An extended version of the Rasmussen's Dynamic Safety Model for measuring multitasking behaviors during medical emergency

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An extended version of the Rasmussen's Dynamic Safety Model was implemented to empirically index team activity during a medical emergency. The video recordings of two emergency training sessions during the simulation of an adverse event with two paramedical teams were analyzed with a coding scheme based on the model. We show that individual's allocation of perceptions and actions to multiple work constraints (i.e., patient's state monitoring, information processing with team, and equipment management) can be dynamically tracked.

INTRODUCTION

A medical emergency represents a complex situation of intervention for caregiving teams in the emergency department (Patel & Cohen, 2008). In addition to the intrinsic complexity of the patient's pathology, care delivery requires the coordination of multiple human and environmental resources in a multitasking context of work. Considering this complexity, the medical team activity must be apprehended as a dynamic adaptive process that emerges from the interaction of several work constraints (Flach, 2012; Cooke & Gorman, 2006; Gorman, Cooke, & Kiekel, 2004).

Conventional approaches to research tend to split this complexity issue into more simple solvable problems by focusing on the measurement of single individual skill effects, like the effect of communication, leadership or better situation awareness (Reader, Flin, Lauche & Cuthbertson, 2006) or to consider the overall team performance at a global scale (Flin & Maran, 2004; McKay, Walker, Brett, Vincent, Sevdalis, 2012). However, neither individual skills decomposition nor a global team performance assessment can provide a complete depiction of the dynamic adaptive processes that emerge from medical emergency as a concurrent multitasking context of work, in which frequent switching from one task or competency to another is required to cope with the evolving dynamic work constraints (Clyne, 2012, Salvucci, 2013).

The purposes of this study are 1) to propose an extended version of the Dynamic Safety Model built by J. Rasmussen (1994, 1997) that treats the medical emergency situation as a dynamic whole; and 2) to present a methodological implementation of this model for tracking multitasking behaviors.

The Dynamic Safety Model

Jens Rasmussen founded his dynamic safety model, also sometimes called "model of system migration", on Gibson's concept of "field of safe travel" (Gibson & Crooks, 1938). This model describes human behaviors as trajectories in an abstract work space bounded by a set of administrative, functional and safety boundaries that constrains workers' degrees of freedom. This model originally distinguishes three organizational boundaries: economic failure, unacceptable workload, and a double limit describing both acceptable functionally objective performance and acceptable perceived performance (figure 1).

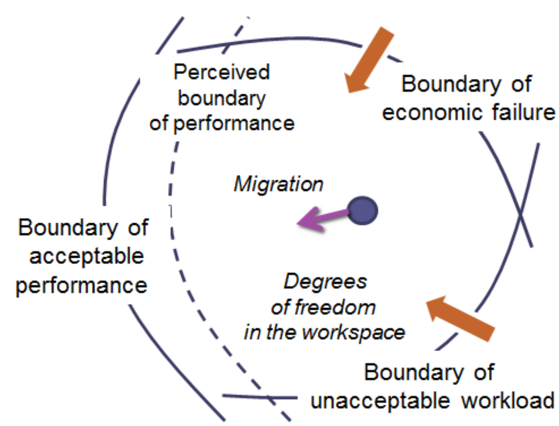

Figure 1. Dynamic Safety Model inspired from Rasmussen (1997)

The economic failure boundary represents the cost limit that can be engaged in the work process by the organization. The unacceptable workload boundary delineates the maximal effort that can be deployed by the actors. According to Rasmussen, these two limits produce a combined pressure on actors' navigation inside the workspace that leads them to migrating gradually toward the boundary of acceptable performance. If the actors cross this latter boundary, then an error or accident is likely to occur. Between the functional and perceived performance boundaries, a critical margin exists that involves risky behaviors. In addition to the pressure exerts by these constraints, the actors' trajectory inside the workspace is influenced by objectives, values and subjective preferences that produce fluctuations in the positioning of each actor.

With this model, Rasmussen suggested a new approach to the control of high risk organizations. The work system is apprehended in terms of interacting constraints, force fields, and behavioral trajectories (see also, Flach & Voorhorst, 2016). Despite its heuristic value, few practical implementations of this model have been reported. In the health domain, it was used to describe the risks generated by new management techniques based on information systems (Cook & Rasmussen, 2005) and the effects of standard procedure violations (Amalberti, Vincente, Auroy, & de Saint Maurice, 2006).

AN EXTENDED VERSION OF THE DYNAMIC SAFETY MODEL TO MEDICAL EMERGENCY

Based on empirical observations during training sessions on a high-fidelity simulator, we proposed an extended version of the Rasmussen's model applicable to medical emergency situations (figure 2).

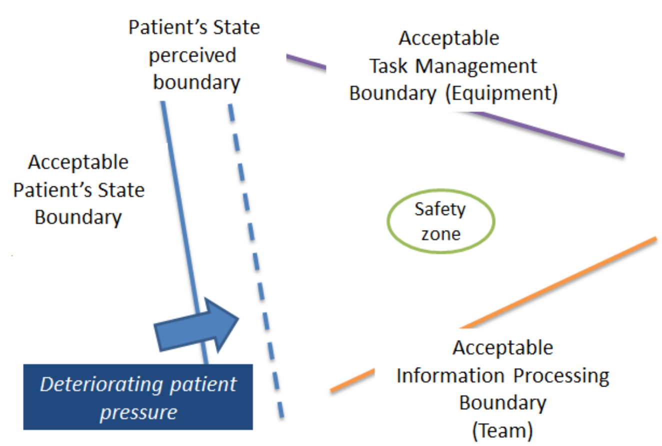

Figure 2. An extended version of the Dynamic Safety Model. At the center of the workspace, a safety zone is ensured by the dynamic coordinated activity of agents. A deteriorating patient produces a pressure that moves the acceptable patient'state boundary

The constraints delineating the workspace

The following three boundaries are suggested for generalizing Rasmussen's model to medical emergencies: (i) the acceptable patient's state boundary, (ii) the acceptable information processing boundary, (iii) the acceptable task management boundary.

The acceptable patient's state boundary corresponds to the main performance criterion for the emergency team. The team provides the patient with medications and assistance to avoid the confrontation with this limit. In some critical conditions, the team can perceive that a first patient's state limit has been crossed that complicates care delivery, i.e. the "Patient's state perceived boundary". In addition, due to a deteriorating patient, the acceptable patient's state boundary can come nearer and reduce the caregivers' workspace size, reducing the degrees of freedom for care delivery. Similarly, the perceived boundary can move according to both the objective patient's state and the level of caregivers' awareness.

The acceptable information processing boundary represents the cost involved in the process of information coming from information systems or from individuals through communication. Information represents complementary cognitive resources that facilitate care delivery. A paper checklist for medication administration, a physiological monitor or exchanges with teammates convey assistance for caregivers. If information processing is too difficult or too time-consuming, then caregivers can reach the information processing boundary.

The acceptable task management boundary concerns caregivers' operations on equipment in the workplace. These operations correspond to concrete actions for preparing the equipment, controlling its use and restoring it after utilization (Morineau, Chapelain, Quinio, 2015). If the required actions for managing equipment are too numerous or too difficult to perform, then the task management boundary can be considered to be reached.

Multitasking and behavioral coordination

Facing these constraints and notably the dynamic fluctuation of the patient's state, each team member can be positioned at a given point in the workspace, and can move from one position to another to cope with these constraints. Also, a given point represents the result of a behavioral coordination process that involves multitasking activity.

To ensure a well-fitted adaptation to the workspace, we suggest that the emergency team should coordinate the processing of the three constraints through adaptive perceptions and actions. At an inter-individual level, it means a good allocation of tasks between agents. At an intra-individual level, it means parallel or alternated time-sharing processes. For instance, a nurse can simultaneously prepare a perfusion (task management), whereas she/he glances at the patient or at a colleague (information processing). If the team succeeds in achieving coordinated behaviors in view of the boundary constraints, then the caregivers will stay at the center of the workspace, that is to say inside a safety zone.

But, if allocation of attention to a particular constraint in the team is longer than optimal, then it would be at the expense of attention to other potential important events associated with other work constraints, leading to tunneling or fixation error (Hall, Rudolph & Cao, 2006; Raby & Wickens, 1994; Wickens & Alexander, 2009). In terms of the Dynamic Safety Model, slow attentional switching between work constraints will increase the likelihood of violating the acceptable patient's state boundary.

IMPLEMENTATION OF THE DYNAMIC SAFETY MODEL

In this section, we present both a scheme for coding caregiving behaviors and statistical elements for measuring the behaviors according to our version of the Dynamic Safety Model. This scheme and these analyses were applied on two training simulations sessions in a health simulation center.

Method

Participants (nurses and nursing aids) were dispatched in two teams that had prior experience working together in their emergency departments. The context of their participation was training sessions performed on a high-fidelity simulator, i.e., a realistic and interactive mannequin. Physiological parameters like heart rate, blood pressure, oxygen saturation and breath were accessible on a monitor. Typical emergency medical equipment was also available in the bedroom.

Two sessions were chosen for a post-hoc analysis on the basis of a global apparent difference in performance level between the two teams. This evaluation has been made by two experts (an anesthetist nurse and a doctor). The performance of team #1 was judged to be good, especially the nursing aid of this team, whereas performance of team #2 was judged to be of lower quality.

The two teams were confronted with the same cardiac arrest scenario. After a briefing stage during which the experimenter presented the general context of the scenario, the nurse and the nursing aids had to ensure the handoff from a paramedic (a nurse) that presented the clinical case and left the room. After about 5 min. 30 sec, the adverse event abruptly occurred. Then, the team could ask for assistance from other caregivers. The sessions lasted about 10 minutes. Only the behaviors of the two caregivers who stayed for the complete session were analyzed.

Coding scheme and measurement

Two classes of behaviors were coded on the basis of video recordings, respectively those relative to the perception field of orientation and those relative to actions performed by caregivers. Note that locomotion was considered as a change in the field of perception rather than an action. Each class of behavior can be oriented either toward the patient, the workplace and equipment (task management), or the teammates or an information system (information processing). A reliability test on the coding scheme showed a significant level of correspondence between two raters ($K=.79$; $p<.001$).

For each caregiver, we calculated the relative frequencies in percentages of performed actions on the patient, task management, and information processing (team). We statistically assessed the equiprobability of these distributions through the Shannon's entropy index. The higher the Shannon's index value is, the more balanced the actions between the three work constraints are. Perceptions oriented towards each work constraint were coded as a set of time durations. The Actogram^{TM} Software was used to process these data.

Results

Table 1 shows proportions of actions oriented towards patient, equipment and team. It also shows the level of balanced repartition among these proportions during the monitoring and treatment periods (H index). Aid.1 and Nurse.1 composed the Team #1. Aid.2 and Nurse.2 composed the team #2.

Table 1. Repartitions of actions in percentages during the monitoring and the treatment periods, and H entropy index

	Monitoring period					Treatment period				
Actions %	Patient	Equipment	Team	H index	n	Patient	Equipment	Team	H index	n
Aid.1	47.6	19.0	33.3	1.5	21	31.6	26.3	42.1	1.6	19
Nurse.1	57.9	15.8	26.3	1.4	19	16.7	33.3	50.0	1.5	30
Aid.2	62.5	25.0	12.5	1.3	8	18.2	45.5	36.4	1.5	11
Nurse.2	69.2	15.4	15.4	1.2	13	30.3	12.1	57.6	1.4	33

During the monitoring period, the largest part of the actions by the teams consisted in interacting with the patient. This is particularly true for Team #2 for which 62.5% and 69.2% of the actions were oriented toward the patient. The H entropy index shows that actions performed by caregivers of team #1 were more homogeneously dispatched between the three work constraints: H index of Aid.1 and Nurse.1 respectively equal to 1.5 and 1.4, during the monitoring phase.

During the treatment period, the main target on which caregivers' actions were performed was not the patient but interaction with the team, except for Aid.2, who performed 45.5% of her actions on the equipment. These actions concerned difficulties with the use of the automatic defibrillator. Once again, the highest H entropy index concerned Aid.1 who distributed her actions homogeneously on the three work constraints.

Figure 3 allows for having a whole depiction of the dynamics evolution of actions allocation for caregivers between the monitoring and the treatment periods. A global migration trend is shown towards actions mainly oriented towards the team, i.e. orders, order following, speaking out, questions, answers and phone call, requested by the detection of the adverse event, and secondary towards equipment use.

This migration is rather parallel for all the caregivers, except for Nurse.2, who were particularly involved in team actions, whereas her relative frequency of equipment actions decreased contrary to other caregivers. During the treatment period, Nurse.2 was particularly involved in a leadership position with numerous orders, and also the use of a speaking up strategy.

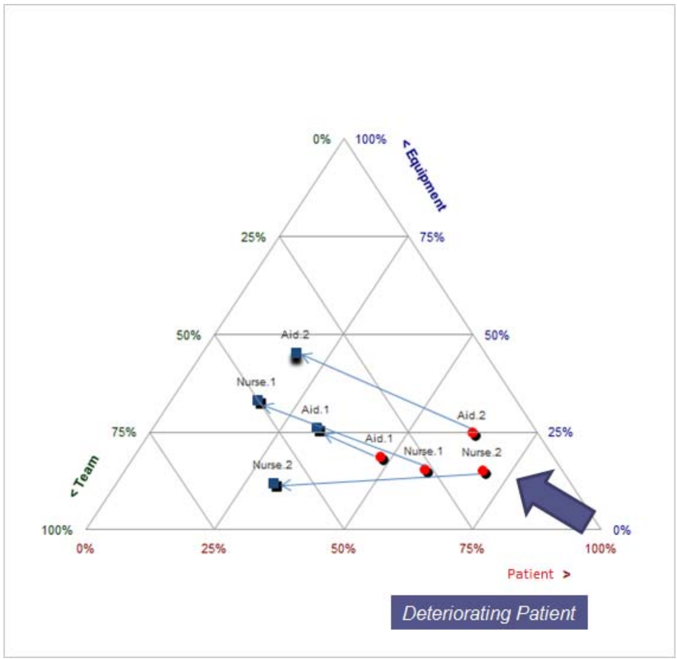

Figure 3. Allocations of actions towards the three work constraints during the monitoring and the treatment periods. The arrows between two points indicate the migration of caregivers after the adverse event.

Table 2 shows time duration of perceptions according to work constraints and scenario periods. During the monitoring period, Team #1 showed more than two times higher numbers of glances towards the patient, equipment and team than Team #2.

Table 2. Perceptual mean time durations in minutes and seconds. In parentheses, standard-deviations; in brackets, min.- max. values, and number of glances (n).

Periods	Participants	Patient	Equipment	Team
Monitoring	Aid.1	0:11 (0:14) [0:01-0:50] n=14	0:10 (0:07) [0:04-0:22] n=5	0:05 (0:04) [0:01-0:16] n=13
	Nurse.1	0:17 (0:18) [0:02-0:54] n=10	0:09 (0:05) [0:03-0:20] n=8	0:04 (0:04) [0:01-0:12] n=5
	Aid.2	0:35 (0:24) [0:03-1:15] n=5	0:10 (0:00) [0:10-0:10] n=1	0:20 (0:13) [0:02-0:33] n=3
	Nurse.2	0:28 (0:20) [0:02-0:56] n=4	0:15 (0:01) [0:14-0:15] n=2	1:46 (0:00) [1:46-1:46] n=1
Treatment	Aid.1	0:13 (0:11) [0:01-0:42] n=13	0:11 (0:07) [0:01-0:20] n=6	0:04 (0:02) [0:01-0:09] n=9
	Nurse.1	0:13 (0:22) [0:01-1:16] n=9	0:18 (0:22) [0:03-1:06] n=8	n=0
	Aid.2	0:21 (0:14) [0:03-0:44] n=6	0:24 (0:24) [0 :02-1 :00] n=5	0:10 (0:00) [0:10-0:10] n=1
	Nurse.2	0:37 (0:28) [0:06-1:13] n=5	0:14 (0:10) [0:05-0:27] n=3	0:26 (0:00) [0:26-0:26] n=1

In particular, Aid.1 showed high numbers of glances towards the patient and the team. Concerning time durations, team oriented perceptions in team #1 (95% confidence interval for Aid.1=[1.5-8.5] and Nurse.1=[0.1-7.9]) were shorter than in team #2 (95% confidence interval for Aid.2.=[14.3-25.7] and Nurse.2=[106-106]). This fact was due to a long hand-off period in Team #2 during which the caregivers where located far from the patient at the room entrance.

During the treatment period, a quite similar pattern of numbers of glances can be observed. We can notice that Nurse.1 did not look at the team, whereas she performed 15 actions oriented towards the team during the same period of time (see table 1). In the same manner, whereas caregivers' actions migrated through the team as target (see figure 3), times duration for team oriented perceptions shows short glances for Aid.1 (mean=4 sec.), and for the other caregivers, few occurrences of glances (0 glance for Nurse.1 and 1 glance for Aid.2 and Nurse.2). This pattern of data was possible through time-sharing between perceptual and action processes in a high workload configuration of work.

Figures 4 and 5 provide a temporal representation of perceptual resources allocation to each work constraint. We can observe the focusing on work constraints during the hand-off stage, the patient monitoring period, the treatment period and the arrival of complementary human resource to cope with the emergency

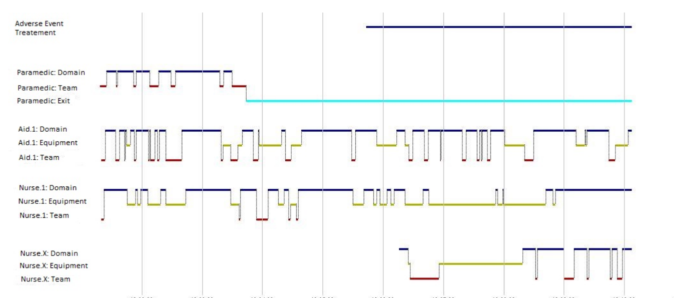

Figure 4: Diagram of perceptual activity for Team #1

In accordance with previous time duration data (Table 3), Figure 4 shows that Aid.1 perceptually navigated rapidly from one constraint to another during all the session. She frequently switched her attention from one constraint to another. Nurse 1 also performed attentional switching between constraints, but for some periods of time no switching towards the team occurred.

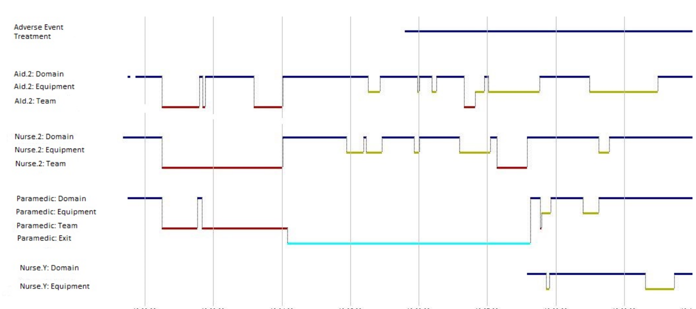

Figure 5: Diagram of perceptual activity for Team #2

In Figure 5 that represents perceptual resources allocation of Team #2, temporal span were globally larger than in Team #1. The caregivers switched from one work constraint to another less frequently. During the hand-off stage, we noticed that caregivers did not pay much attention to the patient, notably Nurse.2 who did not look at the patient during a long period of time. It was necessary that the patient called the caregivers to be considered by Aid.2. After the hand-off stage, the caregivers did not pay attention to the other colleague during a relative long period of time.

DISCUSSION

In this study, we propose a theoretical and methodological implementation of the dynamic safety model originally proposed by Rasmussen. This proposal leads to considering this model as a means to describe the dynamic attunement of agents to work constraints during their activity rather that a way to describe work constraints at an organizational level as originally considered by Rasmussen. This aim leads us to split the original global constraint "workload" into task management and information processing with team boundaries. Additionally, the original abstract performance boundary is concretely defined in our model through the reference to the patient state, in accordance with the ecological approach supported by Rasmussen. This reference to the patient state for considering agent's performance grounds the dynamic safety model in terms of the ecological consequences relative to the domain goal of achieving a health state.

The application of the dynamic safety model to an emergency situation demonstrates the possibility to depict activity concretely through an ecological approach. In this modeling, behaviors are visualized as located in both an objective and subjective work space, whereas usually behaviors are understood as the manifestation of inner processes involving technical and non-technical skills or as deviations from normative prescriptions defined by an organization.

The triangular representation allows for depicting agents' behaviors as located in the work space in a similar manner to the dynamic model representation, with the possibility to describe how these behavioral positions evolve.

The activity diagrams focusing on the three constraining boundaries highlight how perceptual attention dynamically switches from one boundary to another in a multitasking context of work. Particularly, it shows possible attentional tunneling effects, like in the case of the hand-off stage performed by Team #2 that can significantly influence quality and safety in care delivery.

Quantitatively, the Shannon's entropy measure provides an index of the level of coordination of constraints during a given period of work. In our first observation, Aid.1 who was considered as the more efficient caregiver in the studied situation systematically shows a higher entropy index on action distributions on work constraints. While it is difficult to provide an *a priori* optimal value for the entropy measure – a higher value suggests a broader level of awareness or distribution of attention, as opposed to a narrow focus (e.g., tunnel vision). It represents a cognitive positioning in the safety zone at the center of the workspace. Interestingly, to calculate entropy index is a process in accordance with the Rasmussen's proposal that behaviors at work must be envisaged through thermodynamic laws involving combined effect of gradients rather than elementary causal principles.

Whilst these first results demonstrate the feasibility of this methodological approach, obviously it raises more questions than answers. For example, further quantitative research will have to confirm first insights on the relationship between multitasking frequency and performance. As noticed by Wickens (2013), findings on this phenomenon only concern limited data or data collected in simple laboratory experiments. It is an open question as to what are the most effective ways to distribute attention across the multiple constraints shaping the work dynamic. For example, the results here show that higher performance resulted when individuals distributed their attention evenly over the three constraints (i.e., high entropy levels, middle of triangle diagram). However, it is possible that other strategies, such as distributing responsibility across the team for different types of constraints, may be equally effective. This would result in low individual entropy values but broader separation within the triangular information space. That is, one teammate may focus on the patient, while others focus specifically on equipment and communications. Thus, the information metric does not necessarily provide a prescription for effective behavior of individuals. However, it does allow insight into how the micro-structure of individual behaviors combine to address the global demands created by the multiple work constraints – either by distributing individuals to focus on different regions of the constraint space or by having each of the individuals distribute attention broadly to maintain high situation awareness. This reflects the difference between individual and team situation awareness and the different ways that the degrees of freedom associated with multiple team members can be used to meet the global situational awareness demands. In the case of complex teamwork, it is important to realize that there is no "one best way." Rather, one can imagine many different potentially effective strategies for covering the information space with combinations of generalists (high entropy/central locations) and specialists (low entropy/peripheral locations).

CONCLUSION

The important contribution here is to provide an empirical and representational method to better connect observations of team coordination with the theoretical implications of Rasmussen's Dynamic Safety Theory. In this approach, the triangle diagram shows multiple sources of constraint that reflect the situational demands on work. The points in this space reflect how the team members jointly address these demands – in terms of both the distribution of individual attention (the individual entropy measures) and the distribution of responsibility across the group (the individual positions within the constraint field). From a prescriptive perspective, the key to success is ensuring broad coverage over the many different sources of constraint that impact performance quality. From a descriptive perspective, this approach provides a way to visualize the different ways that teams might achieve this broad coverage. Thus, this approach provides one way to connect the micro-structure of individual behaviors to the macro-structure of work domain constraints that may provide insights into the self-organizational or field dynamics of teamwork. Furthermore, this framework can help design ergonomic facilities to arrange the concrete work space used by caregivers (Morineau, Chapelain, Le Courtois, Le Gac, in press).

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