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Dynamics of Communication in Emergency Management

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SUMMARY

This study investigated the dynamics of communication between members of an emergency management team faced with controlling a hazardous chemical spill. The effects of two sets of factors on communication were investigated; task-specific factors pertaining to characteristics of the emergency management task that are constant across different emergency situations, and situation-specific factors pertaining to the unique characteristics of the current situation. The results showed that both these factors were important in determining the pattern of communication between key team members. Verbal exchanges were found both to be correlated with the occurrence of critical events and to follow a 30-minute temporal cycle. The implications of the results for theories of naturalistic decision making are discussed. Copyright © 2002 John Wiley & Sons, Ltd.

In emergency management, individuals must work together to contain and resolve a hazardous event. With each team member performing a specialized function, the effectiveness of the team depends upon the ability of its members to communicate with each other to coordinate activities, to share information, and to implement appropriate strategies (Caldwell, 1997). Decision making is thus said to be distributed across the members of the team (Brehmer, 1991; Rogalski and Samuray, 1993). But without a high level of interaction, distributed decision making will fail. For this reason, a critical factor affecting team function concerns the nature and timing of verbal exchanges between team members.

The present study represents a relatively new approach to naturalistic decision making. Previous research has often been concerned with analyses of the cognitive aspects of decision making, based on the view that the most important determinants of behaviour are the cognitive representations of team members. Our study was based on a different view, namely that many important determinants of behaviour reflect characteristics of the task environment, the problems it poses, and the constraints it provides. On this view, theoretically important relationships exist between features of the task environment and human performance. To illustrate, Vortac *et al.* (1993) examined the behaviour of air traffic controllers in a simulation involving different degrees of traffic complexity. The onsets of various activities (e.g. issuing commands to aircraft) were recorded on-line, and the transition probabilities between different activities were analysed statistically. This analysis revealed a number of dynamical regularities that Vortac *et al.* (1994) explained

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in terms of the creation, by experienced controllers, of behavioural modules or chunks of activities that tended to be performed together, such as updating 'flight progress strips'. Detection of these modules was possible only through behavioural analysis because the controllers themselves were unaware of this aspect of their behaviour. Moreover, the relevance of the modules to cognitive processing was established in a subsequent experiment (Vortac and Manning, 1994), which showed that their disruption by partial automation adversely affected performance. Hence, the search for statistical regularities in task environment or behaviour can help to identify processes underlying performance.

Accordingly, the present study examined the dynamics of verbal exchanges between key members of an emergency management team engaged in the control of a simulated chemical spill. We focused on the temporal distribution of verbal exchanges. Are verbal exchanges more likely during some periods than others? If so, what are the factors that determine periods of increased communication? In this regard, it is useful to distinguish between *task-specific* and *situation-specific* factors. Task-specific factors consist of intrinsic characteristics of emergency management that tend to remain relatively stable across different situations. Such factors may include the rate at which new information accrues or events unfold, the perceived importance of coordinated activity to goal achievement, and the relative ease or difficulty of communication. Experienced team members may develop patterns of communication that reflect these global aspects of the emergency management task, similar to the stable behavioural modules discovered by Vortac *et al.* (1993). In contrast, situation-specific factors relate to characteristics of the current situation that are novel, unique, or unpredictable. Examples of such characteristics include the timing and nature of critical events, the availability of new information at particular times, and sudden failures of equipment.

COMMUNICATION MANAGEMENT

Communication between team members is vital to emergency management. At the same time, individuals must also perform their operational tasks. For example, the task of the incident controller (who bears overall responsibility for the incident) may consist of developing an overall awareness of the situation, generating and testing alternative strategies, and recruiting and committing resources. Cannon-Bowers *et al.* (1993) suggested that as teams become more experienced, two constellations of skills, or *tracks*, evolve. The *taskwork track* involves skills for the execution of individual operational tasks while the *teamwork track* involves skills related to effective functioning as a team member.

Optimal performance requires both good taskwork and good teamwork. For example, in a study by Foushee *et al.*, (1986) the performance of flight crews depended on the amount of task-relevant talk. Similarly, Caldwell and Everhart (1996) found that the number of words exchanged between team members was a significant covariate of performance in a simulated navigation task. Yet under some circumstances, these team-related activities may also compete with other demands on the resources of individuals. That is, at any one moment each team member is faced with the meta-task of allocating resources (such as time) to either taskwork or teamwork. Evidence of competition between these resource demands is found in studies that show an inverse relationship between task-related functions and verbal exchanges. For example, Kleinman and Serfaty (1989) observed that during periods of high workload, communication decreased between team members in a simulated military command and control task. Team members relied on unprompted or 'implicit' coordination involving routinized work patterns, few verbal exchanges, and unsolicited resource transfers (see also Urban *et al.*, 1996). Finally, Orasanu (1990) observed that good cockpit crews scheduled teamwork activities during periods of low taskwork.

The contrast between teamwork and taskwork indicates that communication carries both benefits and costs. This idea has been explored in a number of simulation studies by Billard and Pasquale (1993, 1995). They examined the behaviour of agents that attempted to optimize a payoff matrix by following simple rules. Payoffs were maximized if the different agents accurately predicted the behaviour of other agents, thus successfully coordinating their actions. At any given time, each agent had to select a strategy based on its knowledge of the preferred strategies of the other agents. With perfect knowledge, all agents could converge on a mixture of strategies, each selected with a fixed probability. However, perfect knowledge could only be attained through communication which, in the performance payoffs devised by Billard and Pasquale, incurred a cost (see also Brehmer, 1995). By minimizing communication, each agent could avoid much of this cost but risked acting on out-of-date information, thus jeopardizing coordination and overall performance. Importantly, Billard and Pasquale (1995) observed that for a given communication cost, there existed an optimum communication period that maximized performance. If agents communicated less frequently than optimal, performance was compromised by acting on incorrect information. If they communicated more frequently than optimal, performance was less efficient due to the cost of communication and diversion of time and resources from taskwork.

In summary, one of the principal decisions in a distributed decision-making team concerns the timing and content of communications among team members. Different communications will be perceived as having different values and team members must decide when communication is warranted in order to maintain an optimal level of performance.

MODELS OF COMMUNICATION MANAGEMENT

What factors trigger verbal exchanges between team members in an emergency situation? We consider this question in terms of the earlier distinction between task- and situation-specific factors. We first identify two broad classes of task-specific strategies that team members may adopt on the basis of experience. The first is called the *constant exchange* strategy. Using this strategy, team members choose to communicate with a fixed probability that is determined by the perceived benefit of communication relative to other activities. The rate of communication will therefore be more or less time-invariant. The second strategy, called *periodic exchange*, is based on Billard and Pasquale's (1993, 1995) discovery of an optimum communication delay for a given cost–benefit payoff. If this strategy is used, team members will attempt periodic exchanges of information in order to maintain similar levels of knowledge. As a result, communication patterns should be cyclic—periods of relatively high communication rates should be separated by periods of relatively low rates.

In addition to these task-specific factors, communication may also be affected by situation-specific factors that unfold variably and unpredictably. These may include critical events such as the discovery that a vehicle involved in a traffic accident is carrying a highly flammable liquid, or that a workman is trapped in a burning building. Based on these considerations, one of two strategies may result. The first of these, called the *critical event* strategy, is based on the recognition-primed decision model developed by Klein and his co-workers (e.g. Klein, 1993, 1997, 1998) to describe the cognitive processes involved in naturalistic decision making. This model was developed to account for the results of structured interviews with experienced decision makers (Klein *et al.*, 1989).

The recognition-primed decision model accounts for two fundamental processes in naturalistic decision making; evaluation of the current situation and evaluation of a proposed course of action. According to a recent version of the model, decision makers may respond in one of three ways to a critical event (Klein, 1998). In the first response, called *simple match*, the decision maker recognizes the situation as typical of others dealt with in the past. The decision maker thus uses memory to retrieve a set of plausible goals, expectancies, relevant cues, and, typically, a single action. In the second response, called *diagnosis*, the decision maker is unable to recognize a situation as typical. In order to resolve this uncertainty, the decision maker enters a data-acquisition loop in which additional information is gathered and memory is utilized to construct a coherent story accounting for the data. Once a satisfactory story is generated, the data are recognized as conforming to a typical situation whereupon the simple match response ensues. In the third response, called *evaluation*, there is no ambiguity concerning the nature of the situation, but there is uncertainty concerning the best course of action. In this event, memory is utilized to simulate the effects of different courses of action. Different actions are evaluated serially until one is recognized as achieving previously set goals.

The recognition-primed decision model is primarily a model of *individual* decision making and does not account directly for the role of other team members. In particular, it does not explicitly address the factors that determine communication. However, given the central role afforded to critical events in decision making, it strongly suggests that such events may also drive communication. This may be achieved by one of two mechanisms. First, the decision maker may communicate with fellow team members as an integral part of the cognitive analysis of a critical event. This may arise if information is sought to clarify uncertain inputs, as in diagnosis, or uncertain outputs, as in evaluation. Second, the decision maker may communicate with fellow team members following cognitive analysis of the event. That is, having reached a decision this information is exchanged with other team members in order to maintain coordinated activity. These considerations suggest that periods of increased communication between team members should be positively associated with the occurrence of critical events.

The second situation-specific communication strategy, called the *tradeoff* strategy, is based on the observations of flight cockpit crews by Orasanu (1990). According to this strategy, decision makers choose to communicate information only when current task demands are at a minimum. In other words, teamwork and taskwork are implicitly prioritized such that taskwork takes precedence. If, as seems reasonable, critical events increase task demands, then these should be followed by periods of *decreased* communication. This prediction is the opposite of that made by the critical event strategy.

In summary, we identify four possible strategies that team members may employ to govern communication. The constant exchange strategy predicts a constant rate of communication that is unaffected by either the passage of time or the occurrence of critical events. The periodic exchange strategy predicts that communication rate is unaffected by critical events but follows a regular temporal cycle determined by the optimum communication delay for the task in question. The critical event strategy predicts that communication between team members will increase in the period following a critical event, while the tradeoff strategy predicts that communication will decrease over the same period.

THE INCIDENT CONTROL SYSTEM

The present study examined the patterns of communication between members of an emergency management team consisting of members of the Western Australian Fire and Rescue Service. The teams were organized according to a hierarchical management structure called the Incident Control System (ICS). In this system, an Incident Controller (IC) assumes primary responsibility for emergency management but delegates many of the active decision-making functions to an Operations Officer (OO). Several other functions concerning forward planning and assets management are devolved to a Planning and Logistics Officer (PLO). The ICS fulfils the definition of a team proposed by Cannon-Bowers *et al.* (1993, p. 222), that consists of 'a group of two or more individuals who must interact cooperatively and adaptively in pursuit of shared valued objectives. Further, team members have clearly defined differentiated roles and responsibilities, hold task-relevant knowledge, and are interdependent (i.e., they must rely on one another in order to accomplish goals)'.

A critical feature of emergency management teams, such as ICS, is that while ultimate responsibility rests with the incident controller, decision making is distributed among all team members (Samurçay and Rogalski, 1993). Verbal exchanges between team members are thus an important component of the team's function, and the exchange of information, commands, and requests for action or information provides the primary means for coordination.

In the present study, patterns of communication were recorded during training exercises that simulated a chemical spill. Communication consisted of verbal exchanges between ICS team members during face-to-face encounters. The analysis concentrated on the temporal distribution of communication between both individuals and groups. Based on the predictions of the communication strategies described earlier, we were particularly interested in the relationship between communication rate and the timing of critical events. A critical event was defined as an event that was nominated by the exercise director as relevant to the decision-making activity of the ICS team and the Incident Controller. Training exercises were constructed to provide approximately ten critical events over a 90-minute period, with the exact timing of these events dependent upon the decisions and actions undertaken by the team.

METHOD

Participants

The participants in the study were officers of the Western Australian Fire and Rescue Service in the Perth metropolitan area. As part of their ongoing training, officers participate in a number of exercises at a purpose-built training facility. The present exercises required the attendance of between 15 and 25 officers and three to five vehicles. The exact number of personnel depended on the resources that were available and the decisions of the incident controller.

The aim of the exercises was to familiarize personnel with the Incident Control System (ICS) which, at the time, was being introduced to the Service. Thus, while all participants were experienced members of the Fire and Rescue Service, most had only limited experience with the ICS, with their roles within this system, and of working with other officers serving as team members.

The incident control system

The structure of the ICS consists of four main decision-making elements; incident control, operations, planning and logistics, and sector command, arranged hierarchically. A crucial feature of the ICS is that the decision-making structure expands flexibly in response to the increasing demands of the situation.

Each training exercise consisted of two main phases. In phase 1, all four functional elements of the ICS were allocated to a single person who was designated the Incident Controller (IC) for the duration of this phase. We refer to this individual as *Officer A*. Shortly after the arrival of Officer A, the majority of the ICS team, consisting of two to three fire trucks and about 15 operational personnel, arrive and form a sector command. Acting through this sector command, Officer A initiates actions to control the emergency. After 30–40 minutes, two senior officers arrive, inducing a further expansion of the ICS structure and initiating phase 2 of the exercise. One of the senior officers, *Officer B*, assumes the function of IC while the other assumes the role of Planning and Logistics Officer. During this phase, Officer A assumes the more specialized function of Operations Officer (OO), acting under the new IC. Because of the reallocation of functions at the beginning of phase two, in order to avoid confusion, each officer is identified by their letter, either A or B, in the present study.

The chemical spill scenario

The principal goals of the ICS team were; (a) identification of the chemical, (b) containment and control of the chemical, (c) identification of civilians in danger, (d) planning and implementation of rescue of civilians, (e) securing the safety of Service personnel, and (f) clean up and return to normal function. Apart from the ICS team, several other officers played the roles of a factory manager, two factory workers, a telephone linesman, and a telephone company manager. The factory manager provided information on request concerning the layout of the factory, the nature of the hazardous chemical and the existence of two trapped factory workers who were to be located and rescued. Similarly, the telephone company manager provided information concerning the existence of a telephone linesman who was also trapped and in need of rescue. One other officer functioned as an exercise monitor. Although not part of the ICS team, this officer monitored the conduct of the exercise on behalf of the exercise director and intervened from time to time to assist ICS team members.

The exercise was conducted in an area of about 7500 m^2 situated in the Fire and Rescue Training Facility. A utility building was designated as the ‘factory’ and, on arrival of the Sector Command, an operations zone was established approximately 30 m from the site of spill. Officer A was located in this zone for the duration of the exercise in the role of both IC (during phase 1) and OO (during phase 2). Beyond this zone, the various assets of the ICS team were established. These included fire trucks, a mobile control unit (MCU), and a decontamination area. During phase 2, the IC (Officer B) and the PLO (Officer C) occupied the MCU approximately 20 m from the operations zone. While located in the MCU, it was not possible for these officers to directly observe the activities of Sector

Command. Thus, as team members were not in radio contact, in order for the IC and the OO to communicate with each other, it was necessary either for IC to leave the MCU or for the OO to leave the operations zone.

The present study involves a series of three exercises, each approximately 100 minutes in duration. A different set of officers participated in each exercise.

Recording procedure and transcription

At the beginning of each exercise, a lapel microphone and radio transmitter was attached to Officers A and B.[1] The signal from each transmitter was continuously recorded on a separate track of a four-track tape recorder. The recorded tracks were transcribed making a note of the time and the identity of the speakers. The transcripts were then used to partition utterances into *speech units*, defined as a connected sequence of words uttered by an individual that was concerned with expressing a single idea.[2]

Analysis was limited to a set of three communication channels, called AX, AB, and BX. The AX channel consisted of communications between Officer A (IC in phase 1, OO in phase 2) and the members of Sector Command. According to the ICS, this channel should be primarily concerned with the direct implementation of decisions. The AB channel consisted of communications between Officer A (OO) and Officer B (IC) and existed only in phase 2. According to the ICS, this channel should be concerned with higher-level decision making concerning the situation as a whole and its relationship to the broader issues of public health and safety. The BX channel consisted of communications between Officer B (IC) and all other personnel, including the PLO and other relevant personnel external to the ICS team, and also existed only in phase 2.

Critical events

Table 1 shows the set of critical events in approximate chronological order. An event was defined as critical if it met the following two criteria; (a) it occurred in at least two of the three exercises, and (b) it was assessed by the exercise director as requiring a significant response on the part of either the IC or OO. The exercise director had participated in the development of the training scenario and attended all three exercises.

The time of onset of a critical event was defined as the time of its first mention on the tracks of either Officer A or B. This is the moment at which the event was verbally registered by the respective officers, which in most cases occurred some time after the actual event. Consequently, there are two sets of critical event times, for Officer A and Officer B, respectively.

RESULTS

Amount and type of communication

The mean number of speech units and words per minute for each exercise, phase and channel are presented in Table 2. The number of words per minute correlated highly with

[1]In addition to Officers A and B, recordings were made of two other Officers (the PLO and the exercise director). Their data were not directly used in the present analyses.
[2]The identification of speech units represented an attempt to identify the meaningful components of verbal exchanges. As it turned out, communication rate based on speech units was highly correlated with communication rate based on a simple count of words. While we report results based on speech units, equivalent results were found for words.

Table 1. Timing of critical events for Officers A and B by exercise. Entries correspond to minutes from the beginning of each exercise

		Officer A			Officer B		
No.	Event description	Ex. 1	Ex. 2	Ex. 3	Ex. 1	Ex. 2	Ex. 3
1	First missing factory worker	3	2	4	34	38	47
2	General identification of chemical	3	2	38	34	40	44
3	Second missing factory worker	39	5	4	43	38	47
4	Quantity of chemical determined	15		39	57	58	45
5	Request for sand to absorb chemical	15	25	68	34	52	68
6	Rescue of first missing worker	32	26	24	34	38	47
7	Arrival of Officer B (start of phase 2)	34	33	44	34	33	44
8	Specific identification of chemical	39	44	38	58	56	44
9	Chemical leak contained	69	44	52	74	46	93
10	Rescue of second missing worker	71	53	52	71	63	47
11	Arrival of sand confirmed	62	70	81	62	60	
12	Third missing worker	83	76	83	86	63	87

the number of speech units per minute, with correlation coefficients for the AX, AB, and BX channels of 0.95, 0.97, and 0.93, respectively. While the following analyses are based on speech units, the same results are found for analyses based on words. Thus, for the purpose of subsequent analyses, *communication rate* is defined as the number of speech units per minute.

Communication rate was greater on the AX channel than on either the AB or BX channels. Because the data are not normally distributed, a non-parametric Kruskal–Wallis test was used to examine differences in the quantity of verbal exchanges in the three exercises and, for the AX channel only, between the two phases. Overall, communication rate did not differ between exercises, but on the AX channel, communication rate was greater in phase 1 than in phase 2, $\chi^2(1) = 7.05$, $p = 0.008$. This was expected since the AX channel was the only avenue of communication during phase 1, whereas Officer A communicated on both the AX and AB channels during phase 2.

There was a tendency for exchanges between Officers A and B to preclude simultaneous communication with other individuals. Across all exercises, communication rate on the

Table 2. Mean number of speech units per minute and mean number of words per minute for each channel, phase, and exercise

		Exercise 1		Exercise 2		Exercise 3	
Variable	Channel	Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2
Duration (min)		33	70	32	63	43	57
Speech units per min							
	AX	4.1	4.3	3.9	2.8	5.3	3.1
	AB		3.0		1.8		1.7
	BX		0.9		1.1		0.7
Words per min							
	AX	34.6	36.8	40.1	27.9	43.7	27.8
	AB		24.2		16.8		15.6
	BX		6.0		9.2		6.7

AB channel was negatively correlated with communication rate on the AX channel ($r = -0.31$), and, less strongly, on the BX channel ($r = -0.15$). In contrast, communication rate on the AX channel was positively correlated with communication rate on the BX channel ($r = 0.26$).

Critical events

The time of occurrence of critical events, in minutes from the beginning of the exercise, is also presented in Table 1. Because the arrival of Officer B defines the beginning of phase 2, none of the events defined with respect to Officer B could occur in phase 1. There was also a tendency for several of the events to cluster near the beginning of phase 2 on the Officer B track, reflecting the initial briefing of Officer B by Officer A.

The relationship between the timing of critical events for Officer A and Officer B is shown in Figure 1. The zero point on each axis corresponds to the onset of phase 2 in each exercise. The abscissa corresponds to the relative time of occurrence of each event from the perspective of Officer A while the ordinate corresponds to the times of occurrence from the perspective of Officer B. Figure 1 shows that the majority of events that had occurred in phase 1 are communicated to Officer B within 10 minutes of his arrival, although two events are not mentioned until 20 minutes into phase 2. During phase 2, the timings of events for the two officers are positively correlated, $r = 0.76$, $p < 0.001$. The y-intercept of the best-fitting regression line for phase 2 corresponds to the average delay between the time Officer A first verbally registers an event and the time this event is first communicated to or by Officer B. The observed value is 8.8 minutes, which is significantly greater than zero (one-tailed $t(16) = 2.06$, $p = 0.028$). Thus, Officer B tends to register the occurrence of critical events during phase 2 approximately nine minutes after Officer A.

Time series analysis

A time series analysis was undertaken to examine the temporal characteristics of communication rate and the effect of critical events. An autoregression model was fitted to communication rates on each channel separately for each exercise. Since the residuals at

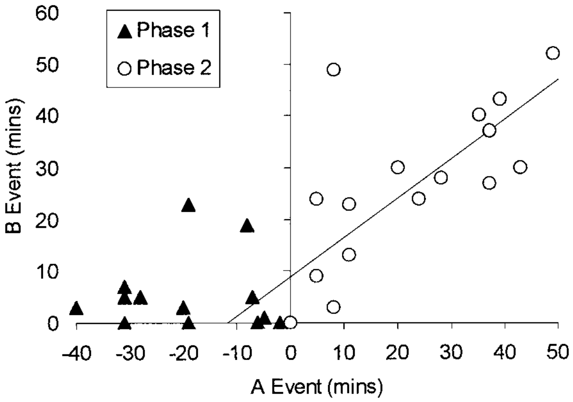

Figure 1. Relationship of the relative timing of critical events between Officer A and Officer B. Events are timed in minutes from the start of phase 2, marked by the arrival of Officer B. The best fitting regression line for phase 2 is also shown

one time interval are not independent of adjacent intervals, an autoregression term of lag one was included in each analysis. In each case, this was successful in eliminating residual autocorrelation. The autoregression model used for the time series analysis can be defined schematically as follows,

$$\text{Communication rate} = \text{constant} + \text{event} + \text{cycle} + \text{autocorrelated error} \quad (1)$$

In this model, the *event* component at time t is defined as the weighted sum of the set of critical events occurring over a preceding 5-minute window.[3] For example, suppose one critical event occurred at time $t-2$, while two other critical events occurred at time $t-5$. In this case, the event component for time t is equal to the sum of one (event) multiplied by the weight for lag 2 and two (events) multiplied by the weight for lag 5. The six event weights, for lags 0 to 5, are free parameters estimated from the data. As a result, this component of the model has six degrees of freedom (df = 6). For the AB and BX channels, critical events were timed from the perspective of Officer B and restricted to phase 2. For the AX channel, critical events were timed from the perspective of Officer A and included both phases.

The *cycle* component of the autoregression model was designed to capture any temporal synchronization of communication. It was modeled as a sine wave of unknown period, phase and amplitude (hence $df = 3$). The period of the sine wave was estimated in the following way. First, the autoregression model was fitted with the *cycle* component removed. Second, the residuals from this fit were submitted to a Fourier analysis and a periodogram constructed. If a temporal cycle existed in the data, there should be an increase in power at periods near the critical period of oscillation. The optimum value of this period was estimated for each time series by searching in the vicinity of periods with greatest power in the relevant periodogram. (Periods less than 10 minutes were excluded because the physical constraints of the exercise environment precluded the synchronization of interactions at this rate.) Finally, using the optimum period for each time series, the full autoregression model was fitted using the maximum likelihood method, and, through backward elimination, the statistical significance of the *event* and *cycle* components were assessed both separately and in combination. Each channel in each exercise was analysed separately.

Exercise 1

The estimated periods for the *cycle* component of equation (1) were 31.2, 31.9 and 15.9 minutes for the AX, AB and BX channels, respectively. The weights for the event component, for lags 0 to 5, are presented in Table 3, and observed and predicted number of speech units are shown in Figure 2. In order to indicate more clearly the main trends in the three time series, a five-point moving average of the observed data is also shown. Of the three channels, the improvement in R^2 (ΔR^2) attributed to the combination of *event* and *cycle* components is significant for both AB and BX channels. For the AB channel, $\Delta R^2 = 0.36$, $F(9, 59) = 4.81$, $p < 0.001$, and for the BX channel, $\Delta R^2 = 0.30$, $F(9, 59) = 2.80$, $p = 0.008$. Communication on the AX channel was not significantly related to either *event* or *cycle* components, $\Delta R^2 = 0.12$, $F(9, 59) = 1.39$, $p = 0.206$.

The individual contributions of the event and cycle components were assessed separately using backward elimination. For the AB channel, the contributions of both

[3]Preliminary analyses suggested that any effect of a critical event on communication rate was confined to a 5-minute window following the event.

Table 3. Regression weights for the event component of the time series analysis for each exercise and channel

Lag	Exercise 1			Exercise 2			Exercise 3		
(min)	AB	BX	AX	AB	BX	AX	AB	BX	AX
0	1.76	−0.32	−0.41	0.74	−0.60	0.87	1.45	0.41	0.94
1	2.10	−0.18	−0.55	−0.09	−0.18	0.46	0.69	−0.01	2.49
2	1.15	−0.04	2.20	1.45	−0.12	−0.07	0.52	−0.17	1.01
3	2.08	−0.34	−0.94	−0.38	−0.34	−0.03	0.99	−0.35	−1.06
4	0.45	1.32	−2.11	−1.56	−0.50	0.21	0.52	−0.20	0.33
5	0.25	−0.15	−0.47	−1.07	−0.19	−0.48	0.22	0.31	−1.26

components were significant; for the *event* component, $\Delta R^2 = 0.24$, $F(6, 59) = 4.80$, $p < 0.001$, and for the *cycle* component, $\Delta R^2 = 0.15$, $F(3, 59) = 6.09$, $p = 0.001$. As Table 3 shows, all the estimated weights for the *event* component were positive, indicating an increase in verbal exchanges following a critical event. For the BX channel, the effects of both components are also significant; for the *event* component, $\Delta R^2 = 0.18$,

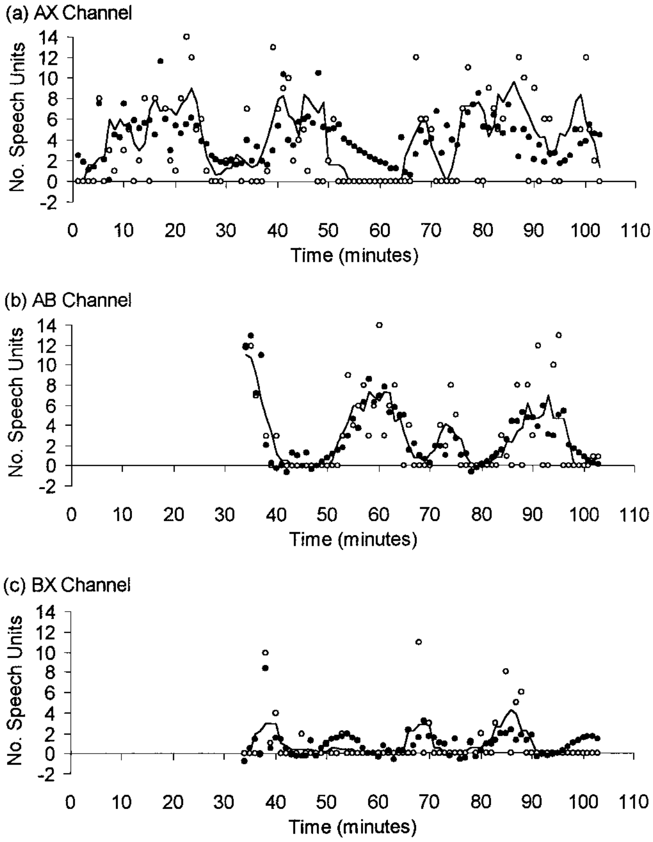

Figure 2. Communication rate on each channel during Exercise 1. Comparison of the observed data (open circles), a 5-minute moving average (line), and the predictions of the autoregression model (filled circles)

$F(6, 59) = 2.46$, $p = 0.034$, while for the *cycle* component, $\Delta R^2 = 0.11$, $F(3, 59) = 2.97$, $p = 0.039$. Unlike the AB channel, five of the six event weights are negative, indicating that critical events tend to *decrease* verbal exchanges on the BX channel. In addition, the cycle components of the AB and BX channels were not in phase. The phase difference was 10.2 minutes, indicating that periods of relatively high communication rates on the AB channel tended to be associated with periods of relatively low communication rates on the BX channel, and vice versa.

Exercise 2

The estimated periods for the *cycle* component of equation (1) were 11.1, 25.3 and 33.1 minutes for the AX, AB and BX channels, respectively. The observed and predicted number of speech units for each channel are shown in Figure 3. The improvement in R^2 attributed to the combination of *event* and *cycle* components is not significant for any of the channels. For the AX channel, $\Delta R^2 = 0.04$, $F(9, 52) = 0.51$; for the AB channel, $\Delta R^2 = 0.20$, $F(9, 52) = 1.59$, $p = 0.143$; and for the BX channel, $\Delta R^2 = 0.10$, $F(9, 52) = 0.75$.

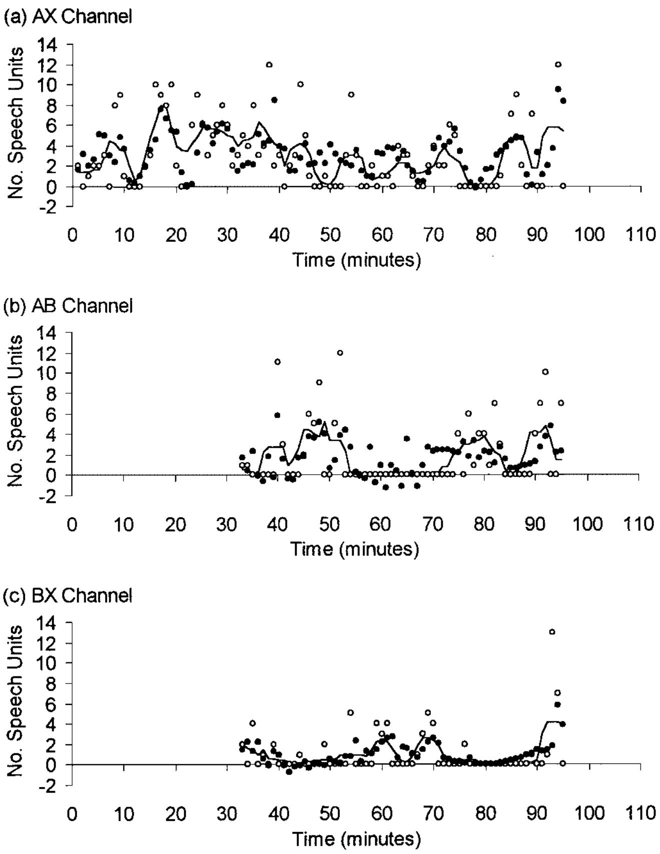

Figure 3. Communication rate on each channel during Exercise 2. Comparison of the observed data (open circles), a 5-minute moving average (line), and the predictions of the autoregression model (filled circles)

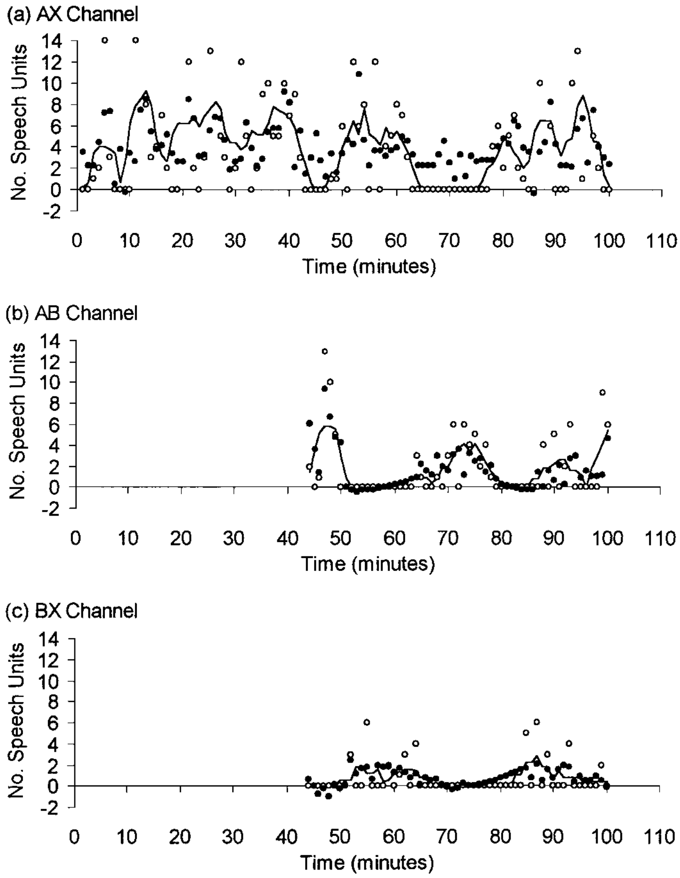

Figure 4. Communication rate on each channel during Exercise 3. Comparison of the observed data (open circles), a 5-minute moving average (line), and the predictions of the autoregression model (filled circles)

Exercise 3

The estimated periods for the *cycle* component of equation (1) were 31.2, 32.2 and 32.2 minutes for the AX, AB and BX channels, respectively. The observed and predicted number of speech units for each channel are shown in Figure 4. As in Exercise 1, the improvement in R^2 attributed to the combination of *event* and *cycle* components is significant only for the AB and BX channels. For the AB channel, $\Delta R^2 = 0.25$, $F(9,46) = 2.18$, $p = 0.041$, while for the BX channel, $\Delta R^2 = 0.29$, $F(9,46) = 2.14$, $p = 0.045$. The effect of these components is not significant for the AX channel, $\Delta R^2 = 0.09$, $F(9,46) = 1.13$, $p = 0.347$. Examination of the separate effects of each component reveals that only the *event* component is significant for the AB channel, $\Delta R^2 = 0.20$, $F(6,46) = 2.53$, $p = 0.034$. As Table 3 shows, all six event weights are positive, as was found for this channel in Exercise 1. In contrast, only the *cycle* component is significant for the BX channel, $\Delta R^2 = 0.22$, $F(3,46) = 4.86$, $p = 0.005$. Again, as in Exercise 1, although the cycle component is not significant for the AB channel, it was out of phase with the BX channel with a phase difference of 10.3 minutes.

Summary

The pattern of verbal communication was found to vary between channels and phases. During phase 1, communication on the sole AX channel showed no evidence of a dominant temporal cycle and was not affected by the occurrence of critical events. The same pattern was observed in phase 2. In contrast, verbal communication on the AB and BX channels was affected by both these factors, but in different ways. Critical events were positively related to verbal exchanges on the AB channel and negatively related to verbal exchanges on the BX channel. In addition, there was evidence of an independent 30-minute cycle in communication rate on both the AB and BX channels. These two cycles were not in phase and thus tended to be negatively correlated with each other.

The pattern described above applied in varying degrees to each of the three exercises. It applied most readily to Exercise 1 and, to a lesser extent, to Exercise 3. Neither critical events nor temporal cycles were important determinants of communication rates in Exercise 2. In order to examine the relationship between the different patterns of communication and the level of performance of the three teams, we asked the exercise director to rate the effectiveness of each team on a 10-point scale. Although essentially a subjective estimate, the director rated Exercise 1 as the least effective (score of 6.5), especially in terms of communication (3/10), while Exercises 2 and 3 were both rated as very good (scores of 8.5–9).

DISCUSSION

The aim of the present study was to examine the factors governing the dynamics of communication between members of an emergency management team. Two general kinds of factor were considered; task-specific factors relating to characteristics of the emergency management task that tend to be constant across different situations, and situation-specific factors relating to unique characteristics of the current situation. Depending on the role of each of these factors, we distinguished four possible communication strategies called constant exchange, periodic exchange, critical event, and tradeoff. While the results of the present study reveal a mixed picture in which the importance of different factors varied between exercises, several conclusions may be drawn. We first discuss the results for each channel separately and then present an integrated account of the entire set of results.

AX channel

There was no evidence in any of the exercises that communication on the AX channel followed either critical events or an intrinsic temporal cycle. It thus conformed to the *constant exchange* strategy. Because this channel involved the Operations Officer (OO) and the Sector Command under his control, it is perhaps surprising that critical events had no discernible effect on communication activity. It might be expected that these officers, who were most intimately engaged with the exercise, would also be most sensitive to critical events.

The absence of an effect of critical events is open to three interpretations. First, because the AX channel recorded Officer A's exchanges with *several* members of the Sector Command, it is possible that exchanges between Officer A and each individual were correlated with critical events, but that these regularities disappeared when exchanges were combined into a single channel. Although this possibility cannot be ruled out, it is called into question by the presence of an effect of critical events on the BX channel, to which similar considerations apply.

A second possibility is that, because Officer A was in close physical proximity to the members of Sector Command during most of the exercise, much communication on the AX channel may have been non-verbal. The availability of non-verbal communication may also explain the absence of a long-term temporal cycle. Billard and Pasquale (1993, 1995) showed that if the cost of communication is low, then it is possible to maintain a high rate of communication without compromising performance. Physical proximity lowers the opportunity cost of communication, thereby allowing a higher sustainable rate.

The third possibility has wider theoretical implications. The view that critical events may affect communication rate is derived from the recognition-primed decision model. This model was developed to account for retrospective accounts of decision making elicited from informants using the critical decision method (Klein *et al.*, 1989). This interview method specifically directs attention to past events and focuses on descriptions of their apparent cognitive sequelae. Informants are encouraged to develop coherent accounts of the incident, their decision-making processes, and the effect of their decisions on outcomes. To do so, the informant must parse the continuous flow of action into a set of discrete events and the responses they elicit, which may retrospectively impose a structure on the recollections that might have been absent during the event itself. It follows that our failure to observe a relationship between critical events and communication rate on the AX channel may signify that, in real time, events are processed continuously as part of ongoing task management, rather than discretely as distinct problems to be solved.

AB channel

In contrast to the AX channel, communication on the AB channel revealed regularities in two of the three exercises. Specifically, there was evidence of both a positive correlation with critical events and an autonomous 30-minute cycle. This suggests that the factors affecting communication on the AB channel were different from those affecting communication on the AX channel. At least three such factors merit consideration.

First, the physical situation that governed communication on the AB channel consisted of Officer B, in the role of IC, maintaining a command post some distance from Officer A and the Sector Command. Thus, communications between Officer A and Officer B had to be deliberately planned and scheduled in a way that communication on the AX channel was not.

Second, the arrival of Officer B induced a functional reorganization by creating an additional management level in the Incident Control System. This new level created the need for explicit liaison between the IC (B) and the OO (A) that can be considered distinct from their individual taskwork and hence fail to be integrated adequately into their ongoing activities. Thus, teamwork may now be perceived as an additional task demand that could only be satisfied periodically.

Finally, it was found that a transmission delay existed between Officers A and B. On average, Officer B verbally acknowledged event-related information approximately 9 minutes after Officer A. Since critical events originated in the vicinity of Officer A, the transmission delay occurred for information flowing from Sector Command to the MCU. This delay may increase the demands on the officers to communicate in order to verify the content of each other's knowledge base and to resolve courses of action. However, given the physical constraints of the situation, such communication carried a relatively high cost in terms of time away from each officer's normal base of operations. Together, these constraints may have induced a periodic exchange strategy. Billard and Pasquale (1993, 1995) showed that when communication carries significant costs, optimal performance is achieved by a strategy of periodic rather than continuous sharing of information.

BX channel

Although the average volume of communication on this channel was considerably lower than that on the AB channel, similar relationships to events and time were observed in Exercises 1 and 3. As on the AB channel, communication on the BX channel was also related to the occurrence of critical events. However, unlike the AB channel, verbal exchanges on the BX channel tended to *decrease* following the occurrence of an event. Communication on the BX channel also showed evidence of periodicity. The period of this cycle was approximately 15 minutes in Exercise 1 and approximately 30 minutes in Exercise 3. As a 15-minute cycle is also the first harmonic of a 30-minute cycle, communication on the BX channel appears to follow a similar time course to communication on the AB channel, the difference being that the respective cycles were out of phase with each other. High rates of communication on the AB channel were therefore associated with relatively low rates of communication on the BX channel.

The results for the BX channel suggest that the regularities observed on this channel may be a direct consequence of similar regularities on the AB channel. If verbal exchanges between Officer A and Officer B increase following critical events, or as a consequence of a temporal cycle, other avenues of communication to and from Officer B are concomitantly attenuated. It should also be noted that while all communication by Officer B has a cyclic component, the only communication by Officer A in which a similar component is observed is that with Officer B. This suggests that the behaviour of Officer B is critical in the formation of a temporal cycle in the present context.

Temporal cycles

A novel outcome of the present study is the observation of a temporal cycle governing communication rate on the AB channel and, to a lesser extent, on the BX channel. This cycle appears to have a period of approximately 30 minutes and is independent of the temporal distribution of critical events. This observation raises two issues. The first concerns the function of the cycle in the emergency management process. The second concerns the factors that determine the period of the cycle.

Both issues can be resolved by appealing to the simulation studies of Billard and Pasquale (1993, 1995), in which cooperative agents must exchange information in order to maintain effective functioning of an overall system. Because communication has an associated cost as well as a benefit, performance is maximized if information is exchanged after a fixed period of time. The length of this period is determined by the relative value of the information and the relative cost of communication. The greater the value and the less the cost, the shorter the period.

In the present study, cycles averaged about 30 minutes. This may reflect the expectations of Officers A and B concerning the number of times they should consult with one another during the course of the exercise. Since phase 2 lasted about 60 minutes, a 30-minute cycle permits up to three periods of maximal communication, once at the beginning of the phase, once in the middle, and once at the end. Alternatively, the observed cycle duration may be a consequence of the average rate of information accrual. On this view, Officers A and B tend to consult when enough events have occurred to give them something to discuss. The more events per unit time, the shorter this period. This view explains the initial increase in verbal exchange at the beginning of phase 2. Interestingly, this peak is not as prominent in Exercise 2 which failed to show a consistent temporal cycle. By increasing the rate at which events occur, it should be possible to reduce the period of the temporal cycle.

It is also possible to view the occurrence of temporal cycles in the present study as an instance of what appears to be a ubiquitous pattern in spoken conversation and social interaction. Temporal cycles have been observed in human speech in terms of both the volume of vocal activity in conversation (Warner, 1979, 1992a), and the fluency of speech in uninterrupted discourse (Roberts and Kirsner, 2000). While the time scales associated with these speech cycles are one to two orders of magnitude less than that observed in the present study, it is possible that similar principles may govern their production. Thus, Warner (1992a,b) has argued that cycles in conversational speech are a consequence of social determinants underlying coordinated activity (see also van Gelder, 1998).

Limitations and conclusions

One limitation of the present study is that it included only three exercises, and that the pattern of communication in some cases differed between exercises. For example, Exercise 2 departed from the overall pattern by showing no evidence of periodicity nor correlations with critical events on any channel. Notwithstanding those limitations, we can cite two reasons why conclusions can justifiably be drawn on the basis of our results.

First, although the number of exercises was small, the number of participants was not. Each exercise involved the cooperation of between 15 and 25 individuals, and thus can be considered as constituting in itself an entire experiment. Indeed, given the large number of individuals involved in each exercise, and given the variability with which the different exercises unfolded even though they shared a common scenario, any similarity in communication patterns between any of the exercises must be particularly noteworthy.

Second, given that our statistical-descriptive approach to dynamic decision making is virtually without precedent in the literature, any statistically reliable identification of a communication strategy is theoretically relevant. Even if a strategy had only been identified in a single exercise, this would constitute an existence-proof that is worthy of theoretical consideration and that may merit future exploration of the boundary conditions of that strategy. We therefore draw conclusions from our findings in terms of the existence of noteworthy phenomena without commenting on their generality.

Most critically, the results of the present study indicate that communication between key members of an emergency management team can be determined by both task- and situation-specific factors. Task-specific factors were the primary determinants of verbal exchanges between the Operations Officer and members of Sector Command in all three exercises and between the Incident Controller and Operations Officer in Exercise 2. In each of these cases, communication dynamics conformed to a *constant exchange* strategy.

In addition, we observed periodic fluctuations in communication rate between the Incident Controller and other team members in two of the three exercises. This cycle was independent of the occurrence of critical events and may be thought of as an adaptation by the Incident Controller to the management of two possibly conflicting channels; vertical communication with the Operations Officer, and horizontal communication with the Planning and Logistics Officer and outside agencies. It is of interest that Exercise 1, in which this pattern was most apparent, was deemed by the exercise director to be poorest in communication effectiveness. We speculate that a *periodic exchange* strategy arises in the context of failure to properly integrate competing demands at the incident control level. On this view, as Incident Controllers gain more experience, use of this task-specific strategy may decline in favour of the constant exchange strategy.

Finally, communication by the Incident Controller in two of the exercises was also affected by the occurrence of critical events, a situation-specific factor. In these cases, critical events increased communication rates between the Incident Controller and Operations Officer, but decreased communication between the Incident Controller and other personnel.

The extent and generality of the present findings can only be gauged by further research. However, the observation that communication between key members of a distributed decision-making team may both follow an intrinsic cycle and be affected by critical events is both novel and unlikely to be restricted to the series of emergency management exercises investigated in the present study. The dynamics of communication in emergency management teams are likely to be functions of a number of variables. The methods employed in the present study offer a means of investigating these relationships and developing a better understanding of how task- and situation-specific factors affect the coordinated activity of members of emergency management teams in the real world.

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