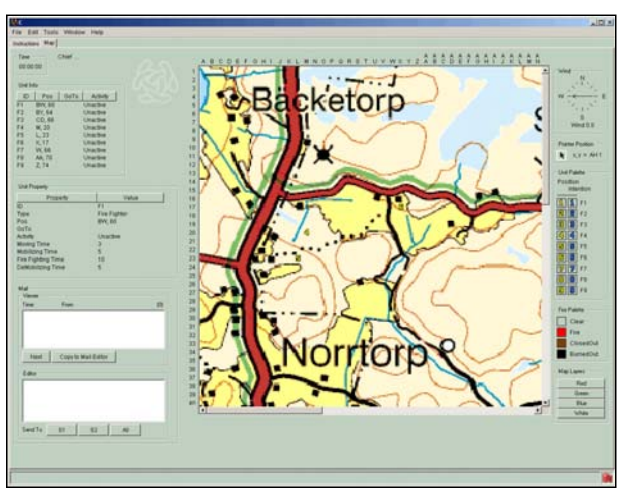

Figure 2. Screenshot of the GIS-equipped terminal for the commanding officers

The Paper-Based Map Condition

In the paper-based map condition the participants acting as commanding officers lack the GIS and can acquire knowledge about the state of the forest fire and fire-brigade positions only by communicating (via e-mail) with their ground chiefs (see Fig. 3). Although this clearly is a less precise and slower way to obtain data about the state of the fire and positions of the fire-brigades, the commanding officers work with a medium, a paper-based map, which requires no technical competence.

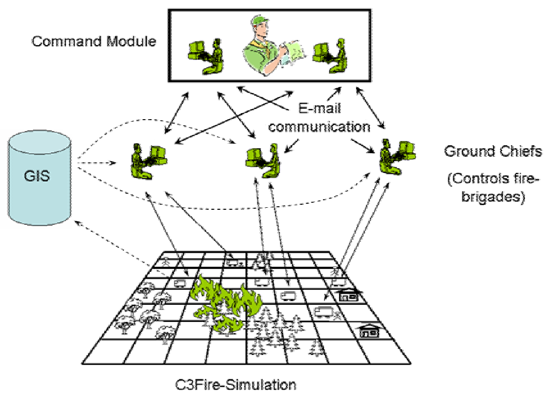

Figure 3. The commanding officers have access to the state of the simulation only through the e-mails they exchange with the ground chiefs and the notes they make on a traditional paper-based map.

The commanding officers have one custom-made paper-based map available. This custom-made map is based on the topographical map (1:50 000) adjusted to the scale 1:17 300 and the C3Fire microworld coordinate system (see Fig. 4, below). Besides the paper-based map, the commanding officers have also access to two communication terminals.

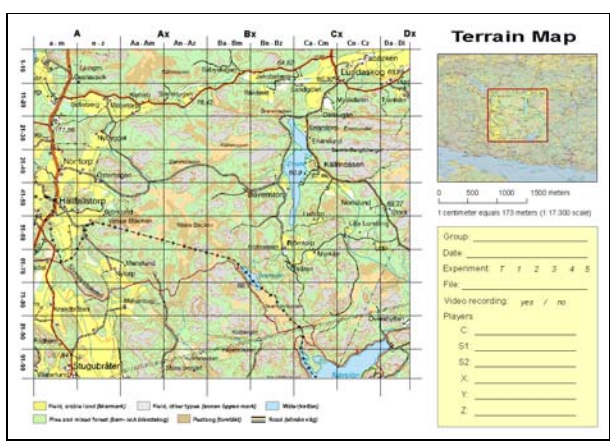

Figure 4. A custom-designed paper-based map the commanding officers use during the sessions.

Ground Chiefs

In both conditions, the ground chiefs have access to a single layer digital map (topographical map, 1:50 000) integrated with the communication tool (see Fig. 5).

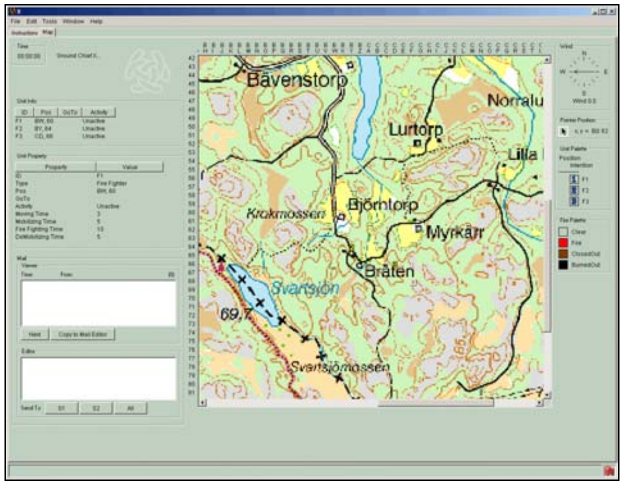

Figure 5. Screenshot of the terminal for the ground chiefs.

Scenario

During the particular trials, three forest fires start on different places. The location of the fires is different in each trial. This is same for all the 22 teams. Each trial is also defined with a scenario. The scenario contains information about wind direction and its strength as well as messages, which are sent automatically to the participants to help them create an understanding of the situation. The design of the scenarios is made in such a way that a team that uses all of their resources on only one fire has problems in extinguishing the other two fires. Inattentive commanding officers also face issues of missed incoming messages concerning new fires. Consequently this inattention leads to a slower response and greater loss of terrain, i.e., greater number of burned out cells.

Data Collection

The dependent measure is non-burned out area. This measure is commonly used in the fire-fighting tasks (Svenmarck and Brehmer, 1991; Johansson et al., 2000). Each trial represents one measure in respect to performance. At the end of each trial, the percentage of non-burned out cells is counted and used as a performance measure (a high score is desired). This is motivated by the fact that a successful team should be able to respond quickly to incoming alarms while at the same time use their resources effectively in order to minimize the consequences of the forest fires.

All e-mails sent between the participants are also saved into a log-file. Information about sender and receiver, as well as time when the e-mails were sent, received and opened are also documented.

RESULTS

The results presented in this section are the outcome of the quantitative data analysis, which is based on the log-file data concerning the fire-fighting performance and e-mail communication. The results are based on data from a total of 22 teams (eleven in each condition), consisting of six participants in each team.

Non-Burned Out Areas

The first overall measure of non-burned out area between the two conditions clearly show that the command teams using GIS performed better than teams using a paper-based map in terms of percentage of saved area (see Fig. 6).

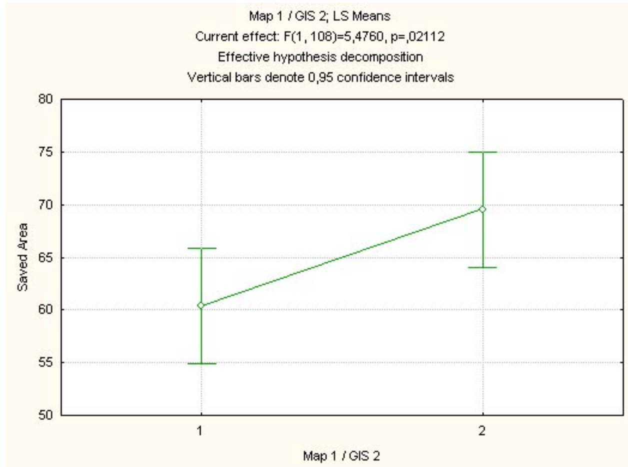

Figure 6. Non-burned out area in the two conditions: the teams using paper-based maps are presented as 1; the teams using GIS as 2. A significant difference between the two conditions is calculated to P=0,021 (N=22).

The main result from the statistical analysis of the non-burned area is thus that there is a difference in terms of performance between the two conditions if the mean of all trials in each condition is considered.

Communication Density

The number of e-mails sent between the commanding officers and the ground chiefs suggests that GIS reduce the need for communication between the commanding officers and the ground chiefs. The statistical analysis of the data (see Fig. 7) shows that there is a significant difference between the conditions in terms of the number of sent e-mails ($P<0,01$). In the GIS condition, there is an average of 92 e-mails in each trial and in the paper-based map condition, there is an average of 140 e-mails ($P<0,01$, N=22).

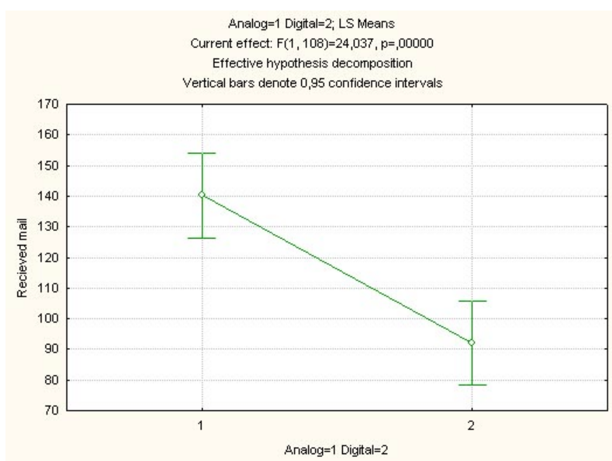

Figure 7. Number of exchanged e-mails in the two conditions (teams using paper-based maps = 1, teams using GIS = 2). There is a significant difference (P<0,01) between the two conditions.

DISCUSSION AND CONCLUSIONS

This study was designed to investigate the use of GIS and its performance and communication impacts on emergency response operations, an important and highly relevant question for both EM and GIS research. Summarizing the findings concerning the performance and communication the following conclusions may be drawn:

- *GIS improves performance of command teams* - Command teams using GIS performed significantly better than command teams using paper-based maps. The commanding officers in the GIS teams had, besides the situation reports from the ground chiefs, also access to accurate real-time data on positions of the fire-brigades and the fire outbreak, which contributed to improved performance of these teams.
- *GIS reduces communication volume* - Communication volume between the commanding officers and the ground chiefs was reduced when supported with GIS. Command teams using GIS exchanged significantly fewer messages that command teams using paper-based maps. The commanding officers in the GIS teams could see what was going on in the field and had thus less need for information concerning position of the fire-brigades and the fire outbreak.

The results of this study support the statements about the capabilities and benefits of GIS. Relatively simple GIS applications combining real-time positioning of resources and sensor data improves performance of command teams, reduce their communication volume, and do not require extensive training of the users compared to the traditional command and control work using paper-based maps.

Besides the empirical findings, this study also makes methodological contribution. By incorporating GIS functionality in the C3Fire microworld, we have combined the basic features of a modern GIS and a well-established research tool, which allow to further investigate the pros and cons of GIS usage in complex situations under controlled forms, something that is difficult to achieve in traditional evaluation studies. This includes studies on effects of new functions, different types of geospatial data and their visualization on collaborative time critical work. The log-files generated in the C3Fire microworld allow not only analysis of the simulation generated data but also the actual work processes and communication of the participants, i.e., non-GIS related factors that may influence the performance in a real work settings. Thus, the GIS functionality introduced into the already established research conducted with microworld simulations has opened a novel field of exploration in the area of GIS and EM.

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