Changes in Team Communication Patterns in Critical Situations

Using REM to study the difference in communication patterns between critical and non-critical situations

Floris van den Oever, S1864394

Master's thesis for Human Factors and Engineering Psychology

Under the guidance of Jan Maarten Schraagen

University of Twente

08-07-2019

Abstract

Teams operating in time-pressured, dynamic environments frequently need to cope with critical situations varying in complexity and hazard. To cope with critical situations, teams may have to adapt their communication processes. Adaptation of team communication processes has been studied mostly at relatively short time frames (minutes). Literature on adapting communication at longer time frames (hours) is limited. This study used the Relational Event Model to compare team communication in critical and non-critical situations of pediatric cardiac surgeries and Apollo 13 Flight Director's voice loops. Teams showed some flattening of communication structures in critical situations. Both teams maintained institutional roles and displayed closed-loop and information seeking communication. The exact way teams adapt to critical situations may differ depending on team and team size. Findings may inform team training procedures or team structure development.

Keywords

Resilience; Adaptation; Team Communication; Coordination; Relational Event Framework.

Contents

Abstract 1
Keywords 1
Contents 2
Introduction 3
  Team adaptation in critical situations 3
  The role of communication 4
  The Relational Event Model 4
  Research aims and outline 6
Systematic Literature Review 7
  Method 7
    Eligibility Criteria 7
    Search 7
    Data collection process 8
    Risk of bias in individual studies 8
  Results and Discussion 9
    Study selection 9
    Individual studies 10
    Synthesis of results 28
    Frameworks for studying team communication 29
    Communication patterns 32
    Limitations 41
Natural History Study 42
  Method 42
    Data sources 42
    Categorization of data into critical and non-critical situations 45
    Data preparation 46
    Analysis 47
  Results 49
    Premodeling descriptive statistics 49
    Model Selection 50
    Parameter Estimates 53
    Comparison of extreme situations 57
  Discussion 59
    Limitations 65
  Research implications 66
  Practical implications 67
  Conclusion 67
References 68

Appendix: Coefficient tables 74

Introduction

Team adaptation in critical situations

Teams deal with situations of various levels of complexity and hazard. Especially teams operating in time-pressured, dynamic environments cope with these kinds of situations (Burke, Stagl, Salas, Pierce, & Kendall, 2006). Such situations place a high demand on the skills and capabilities of teams, necessitating rapid situational assessment and adaptation to, often unexpected, changes (Kozlowski, DeShon, Schmidt, Chambers, & Milner, 2001). In this report, situations that have high levels of both complexity and hazard are defined as critical situations. In critical situations, teams must adapt in order not to break down and fail to achieve their goals (Kozlowski et al., 2001; Woods & Hollnagel, 2006).

Studying the adaptability of teams is useful because more knowledge on the topic can help to improve the adaptability of teams. Team adaptability is becoming more important as a result of increasing complexity and unpredictability of organizations and work environments (Baard, Rench, & Kozlowski, 2014). In accordance with the bounded rationality syllogism (Woods & Hollnagel, 2006), teams have limited resources and capabilities and therefore are fallible. This means that teams can never have all the resources and capabilities required to cope with every possible situation they might encounter (surprise is universal), and they run the risk of saturation of their adaptive capacity (Woods, 2018). Therefore, teams must adapt when demands change (Woods & Hollnagel, 2006) and align and coordinate with multiple interdependent units in a network (Woods, 2018). Teams must develop strategies that handle fundamental trade-offs produced by the need to adapt to changes in an uncertain world (see Hoffman and Woods, 2011). Salas, Sims, and Burke (2005) state that adaptive performance is an integral component of teamwork. Because the adaptability of teams is so vital to their success, it is beneficial to study the adaptability of teams.

To gain understanding of the adaptability of teams it is necessary to study team processes that change when teams encounter critical situations; processes that teams adapt in order to cope with critical situations. Woods and Hollnagel (2006) describe multiple processes related to team adaptability. For example, the anticipation of workload; revision of assessment, and its opposite, fixation; coordination; centralization of decision making; premature narrowing; oversimplification; tempo escalation; coupling; and managing workload among others. Kozlowski et al. (2001) found that, in critical situations, expert team members shift from skill reproduction to skill generalization. Barth, Schraagen, and Schmettow (2015) analyzed the centrality of communication patterns to study team adaptability in complex situations. Butts, Petrescu-Prahova, and Cross (2007) state that teams in emergency situations must adapt resource usage and allocation to changing conditions. Serfaty and Kleinman (1990) found that, as situations become more complex, teams adapt their decision making and coordination strategies.

The role of communication

Since these processes of adaptation occur at the team level, it is axiomatic that they involve communication between team members (Cooke, Gorman, Meyers, & Duran, 2013). Some studies have found that communication patterns change when teams encounter critical situations (e.g., Baard et al., 2014; Butts, 2008; Gibson, 2003; Leenders, Contractor, and DeChurch, 2016). Multiple studies have applied Social Network Analysis (SNA) (see Wasserman and Faust, 1994) to teams in various domains (e.g., medical (Barth et al., 2015), military (Houghton, Baber, Stanton, Jenkins, & Revell, 2015), and sports (Lusher, Robins, & Kremer, 2010)). Although SNA provides detailed measures of, amongst others, the centrality of actors in networks, it is limited in its ability to study how communication patterns develop over time. Team adaptation studied in the form of changes in communication dynamics over time can give a more fine-grained portrayal of communication. Moreover, anecdotal evidence suggests that entrenched communication patterns may have a detrimental effect on patient safety (Fowler, 2013), airplane passenger safety (BEA, 2012), combat effectiveness (Roberts and Dotterway, 1995), or even entire organizations such as NASA (Vaughan, 2006). Correspondingly, Leenders et al. (2016) argue that team processes ought to be studied with more temporal constructs and Stachowski, Kaplan, and Waller (2009) suggest that communication patterns among team members during critical situations may be antecedents of team effectiveness. It is therefore important to take the patterns of communication over time into consideration when studying team adaptability.

The Relational Event Model

Studying communication over time can be done with the Relational Event Model (REM) (Butts, 2008), a framework to model the history of relational events within a group, taking the next relational event as the dependent variable and various communication patterns as independent variables of which the likelihood of them predicting the next relational event can be estimated (Pilny, Schecter, Poole, & Contractor, 2016). By applying Butts' (2008) REM on the communication dynamics during the Air France 447 incident, David and Schraagen (2018) showed how communication patterns can be used to study adaptation at the ‘transaction level’ (Schraagen, 2017), a new ‘system level’ of Newell’s (1990) “bands of cognition”. Newell (1990) distinguished biological, cognitive, rational, and social ‘strata’, each defined by a particular time band during which processes take place. For instance, the typical cognitive processes take place between 100 msec and 10 sec and the typical rational processes between minutes and a few hours. At the transaction level, processes take between an hour and several hours. the entity to be described is a network of interconnected units of adaptive behavior (i.e. a powerplant controlroom team or a cockpit crew). As units of adaptive behavior interact over time, regularities in behavior emerge. These regularities may be visible in the form of ‘patterned interactions’ and may be studied by methods such as SNA or REM. David and Schraagen (2018) provided insight into the changes of multiple communication patterns of a team entering a critical situation. However, a limitation of this study was that the cockpit communication that was studied did not extend beyond 20 minutes and mostly involved two actors, limiting the diversity of the communication patterns that could be studied. Further investigation of communication patterns of larger teams across longer time spans is warranted. Therefore, this study built upon the results found by David and Schraagen (2018), applying Butts' (2008) REM to compare transaction level communication patterns of teams other than cockpit teams in critical and non-critical situations.

To continue on the road to developing better team communication structures or training procedures for team interactions, further investigation of communication patterns of larger teams at the transaction level is warranted. Therefore, this study will apply Butts' (2008) REM to investigate transaction level team communication in critical situations to build upon the results found by David and Schraagen (2018). This will be done on teams other than airplane cockpits, with more team members. Teams other than cockpit crews are preferred because then changes in patterns of communication can be discerned across a wider range of teams and situations. Teams with more team members are preferred because it promotes the occurrence of a greater variety of communication patterns, such as Triadic Effects (Butts, 2008). In line with Woods and Hollnagel's (2006) notion of ‘patterns’, teams from different domains are expected to adapt to critical situations in similar ways and thus change communication patterns in similar ways (see also Van Diggelen, Neerincx, Peeters, and Schraagen, 2019). As such, studies applying REM to other teams than cockpits, from multiple disciplines and in varying situations, are expected to find similar changes in communication patterns when said teams encounter critical situations.

Research aims and outline

This study has three aims. The first aim is to observe whether communication patterns captured with Butts' (2008) REM are different when teams are in critical situations, compared to non-critical situations. Woods and Hollnagel (2006) discuss how teams adapt and extend their performance in critical situations. Changes in communication patterns play a role in these adaptations (see also Xiao, Seagull, Mackenzie, Ziegert, and Klein, 2003). More insight in which communication patterns differ between critical and non-critical situations and how these communication patterns differ can be useful for developing better team communication structures or training procedures (Manser, 2009). The second aim is to evaluate the generalizability to other teams of the differences in communication patterns found (David & Schraagen, 2018). In line with Woods and Hollnagel's (2006) notion of 'patterns', teams from different domains are expected to adapt to critical situations in similar ways and thus change communication patterns in similar ways (see also Van Diggelen et al., 2019). As such, studies applying REM to other teams than cockpit teams may find similar differences in communication patterns when those teams encounter critical situations. If patterns found in the current study are similar to those found by David and Schraagen (2018), their generalizability extends to those domains and can be expected to occur in teams in critical situations of yet other domains. The third aim is to evaluate the concurrent validity of applying REM to team communication on the transaction level. Support for validity is gained if the results are consistent and in line with the results of David and Schraagen's (2008) because data is collected from multiple sources (Spector, 1992). Furthermore, if differences in communication patterns between critical and non-critical situations are found, this provides a demonstration for the applicability of REM for studying team communication on the transaction level.

To achieve these aims, three research questions will be investigated: (a) Do team communication patterns captured with Butts' (2008) REM differ between critical and non-critical situations? (b) Can patterned communication differences be discerned across different teams encountering critical situations? (c) How do these differences compare to those found by David and Schraagen (2018)?

The remainder of this report is organized in two parts. The next section describes the examination of relevant literature reviewed according to the PRISMA statement (Moher, 2009), establishing a framework for investigating and answering the research questions, selecting communication patterns of interest, and formulating hypotheses about the differences of these patterns between critical and non-critical situations. The second section describes the natural history study of critical and non-critical situations.

Systematic Literature Review

A literature review was conducted to explore the contemporary scientific knowledge concerning team communication patterns during critical situations and frameworks to investigate this topic. As such, the research question is: What have studies focusing on communication patterns found that applies to teams in critical situations, with a focus on the Relational Event Model? The literature review followed the PRISMA statement for systematic reviews to the extent permitted by the extracted literature (Moher, 2009).

Method

Eligibility Criteria

Literature was sought which concerns team communication and/or REM. The reviewed literature was not focused on a medical intervention. Studies of various designs and populations were deemed worthwhile for investigation, even studies that applied REM to study communication in other contexts than teamwork because these improve understanding of communication patterns that can be studied with REM. Documents retrieved for the review were restricted to those written in English and published after 1985.

Search

The search was conducted in SCOPUS, which includes all relevant human factors journals. The last search date was 08-02-2019. The following search string was used:

(TITLE-ABS-KEY ("Relational Event Model" OR "Relational Event Framework" OR "Relational Event Network") OR (TITLE-ABS-KEY (framework OR model W/2 communication* AND team OR group OR "social setting" AND critical* OR "critical situation" OR complex* OR "complex situation" OR emergency OR disaster)) AND NOT TITLE (wireless OR robot*) AND NOT (youth* OR adolescent* OR child* OR "computer network").

This string finds publications related to REM, as well as publications using other frameworks or models about communication related to teams, critical situations, and synonyms thereof. Some terms were explicitly excluded to reduce the number of publications found on topics that were not of interest. Namely, communication in robot or computer teams or non-adults.

Data collection process

A data extraction sheet was developed based on Schraagen and Verhoeven (2013). Qualitative summaries were written for the studies in this data extraction sheet, in accordance with the PRISMA statement (Moher, 2009). Studies were summarized. The following components were summarized, if present: (a) Study type and focus on critical or non-critical situations; (b) Study methods (e.g., method of data collection, experimental design, sample size), including unit of study characteristics (e.g., a disaster response communication network, cockpit crew, surgical teams) and the applied framework or model (e.g., REM, SNA); (d) Studied variables (e.g., communication patterns, relational events, personal characteristics). If discernable, dependent and explanatory variables; (f) Findings (e.g., effects of significant variables, communication patterns, social networks); (g) Methodological limitations (e.g., Limits of communication media, limited samples, possible confounding variables).

Risk of bias in individual studies

Risk of bias at the study level was assessed based on methodological limitations of the studies. These were extracted from the studies themselves and, in some cases, based on the reviewer's judgment. For example, many, but not all, studies used pre-existing, validated frameworks for studying communication. Some studies focused on specific populations which may limit generalizability to other populations. Other studies relied on volunteers or snowball sampling and risked self-selection bias. When researchers failed to discuss their own limitations, this was mentioned in the summary. These risks of bias were taken into consideration in the synthesis of the results.

Risk of bias across studies may be present due to publication bias and selective reporting within studies. Concerning reporting bias, no protocols of studies were found to evaluate reporting bias (Liberati et al., 2009). However, none of the studies had a discrepancy between the outcomes listed in their method section and those discussed in the results. Given the inclusion of studies from 1985 onwards, differences in outcome reporting may be expected because demands put upon researchers in reporting outcomes in terms of levels of statistical detail have changed over time.

Results and Discussion

Study selection

56 studies were selected. Eligibility assessment of the records was carried out. Figure 1 shows the flow of study selection through the phases of the systematic review. First, studies from the following irrelevant subject areas were excluded: Agricultural and Biological Sciences; Biochemistry, Genetics, and Molecular Biology; Chemical Engineering; Chemistry; Earth and Planetary Sciences; Economics, Econometrics, and Finance; Energy; Environmental Science; Immunology and Microbiology; Material Science; Pharmacology, Toxicology, and Pharmaceutics; Physics and Astronomy; and Veterinary. Next, two duplicates were removed and eight articles from other sources were included. Of the remaining 439 articles, the eligibility was assessed based on abstracts. 359 articles that were insufficiently related to the topics of study were excluded. For example, articles in which "communication" did not refer to the communication between human actors. Subsequently, the remaining 80 articles were selected for assessment of eligibility based on the full-text. Based on full-text assessment, 24 articles were excluded for reasons such as insufficiently fitting the topic (e.g., Akama, Cooper, & Mees, 2016), not presenting empirical data (e.g., Hachour, 2008), Redden, Elliott, Turner, & Blackwell, 2004), being insufficiently detailed or methodologically deficient (e.g., Musa, Abidin, & Omar, 2016), or being opinion articles. Figure 1 summarizes the selection process in a PRISMA flow diagram (Moher, 2009) following the example of Liberati et al. (2009).

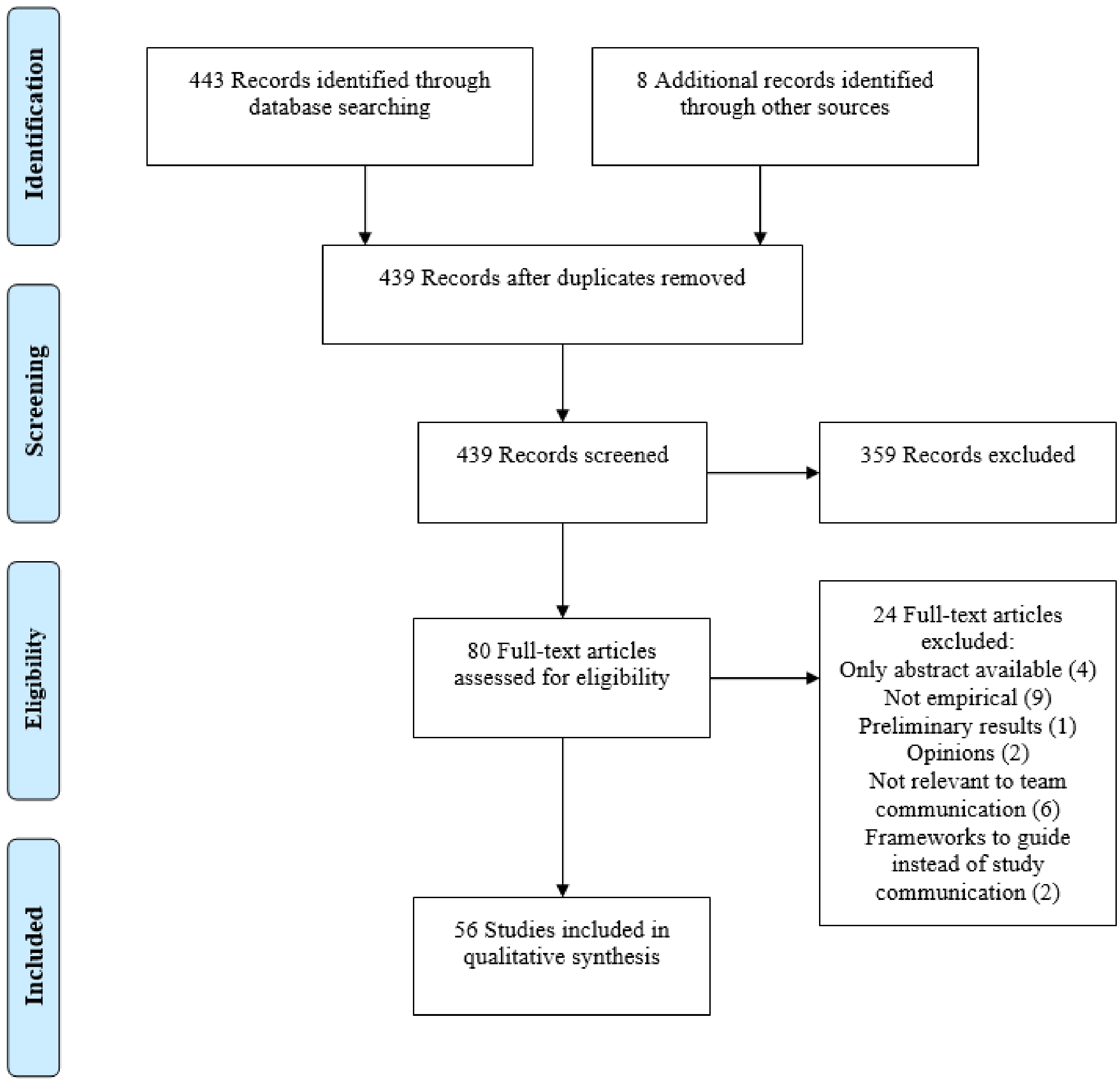


Figure 1. The selection process used to identify appropriate published studies about team communication and REM.

Individual studies

The 56 included studies varied widely in the methodology used as well as the focus on situation types: critical, non-critical, or both. Studied situations were deemed critical when publications described the situations in terms fitting the definition given in the introduction: situations that have high levels of complexity and hazard are defined as critical situations. For example, as concerning critical situations (Manser, Harrison, Gaba, & Howard 2009), emergencies (Pilny et al., 2016), disasters (Butts et al., 2007), crises (Jahn & Johansson, 2018), or complex problem-solving situations under time pressure (Hutchins, Bordetsky, Kendall, & Garrity, 2007). Situations were judged as non-critical when such descriptions were not given (e.g., DuBois, Butts, McFarland, & Smyth, 2013; Quintane, Conaldi, Tonellato, & Lomi, 2014) Furthermore, publications were categorized based on type, ordered by rank of validity associated with these types, see Table 1. This categorization was informed by methodological sources such as Cook, Campbell, and Shadish (2002). The category "Natural history study" was adopted from Woods and Hollnagel (2006). Summaries of the individual studies are shown in table 2.

Table 1. The number of studies analyzed per study and situation type.

Type	Situation	N
Natural history	critical	6
	non-critical	11
	both	2
Literature review	critical	
	non-critical	
	both	1
Observational study	critical	
	non-critical	4
	both	3
Mixed methods	critical	2
	non-critical	1
	both	1
Quasi-experiment	critical	1
	non-critical	2
	both	
Simulator quasi-experiment	critical	10
	non-critical	2
	both	1
Panel study	critical	
	non-critical	4
	both	
Case study	critical	1
	non-critical	3
	both	
	Uncertain	1

Table 2. Summaries of the individual studies, including the characteristics, results, and methodological limitations.

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
David & Schraagen, 2018	Natural history of critical and non-critical situations	Statistical analysis of communication of transcripts of the last two hours of the AF447 flight. The cockpit crew consisted of three members. Analysis was done using REM	Dependent: the next relational event. Explanatory: fixed effects, preferential attachment, triadic effects, persistence, recency, and participation shifts (p-shifts). The P-shifts modeled were reciprocity, handing off,	There were 445 relational events. P-shifts, recency, persistence, and preferential attachment have strong marginal effects. Triadic effects are weak. Reversal of P-shift effects and preferential attachment in emergency situations suggests that pilots fall back on non-standardized local patterns of communication. Stronger recency and persistence in emergency situations suggest more communication to	estimates of triadic effects and P-shifts may be unprecise because only two nodes were present during large parts of the data. Non-human nodes were not considered. The applied BIC estimation favors smaller models than AIC would

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
			persistence of source or target, and attraction	cognitively readily available team members	
Lingard, Reznick, Espin, Regehr, and DeVito (2002)	Natural history study of critical and non-critical situations	128 hours observation of communication of operation room (OR) teams in 35 operations and unstructured interviews with participants. No framework for analysis was mentioned	Dependent: Communication patterns Explanatory: communicative events coded with tension levels	Communication among OR team members is subtler and more complex than the openly combative style that gets portrayed in media Higher-tension events occurred most between surgical and nursing staff novices reacted to tension by either mimicry of the teacher's discursive style or posture or withdrawal from the communicative sphere	The nature of the study only allowed to study visible responses to team tension. Adding measures of attitude may have given more insight. It was not stated how large the OR teams were
Butts et al. (2007)	Natural history study of a critical situation	Statistical analysis of three and a half hours of interpersonal radio communication networks and interactions among four groups of first responders at the scene of the World Trade Center (WTC) on 9/11. Communication was analyzed using SNA. Police reports were also analyzed	Dependent: network positions and ties Explanatory: specialized in emergency response, formal institutional role associated with coordination	A high degree of heterogeneity of individual in communicative activity. Heterogeneity of individual position within the communication structure. Homogeneity across responder types; no evidence for differences in the distribution of communication activity between specialists and non-specialist responders. Emergent coordinative activity played a prominent role, but responders with institutionalized coordination roles were more likely to act as coordinators than those without coordination roles. A larger than expected overall connectivity of the police response network	Actor to group communication was not modeled. Binary tie data: either there is a tie or not. No insight in varying amounts of communication. Some statistical data is aggregated from police reports written after the incident and therefore sensitive to memory bias as well as researches degrees of freedom
Butts (2008)	Natural history study of a critical situation	Statistical analysis of three and a half hours of interpersonal radio communication networks and interactions among police officers at the scene of the WTC on 9/11. Police reports, using REM	Dependent: the next relational event. Explanatory: individual-level heterogeneity, preferential attachment, triadic effects, cognitive effects, conversational norms	There were 1131 relational events. A combination of cognitive/behavioral effects and local rules best predicts the dynamic behavior of WTC radio communication networks. Local rules (p-shifts) have a strong impact. Recency is important. Persistence and preferential attachment had a weak effect compared with recency and p-shift effects. Triadic effects were significant in half the transcripts with little consistency in strength or direction. There is a substitution effect between preferential attachment and fixed effects. Centrality within	Data is ordinal because no exact temporal information was available. No limitations were discussed in the article

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
				networks was largely due to factors other than institutional status	
Au, Lo, and Hoek (2009)	Natural history study of critical situations	Statistical analysis 50 hours of time-stamped communication data of an Air and Space Operations Center team with 11 members based on speech and chat logs, using	Dependent: Importance of operators to social and situational awareness. Explanatory: Centrality sociometric status, and information objects	Two actors have more connectivity than the others, the Dynamic Targeting Officer (DTO) and the Command and Control Duty Officer. (C2DO) The DTO has high centrality and sociometric status, the C2DO has high centrality. Incorrect information objects due to high workload limited situational awareness	No limitations were discussed in the article. Loss of information due to the aggregation of fine-grained data to social networks
Goguen and Linde (1983)	Natural history study of critical situations	Statistical analysis of eleven cockpit communication transcripts of critical situations, each lasting at least 30 minutes. based on the Speech Act theory	Crew recognized emergency, crew recognized problem, operational relevance, mitigation/aggravation, topic	Speech acts to superiors are more mitigated. Speech acts are less mitigated in crew recognized emergencies and problems. Subordinates plan less than superiors. Planning and explanation are less common in crew recognized emergencies and problems. Topics are less likely to be picked up in mitigated speech. More mitigated suggestions are less likely to be ratified	Due to the research being based on multiple transcripts of unique events it is impossible to form hypotheses correlating linguistic patterns with specific types of events in the real world. Due to the absence of video recordings, it is difficult to tell what actions crew members took and their relation to the linguistic patterns
Quintane et al. (2014)	Natural history study of a non-critical situation	Statistical analysis of an open source software project with two releases, using REM with a two-node networks extension	Dependent: the next relational event. Explanatory: Prior edge, prior activity, prior popularity, out-in assortativity, four-cycle. Actor attributes: core developers, severe software bug, core severe	There were 4348 relational events, 194 active contributors, and 1208 active software bugs. The extension performed well on the large dataset with many actors. There were patterns of hierarchy, high initiator, preferential attachment, centralization, and four-cycle, which show the emergence of a social organization of problem solving that cannot be reduced to individual self-interest	No limitations were discussed in the article. No statistical model selection. The study was based on sequential REM, while a two-node extension was more applicable
Jahn and Johansson (2018)	Natural history study of a critical situation	Qualitative analysis of communication in 10 crisis response team meetings during a wildfire. Between 9 and 18 members were present. Analysis was done using the	Dependent: adaptive capacity Explanatory: membership negotiation, reflexive self-structuring, activity coordination, and institutional positioning	Reflexive self-structuring is important for the adaptive capacity of a new team. A consistent meeting procedure is helpful. Further adaptation is possible through activity coordination	No limitations were discussed in the article. Transcription and inductive coding were done without double coding.

Study	**Study Type**	**Study methods**	**Variables**	**Findings**	**Methodological limitations**
		Structurational Model			
Quintane and Carnabuci (2016)	Natural history study of non-critical situations	Statistical analysis of email communications in a consulting agency, using REM with a two-node networks extension	Dependent: The next relational event Explanatory: recency, triadic closure, inertia, high initiator, preferential attachment	There were 75,308 relational events. Brokers engage more often in recency and when they do, they often instigate triadic closure	Email communication is only one medium of communication. Communication through other media was not included in this study
Vu, Pattison, and Robins (2015)	natural history study of a non-critical situation	Statistical analysis of learner activity and clickstream data generated by 33,527 learners in a Massive Open Online Course. Relational events studied were 28.263 drop-outs, 7141 forum posts, and 14.140 quiz submissions, using REM with an extension for stratification	Dependent: drop-out, forum post, quiz submission. Explanatory: user questions, user degree, user activity, user degree x activity, thread view, thread degree, thread activity, thread degree x activity, thread degree and quiz scores, degree assortativity, activity assortativity, user two-paths, user two-paths and quiz scores, thread two-paths, thread two-paths and quiz scores, edge view, edge activity, three-paths, three-paths and quiz scores, edge activity x three-paths, edge activity x three-paths and quiz scores, user post recency, thread age, user forum votes, thread forum votes, forum vote assortativity, edge forum votes, user active time, user forum view, user wiki view, user video view time, user quiz recency, user quiz scores, user pass	Drop-out was predicted by low user active time, low quiz scores, passing the course, low interaction with course materials, low and dispersed activity on forums. A high number of forum posts has a negative relation with drop-out. forum posts were predicted by user activity variables as well as thread popularity, especially if high-performing learners contributed. Active learners are less likely to contribute to popular threads. Learners tend to post on threads they have posted to before. Learners with common interests in the past tend to take part in the same forums. Activity in the course and interaction with course materials, as well as high quiz scores predict post behavior. Test submission was predicted by user active time, activity in the course and high interaction with course materials. Forum activities had no effect on quiz submission. Higher quiz performance was related to more submissions	No limitations were discussed in the article. No model selection based on the fitness of effects; All proposed effects were included. Possible bias because due to lack of time-varying network effects, behavior may change over time as learners got familiar with the MOOC environment

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
			achievement, user current quiz score		
DuBoi et al. (2013)	Natural history story of non-critical situations	Statistical analysis of 297 high school classroom sessions, using REM with a hierarchical extension	Dependent: The next relational event. Explanatory: The participation shifts: PSAB-BA, PSAB-BY, and PSAB-AY. Contextual effects: is teacher, is female, recency, teacher-class, teacher-class repeat, student-class, same race, same gender, are friends, adjacent seating	Applying a hierarchical extension of REM is beneficial for modeling heterogeneity across event sequences compared to other approaches, especially in the case of poorly informed parameters from individual sessions. For example, when the racial mix within a particular classroom proves few opportunities for cross-group interaction	No limitations were discussed in the article. It is unclear how many relational events were observed. Pooled modeling is a simpler method than hierarchical modeling if coefficients are similar across events sequences
Brandenberger (2018)	Natural history study of a non-critical situation	Statistical analysis of legislative cosponsoring events of the 113th U.S. Congress, using REM with a two-mode network extension with extensions for model estimation with unique target nodes or inherent time-dependence in target node set composition	Dependent: the relational event. Explanatory: three types of reciprocity with five levels of time weights: reciprocity as a dynamic, reciprocity in active cosponsoring, reciprocity in passive cosponsoring, inertia, similarity, shared partners, member activity-active sponsoring, member activity-passive sponsoring, short-term bill popularity, bill popularity among ideologically different members	There were 123,587 relational events. Republican members reciprocate previous support by working together on new bills if they received cosponsoring support within the past few months. Democratic members, on the other hand, exhibited negative effects of reciprocity on the formation of new collaboration clusters. Reciprocity does not help to resolve the waiting game	Large amounts of noise in cosponsoring data may produce biased results. Two-mode REMs are limited in several ways: (a) they demand a specific data structure, (b) they are computationally intensive in the case of large datasets, (c) REMs can have problems with omitted variable bias if the endogenous network effects are not specified correctly or adequately. Goodness-of-fit statistics may help
Lomi et al. (2014)	Natural history study of a non-critical situation	Statistical analysis of collaborative patient referral relations linking a network of hospitals during the period of 2005-2008, using REM	Dependent: the next patient referral event Explanatory: reciprocity, assortativity, repetition, transitive closure, cyclic closure, hospital capability	3461 referral events connecting 35 hospitals were studied. Patients were likely to be sent to more capable hospitals. Hospitals tended toward reciprocation, transitivity, assortativity and to rely on prior relations	High computational requirements were needed and may limit studies with larger datasets. The values of hospital-specific covariates are updated yearly, so the assumption had to be made that these would be constant. Some measures of hospital

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
					capability may be unobserved
Amati, Lomi, and Mascia (2019)	Natural history study of a non-critical situation	Statistical analysis of collaborative patient referral relations linking a network of hospitals during the period of 2005-2011, using REM with an extension focusing on the time variation of processes	Dependent: the next patient referral event Explanatory: preferential attachment, reciprocity, inertia, assortativity, closure, fixed effects	8363 referral events connecting 35 hospitals were studied. Positive effects were found for reciprocity, persistence, assortativity by intensity and cyclic closure negative effects were found for recency, assortativity by degree and transitive closure. Reciprocity was less likely to be observed on Thursdays than on the rest of the weekdays, no daily variation was found for inertia and assortativity. Cyclic closure operates only on Thursdays and Fridays	No limitations were discussed in the article. Triadic effects were not considered. The influence of other relational events than patient transfers was not considered. Hard to reproduce
Benham-Hutchins and Effken (2010)	Natural history study of non-critical situations	Five patient transfers between four hospital units in an acute care setting in a university hospital in the US were studied, data was gathered by means of observation and questionnaires distributed to 25 participants selected by snowball sampling, analysis was done using SNA	Dependent: Communication network structures during patient handoff Explanatory: Betweenness centrality, closeness centrality, eigenvector centrality, total degree centrality, betweenness network centralization, and Hierarchy	The network consisted of 18 actors. Handoffs had low betweenness centralization, indicating that there was no centralized structure in emergent communication networks. Hierarchical structures were observed with the admitting unit nurse and emergency department attending physician in gatekeeper positions. No dyads, triads or cliques were observed. Overall actors were satisfied with the communication they were able to obtain. Information systems with multiple channels increase workload. Policies have a strong influence on communication patterns	Response rates may cause bias to social networks. Networks included actors that were not observed or found through snowball sampling, which may have influenced out degree centralization. Limited generalizability due to handoffs providing a snapshot view of a single transfer, there were varying network structures. There may be informant bias and the discrepancy between recall and self-report and actual behaviors
Liang (2014)	Natural history study of non-critical situations	Quantitative analysis of communication patterns on online political forum discussions using REM	Dependent: the next relational event Explanatory: ideology, conversational norms, structure, common interest, opinion congruity	There were 1178 participants and 171338 relational events. Conversational norms had a large positive effect, as well as popularity and recency received. Recency send had a negative effect. Triadic effects were small but present. Actors were more likely to send to people of an opposing political ideology	Low generalizability due to a focus on a specific political forum and because participation in web forums is a self-selection process. No model selection was carried out. It is unclear how data from different datasets were pooled
Lerner and Lomi (2019)	Natural history study of non-critical situations	Quantitative analysis of collaborative work in Wikipedia using REM with an extension for two-mode	Dependent: The next relational event. Explanatory: repetition, article popularity, user activity, 4-cycle, page views for	There were 87000 users connected to 4000 articles by more than 950000 relational events. A high positive effect was found for edit repetition and article popularity, indicating centralizations. A small positive effect for edit 4-	No limitations were discussed in the article. Fixed effects of users may have given more insight into role taking

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
		networks and a novel software program	both editing and talking	cycle was found indicating group forming. A negative effect was found for edit assortativity, indicating that popular contributors contribute to non-popular articles. Natural role taking of talkers and editors was visible in activity levels	
Lerner and Lomi (2018)	Natural history study of non-critical situations	Quantitative analysis of edits and deletion of edits in controversial Wikipedia articles using REM with an extension for two-mode networks and actor orientation	Dependent: the next relational event Explanatory: reputation of source, reputation of target. For undo and redo actions: repetition, reciprocation, outdegree of source, indegree of source, outdegree of target, and indegree of target. Four triadic effects: friend of friend, friend of enemy, enemy of friend, and enemy of enemy	1206 articles were studied, with each on average 3416 edits by 1872 contributors. Balance theory seems to explain the behavior of actors. Actors seem to classify others into “friends” and “enemies” and this classification has consequences for the way users evaluate the contribution of others. However, the reputation hypothesis is also supported. Actors evaluate the reputation of others and undo and redo accordingly. Actors took on roles of content providers or editors	Lack of consideration of the semantics may limit insight. Not all communication channels available to the actors were considered. The quality of articles was not taken as an explanatory variable but may have had a large influence. Fixed effects of users may have given more insight into roles actors take, such as moderator or contributor
Vu, Lomi, Mascia, and Pallotti (2017)	Natural history study of a non-critical situation	Statistical analysis of collaborative patient referral relations linking a network of hospitals during the period, using REM with an extension to control for event-specific effects	Dependent: the next relational event Explanatory: out degree, out intensity, in degree, in intensity, recent sending, recent receiving, repetition, reciprocity, assortativity by degree, assortativity by intensity, transitive closure, cyclic closure, sending and receiving balance	2709 patient transfers between 35 hospitals were analyzed. Aggregated results masked a considerable level of heterogeneity. Differences were found in different network compositions. In within-specialty networks, hospitals were selected regardless of levels of competition. In between-specialty networks, hospitals were chosen based on competitiveness and similarity. In intensity was positive between specialties, but negative within specialties. Overall, recency was negative. Out intensity, out degree, in indegree and repetition was positive.	No limitations were discussed in the article. No statistical model selection is carried out. Not all the found effects are discussed
Manser (2009)	Literature review of studies concernin g critical	Structural literature review with measures for reliability,	No specific variables were used	Teamwork is critically important in assuring patient safety. Relevant aspects of teamwork are quality of collaboration, SSM,	No limitations were discussed in the article. Not to full PRISMA standards

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
	and non-critical situations	developing a framework for the analysis of team communication		coordination, communication, and leadership. So far, no direct link between communication patterns and patient outcomes has been established, but models of communication are expected to improve team functioning and patient safety	
Barth et al. (2015)	Observational study of critical and non-critical situations	Observation of communication patterns during different phases of 39 surgeries, using SNA for analysis	Dependent: Centralization Explanatory: network-level degree centralization, density, closeness centralization, betweenness centralization, and reciprocity	Frequency of communication was lower in complex procedures. There was a considerable degree of reciprocity. Most communication occurred between perfusionist 1 and surgeon 1. These actors were the most frequent senders; surgeon 1 also was the most frequent receiver. Anesthetist 1 had a strong sender and receiver role as well. In complex procedures, the network structures were flatter, denser, and less closed, enabling higher levels of information sharing. Higher degrees of density and reciprocity during transition phases indicate more information sharing and closed-loop communication	Aggregation of data with SNA may limit insight into fine-grained communication patterns. Data was observed during live sessions. While rigorous reliability measures were taken, some events may have been missed by observers
Xiao et al. (2003)	Observational study of critical and non-critical situations	Analysis of direction and frequency of communication in 18 videotaped trauma resuscitations. Content was measured in two categories: questions and instructions.	Dependent: Communication frequency, direction, and type (instruction or question) Explanatory: Task urgency and shared experience among team members	Under higher task urgency, the proportion of communication from the team leader grew from 9% to 15%. There also was a higher proportion of team communication between the team leader and senior member of the team. During urgent situations, fewer questions were asked and more instructions were given	Not all team members were treated equally. Only three initiators were considered. The rest of the team (e.g., nurses) were categorized as “other”. Only four cases depicted high task urgency. While discussing the proportional frequency of team members, overall communication frequency was not mentioned
Schraagen (2011)	Observational study of critical and non-critical situations	Quantitative and qualitative analysis of team communication processes in 40 surgeries. Qualitative analysis was done based on the NOTECHS	Dependent: explicit coordination, heedful interrelating, support behavior, and decision making Explanatory: non-routine events	Explicit coordination was most frequent, followed by heedful interrelating, support behaviors and decision making. Surgeons displayed more coordinating behavior than anesthetists; anesthetists displayed more heedful interrelating. Little decision making, heedful interrelating and	The study concerned one team in one medical specialty, limiting generalizability. Data was observed during live sessions. While rigorous reliability measures were taken, some events may have been missed by observers

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
		coding framework		support behaviors were observed in perfusionists and nurses. The team relied largely on explicit coordination to deal with routine events. Non-routine events predicted explicit coordination processes for anesthetists and nurses. Heedful interrelation in complex situations may be related to better patient outcomes	
Manser, Foster, Flin, and Patey (2013)	Observational study of non-critical situations	Patient handover communication was studied and compared to self-ratings of handover quality by means of ANOVA and MANOVA. No framework for analysis was mentioned	Dependent: handover quality Explanatory: 31 types of handover behavior	a total of 117 patient handovers were observed at three postoperative care transitions. Higher quality handovers were related to more assessments and less information seeking. Information seeking behavior may be compensatory. A large variety was found in what clinicians think makes a good handover	The observational nature of the study did not allow for the control of confounding variables. Some participants were observed multiple times, for which countermeasures were taken. No causal inference can be made due to the analysis performed. The study was carried out in one hospital
Stainback, Sawhney, and Aikens (2011)	Observational study non-critical situations	Observational study of six car racing teams, using the novel Communication Productivity Model	Dependent: Racing performance Explanatory: Technical word density, Racing stop word density, Quality word density	Technical word density and racing stop word density had positive relationships with racing performance	No limitations were discussed in the article. Determining the significance of communication relative to the productivity of multiple teams was not possible
Zhang et al. (2016)	Observational study of a non-critical situation	Sector capacity estimation based on air traffic control (ATC) workload as measured by control communication frequency	Dependent: The number of controlling communication events Explanatory: the number of aircraft of the different traffic flows	Control events happened 61 times/hour. The ratio between the approach and departure is roughly 1:1. The number of control events is proportional to sector capacity. From the perspective of controller workload, limiting the number of control events per unit time limits the ultimate sector capacity	Limited generalizability to ATC centers with different numbers of control sectors.
Sevdalis et al. (2012)	Observational study of non-critical situations	Quantitative analysis of communication in 20 laparoscopic and 20 open surgical operations. Analysis was based on a	Dependent: Communication patterns, content, purpose, and type Explanatory: Type of surgery	Surgeons initiated about 80% and nurses 15% of all communication. Anesthetists initiated very little communication. Surgeons received about 48 % and nurses about 39% or communication. Laparoscopic surgery communication was more directive and contained	Data from one general surgical procedure in one hospital may limit generalizability. Observer bias may have occurred.

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
		novel framework built on two models of team communication		more inquiries. Overall, equipment- and procedure-related issues were most discussed.	
Weller et al. (2014)	Mixed methods study of critical and non-critical situations	Comparison of anesthesiologists' communication in simulated routine and crisis surgeries and comparable routine surgeries in the OR. Manser's (2009) coding framework and ANOVAs were used for the analysis	Dependent: Fixed effects, task assignments, information requests, response to suggestions, statements of fact, verbalizations of patient status, assessment of patient status, anticipation of future events, proposal of action plan. Explanatory: Criticality of situation	48.7% of communication events involved the sharing of situational information about the patient. There was no difference in communication between routine OR and routine simulation operations, but there was a difference between simulated crisis and routine operations. Verbalizations and assessment of patient status, as well as proposals for plans of actions, happened more in crisis situations. The target of communication was the same in routine and crisis situations	Convenience sampling was applied. A novel coding framework was used.
Calder et al. (2017)	Mixed methods study of critical situations	18 emergency resuscitation team members were interviewed. 30 simulated resuscitation video recordings and 12 live resuscitations were observed. Qualitative communication content analysis was used, as well as SNA	Dependent: shared mental models (SSM), communication patterns in terms of types of communication, content of information exchange and types of team interactions, and information needs for team situational awareness	2625 relational events were observed in the simulation videos and 2128 in the live observations. The most responsible physician, recording nurse, and senior resident were the most central figures. Environmental factors limiting communication caused problems for SSM. The most common types of communication involved statements, requests, questioning and acknowledging. These are seen as required for team situational awareness, as well as conveying information about the patient, environment, task, and time	The study was conducted in a single center and may not be generalizable. Interviews relied on volunteers, so there is a risk of self-selection bias, social desirability bias, and recall bias. Interviews were not based on a standardized interview questionnaire. However, they were designed using psychology and clinical resuscitation expertise of the investigative team. Observations of the simulations may suffer from the Hawthorne effect. Transcriptions of video recordings were done by a single investigator (10% was verified by a clinician investigator). Live observations risked data loss
McKinney and Smith (2005)	Mixed methods study of critical situations	Qualitative analysis of personal experience, interviews, reports of mishaps, training guides,	Performance, communication, characteristics of effective starts, training methods	Cockpit crew performance in critical situations was improved by (a) deliberate early expression and commitment to specific communication values; (b) selection of distinct and varied communication interactions;	The developed model may only be applicable to cockpit crews. This study only provides minimal proof of the findings, further empirical evaluation is necessary

Study	**Study Type**	**Study methods**	**Variables**	**Findings**	**Methodological limitations**
		and conference proceedings about cockpit crews. No framework for analysis was mentioned		(c) a team's capacity to apply new interactions during a critical situation; (d) crewmembers' awareness of their communication responsibilities and role	
(Liu, Manias, and Gerdtz (2012)	Mixed methods study of non-critical situations	Observations, field interviews, video-recordings, and video reflexive focus groups were conducted focusing on nurses during patient handovers in a hospital. Fairclough's critical disclosure analytic framework was used for analysis	No specific variables were studied	In total 290 hours of observation, 72 field interviews, 34 hours of video-recordings and 5 reflexive focus groups were analyzed. Handovers in private spaces prioritized organizational and biomedical discourse, with little emphasis of effectiveness or medication treatment. Spatial structure caused added complexity. Handovers at bedsides facilitated medical communication. Handover across wards caused communication breakdowns	Participants were invited, those who were less confident in their communication skills might have been unintentionally excluded. The first researcher may have been somewhat subjective due to her nursing background
Hutchins et al. (2007)	Quasi-experiment of critical situations	Analysis of verbatim transcripts from two series of experiments wherein teams collaborated to solve complex problems. Three Maritime Interdiction Operation teams and four air warfare teams participated. Analysis was done using content analysis in the framework of the Model of Team Collaboration	Dependent: The method of team collaboration Explanatory: communication acts coded as cognitive processes in four categories: Knowledge construction; collaborative team problem solving; team consensus; and outcome, evaluation and revision	Seven teams participated. Teams consisted of six members. Most communication acts were in the knowledge construction category, showing that individual knowledge construction is important and reflects the high degree of uncertainty of the situations in which the teams acted. Collaborative team problem solving was also important, especially getting a shared understanding. Only a few communication acts in the categories team consensus and outcome evaluation happened. Indicating that decision making was probably not collaborative	No limitations were discussed in the article. Coding process is unclear. No mention of multiple codes or inter-rater reliability
Gorman, Cooke, Amazeen, and Fouse (2012)	Quasi-experiment of non-critical situations	Quantitative analysis of the communication of three-person teams carrying out a series of 40 minutes UAV reconnaissance	Dependent: team effectiveness Explanatory: communication determinism, unique patterns extracted, average pattern length	Teams that were not mixed displayed higher communication determinism than mixed teams. Mixed teams suffered a performance decrement following the mixing but became more adaptive later while	The rigidly structured team task studied may not represent other tasks. Interactions were studied at the ordinal level, not the interval level. No specific communication patterns were studied

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
		missions. Half of the teams were mixed halfway through. Communication was analyzed with recurrence analysis for nonlinear time series		performing as well as intact teams	
Boies and Fiset (2018)	Quasi-experiment of non-critical situations	Forty-four teams of 2-4 members completed a complex task after watching different leadership videos. Team interactions were transcribed and coded. Mental models were measured by rating scales. The relations between communication patterns and leadership styles were studied using ANOVA and the Tukey post hoc HSD analysis	Dependent: team SMM and task SMM emergence Explanatory: three leadership manipulations: inspirational motivation, intellectual stimulation, control	Communication patterns may explain how intellectual stimulation and inspirational motivation influence SMM emergence. Task-related communication mediated the relationship with task SMM. Team-related communication mediated the relationship with team SMM and task SMM in the case of inspirational motivation	The temporal nature of SMM emergence was not measured
Manser et al. (2009)	Simulator quasi-experiment of simulated critical and non-critical situations	Analysis of coordination patterns of 24 two-person anesthesia teams. The framework for observation of coordination patterns was based on multiple existing systems, interviews, and field notes. Statistical analysis was done with ANOVAs	Dependent: Coordination patterns Explanatory: Team clinical performance score and situation criticality	Information management and task management was higher in the critical situation than in the non-critical situation. Higher performing teams exhibited less coordination of actions or tasks and more coordination of information in the first five minutes of a crisis than low performing teams	Analysis of inexperienced teams in one clinical event may reduce generalizability and variables that influence performance may have been overseen

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
Davis et al. (2017)	Simulator quasi-experiment of critical situations	Retrospective analysis of the communication behavior of 7 operative teams during the response to a simulated emergency, using the closed-loop communication framework	Call-outs, check backs, closed-loop episodes	7 simulation sessions were analyzed with a total of 42 participants. Surgeons and nurses sent significantly fewer call-outs than anesthesiologists. Directed call-outs received more check backs (18%) than non-directed (11%). 7% of directed call outs and 2 % of non-directed call outs resulted in closed-loop communication. During periods immediately following critical clinical changes, the association between directed communication and check backs disappeared entirely, while it significantly increased check-backs in calmer periods	There may be unknown confounders because retrospective analyses were conducted. Prior relationships among team members or hierarchical relationships could have affected communication patterns. Communication behavior was coded by only one researcher, however similar studies with a second coder described no issues of inter-rater reliability. A large chance of false-negative in finding no relationship between directed communication and closed-loop communication due to low prevalence
Pilny et al. (2016)	Simulator quasi-experiment of a critical situation	Statistical analysis of radio communication of a multi-team system consisting of two co-operating military teams which had to navigate a critical situation in a simulator. As well as pre-experiment surveys, using REM	Dependent variable: the next relational event. Explanatory variables: Inertia, reciprocity, captain as sender, cross-team relay, trust	298 relational events were observed. Intrateam communication was most prevalent, then stinger team and then cross-team. Inertia was positive and significant. Reciprocity was not significant. Although captains sent more messages, drivers were more likely to send the next message. Cross-team relay was insignificant. Trust was positive and significant	No limitations were discussed in the article. Both teams consisted of only two members, limiting possible communication patterns such as triadic effects. Fixed effects may have played a role, since there was a clear role division in the teams but weren't studied
Schecter, Pilny, Leung, Poole, and Contractor (2018)	Simulator quasi-experiment of a critical situation	55 four-person teams played a military-style strategy game. Text chats were analyzed, using REM	Dependent: Perceived levels of coordination and sharing of information Explanatory: inertia, reciprocity, triadic closure, activity, preferential attachment	35829 events across 200 people organized into 55 groups of four were analyzed. A negative propensity towards activity and preferential attachment were linked to higher coordination and effective information sharing. Propensity towards inertia, triadic closure, and reciprocity were linked to higher levels of coordination and effective information sharing	Participant behavior was at least in part shaped by military training, limiting variability in interaction patterns. Short (one hour) simulation limits generalizability. A content-free approach limits depth of insight. The small effect sizes and a large dataset suggest that effects

Study	**Study Type**	**Study methods**	**Variables**	**Findings**	**Methodological limitations**
					may have been spurious
Cumin, Skilton, and Weller (2017)	Simulator quasi-experiment critical situations	Analysis of transcripts of 39 simulated emergency surgery scenarios with 20 OR teams, each taking part in two simulated scenarios. No framework for analysis was mentioned	Dependent: Transmission of clinically relevant information in the form of information probe Explanatory: Formal team communication instances: pre-case briefing, sign in, and time out. Informal communication instances	The whole team was 5 times more likely to correctly answer post scenario questions if a probe was mentioned during formal team communication and 4.1 more likely to recall a probe if it was mentioned in response to a question during the scenario. Consultant surgeons, anesthetists, and circulating nurses were more likely to mention information probes than scrub nurses, anesthetic technicians or surgical trainees. Failures in effective communication were common	Interrater comparison and agreement were carried out, but no calculation of interrater reliability is given. Acting in a simulation rather than a naturalistic situation may have affected the likelihood of sharing information. Generalizability may be limited because the study was undertaken with the staff of two hospitals in Australia. A large spread in confidence intervals (CI's) suggests an estimate of effect size could be limited
Dunn, Lewandowsky, and Kirsner (2002)	Simulator quasi-experiment of a critical situation	Analysis of the temporal distribution of radio communication between individuals and groups of an emergency management team in a training exercise that simulated a chemical spill, analysis was based on communication frequency	Dependent: communication rate Explanatory: timing of critical events and intrinsic temporal cycles	Communication rate between key members of a distributed decision-making team in critical situations may both follow an intrinsic cycle and be affected by critical events	Only radio communication transcripts were used, person-to-person communication was not registered, which may cause bias. Patterns of communication in exercise two were different than one and three, which reduces the credibility of findings
Grimm et al. (2017)	Simulator quasi-experiment of critical situations	Observation of the communication flow of three neurosurgery teams in simulation scenarios. Analysis was done using Discrete recurrence analysis	Dependent: communication determinism Explanatory: perturbations in the team environment	Team communication patterns are different immediately after perturbations in the team environment (i.e. patient goes into anaphylactic shock)	It is unknown whether this algorithm is efficient enough to truly detect perturbations in real-time for a variety of team process measures. Parameter selection is somewhat arbitrary. Time series with different window sizes may be slow
Siassakos, Draycott, Montag	Simulator quasi-experiment of a	Content analysis to compare communication patterns	Dependent: Communication patterns Explanatory:	The two teams that received training had an increase of directed commands increasing the likelihood of tasks being acknowledged and performed.	No pre-test observation of dependent variables. The small sample size limited statistical analysis

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
ue, and Harris (2009)	critical situation	between four medical teams in an obstetric emergency. Two teams received teamwork behavior training beforehand. No framework for analysis was mentioned	Teamwork behavior training	In all teams a clear hierarchy was visible. The senior doctor and primary midwife played central roles. Due to unclear roles and responsibilities, team situational awareness and clarity of responsibilities was low, causing errors	
Stachowski et al. (2009)	Simulator quasi-experiment of critical situations	Quantitative analysis of communication patterns of 14 nuclear powerplant control room teams dealing with a simulated crisis. No framework for analysis was mentioned	Dependent: Communication patterns Explanatory: Team effectiveness	Higher performing teams exhibited fewer, shorter and simpler interaction patterns during critical situations. They also showed fewer established, systematic patterns	Only a small sample of teams were studied. No control conditions of non-critical situations were available
Granlund, Granlund, Dahlbäck, and Johansson (2010)	Simulator quasi-experiment of critical situations	18 crisis management teams responded to simulated crisis situations; Nine participant groups consisting of six members each in two conditions, summing up to 108 participants. Communication was recorded. Content was coded based on a framework developed by Svenmarck and Brehmer (1991). Content and frequency of communication were analyzed	Dependent: communication patterns: questions, information, order, and other Explanatory: Geographical information system, paper map	Teams with a geographical information system communicated less, especially about information, but gave more orders	No limitations were discussed in the article. Only email communication was studied. Some communication may have happened through other media
Leenders et al. (2016)	Simulator quasi-experiment of a	Analysis of the communication patterns of two two-team systems in a	Dependent: The next relational event. Explanatory: Inertia	Inertia and reciprocity were positive, indicating routinized communication. Interteam reciprocity was not significant for one multiteam system and	A rather small sample with two multisystem teams consisting of two teams of two persons may limit

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
	critical situation	simulated conflict zone, applying REM	reciprocity; interteam reciprocity; and interteam mimicry	negative for another. Interteam mimicry was positive for one system and negative for the other	generalizability. No possibility of studying triadic effects due to the small team size. Various effects that may have been interesting, such as fixed effects, were not studied
Weil et al. (2008)	Simulator quasi-experiment of non-critical situations	Analysis of stored communication from electronic chats in an Air and Space Operations Center simulation. The Flow Analysis of Utterance in Teams (FAUCET) was used for analysis	Dependent: team performance Explanatory: communication chains: sequences of communication events	Four teams of five students participated in a combined total of 53, forty-minute scenarios. Regularities in the structure of a team's communication flow were associated with good performance. More chat events may also be related to higher performance	Chat occurred in multiple threads across multiple chat rooms, which made flow analysis more difficult
Bierhals, Kohler, and Badke-Schaub (2007)	Simulator quasi-experiment of non-critical situations	Eight teams solved complex design problems in a gaming simulation. Questionnaires were taken, and performance data was collected. Interactions of the worst and best performing teams were compared. Analysis was done using the KATKOMP communication categories	Dependent: Team performance. Explanatory: Development of shared mental models (SSM) of task, process, team, and competence; Communication categories: Content, process, and relationship; patterns of communication	High overall, process, and team dyadic SMM were high performance. SMM about tasks was less important. More discussion led to better SMM. Communication categories were similar for the high and low performing teams. The low performing team did show more relationship communication. A flatter communication structure was related to better SMM. Discussion of contradictory goals was related to higher performance. Frequent transitions between planning, analysis, and evaluation was related to higher performance. Critical situations may instigate the development of SMM	The results are limited to self- organizing groups in complex situations. Autocratically leaded groups may be able to rely on coordination done by the leader
P. D. Patterson et al. (2013)	Panel study of non-critical and critical situations	SNA of team communication patterns at different times of the day in a hospital emergency department-based 336 survey results by 103 unique respondents	Dependent: Network density, network centralization, in-degree centralization. Explanatory Patterns of communication flow	Network density and centralization varied based on topics of communication and between night and day shifts. Medical advice was more often sought from central actors, while general socializing and problem solving were more distributed. High indegree-centrality indicates popularity of the charge nurse and attending	Brief periods of assessment. Surveys are an indirect measure of communication and may suffer from recall bias. Operational and demographic characteristics may not generalize to other settings

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
				physician as well as a few other team members	
Ngo et al. (2014)	Panel study non-critical situations	Constructing process models, conducting interviews and focus groups with trauma personnel. Estimating waiting time based on reported waiting time. Analysis of decision-making processes was done using the Hurwicz Alpha Criterion	Dependent: Variability in communication. Explanatory: estimated waiting times at each step of the admission process from the Emergency Department to other departments. Opinions about the admission process.	Large variability in communication occurs, especially when concerning consults and the bed center, resulting from a lack of situational awareness and external procedures	Basing waiting time estimations on interviews is not a reliable measure.
Alsamadani, Hallowell, and Javernick-Will (2012)	Panel study non-critical situations	Interviews and questionnaires were collected from nine work crews of five to 12 members. Analysis was done with SNA	Dependent: Accident rate Explanatory: Centrality, density, and betweenness	No relation was found between accident rate centrality and betweenness. Density of communication reduces accident rates. Using multiple types of safety communication reduces accident rates	Low generalizability due to the specificity of the sample. Risk exposure was not controlled for
Bellury, Hodges, Camp, and Aduddell (2016)	Panel study of non-critical situations	18 surveys were taken from registered nurses and focus group discussions with 33 nursing assistive personnel were conducted. Analysis was done according to the “Big Five” framework	Leadership, performance monitoring, back-up behaviors, adaptability, team orientation, SSM, closed-loop communication, and mutual trust.	A discrepancy in mental models, opinions on closed-loop communication and shortage of mutual respect may have a negative influence on performance	Different data collection methods were used for subgroups of the sample
E. S. Patterson, Cook, Woods, and Render (2004)	Case study of a non-critical situation	Analysis of a case of communication breakdown causing medication error to identify communication patterns from Human Factors literature. No framework for analysis was mentioned	Communication patterns described in human factors research	Several communication patterns may have contributed to the medication error: Lack of mentioning intent in communication; Limited communication during handoff; Unclear division of responsibilities and tasks; difficulty in accessing specialized expertise; failure to break fixation; reluctance to question people with greater authority; limiting properties of communication medium	Low generalizability. Not empirical, but based on a deeper understanding of the complex interconnected nature of communication processes

Study	Study Type	Study methods	Variables	Findings	Methodological limitations
MacKellar (2012)	Case study of a non-critical situation	A software engineering course group was studied. Communication events were collected in diaries and analyzed qualitatively and with SNA	Recipient, communication mode, reason for communication, communication outcome	Communication was highly centralized but less so in the lower performing group. The lower performing group reported more unsuccessful communication events, phone communication, and fewer face-to-face communication. The more successful groups had communication brokers	Results are preliminary and only based on the analysis of one iteration of a software engineering course. Insights may be limited due to the low reliability of collecting data through diaries
Salem (2008)	Case study of non-critical situations	Semi-structured interviews of three case studies of organizational changes. Analysis was done based on Complexity Theory	Dependent: Adaptation of organizational structures. Explanatory: frequency of communication, hub forming, trust, humor, quality of interpersonal communication, conflict avoidance, centralization	Adaptation of organizational structures were decelerated by seven communication patterns: insufficient communication, local hub forming, global distrust, lack of productive humor, pour interpersonal communication, conflict avoidance, and an inappropriate mix of centralization and decentralization	The integration of three studies improves generalizability, but it is still low. Only one study employed quantitative data along with qualitative data
Greenberg et al. (2007)	Case study of closed surgical claims. It is uncertain whether these were critical or non-critical situations	Cases were retrieved from four malpractice insurance companies. Two surgeon-investigators conducted a secondary review, disagreements were resolved by consensus review or a third investigator. No framework for analysis was mentioned	Dependent: Communication breakdown Explanatory: Status asymmetry; conflicting team goals; handoff among providers; transfer of patient; ambiguity of roles, responsibility, and leadership; counting protocols; period of high workload	most communication breakdowns happened between a single transmitter and receiver. Breakdowns occurred approximately equally as often during pre-, post- and intraoperative care. The attending surgeon is most frequently involved. Hand-offs and transfers are especially vulnerable	Malpractice claims as a proxy for safety may give a different image of communication breakdowns than overall medical communication breakdowns. Cases without error and/or injury were excluded, which may have caused an incomplete representation of failures in medical care

Synthesis of results

First, frameworks for studying team communication are discussed and compared. Then, REM is discussed in more depth. After that, communication patterns that are interesting to study team communication in critical and non-critical situations are examined. Reviewed publications studied communication patterns in various kinds of teams and groups. Communication patterns from all kinds of groups were considered. However, communication patterns in work teams such as surgical teams and military teams were deemed most interesting, because these are most probable to encounter critical situations.

Frameworks for studying team communication

Multiple frameworks have been applied to study team communication. Comparing these gives insight into advantages and disadvantages as well as popularity. In this study, a framework is defined as a systematic structure for handling and analyzing data. In total, 16 different frameworks were found. Some of these frameworks were used with specific extensions. Besides that, some studies worked without a specific framework or solely with frequencies in communication patterns. A commonly applied framework is Social Network Analysis (SNA). For example, Barth et al. (2015) used SNA to find that communication was centralized around surgeon one and perfusionist one. Furthermore, the team adopted flatter communication structures in critical situations. Au et al. (2009) used SNA to find that Air and Space Operations Centers follow hierarchical communication structures in critical situations. However, as Quintane et al. (2014) pointed out, SNA such as applied in the frameworks of Exponential Random Graph Models (Frank & Strauss, 1986) and Stochastic Actor-Oriented Models (Snijders, 2001) only gives an aggregated picture of communication, losing information on fine-grained, temporal patterns. Various authors have criticized such aggregated methods, stating that communication is a continuous process of events that occur over time and is better measured in a time sensitive manner (e.g., Butts, 2008; Leenders et al., 2016; Pilny et al., 2016). Barth et al. (2015) ingeniously adapted to this problem by applying SNA to various phases of surgeries. However, these remain snapshots insensitive to some communication patterns. Another framework for studying communication patterns is Recurrence Analysis (Gorman et al., 2012; Grimm et al., 2017). While this is a time-sensitive framework, it only measures the determinism (how organized communication patterns are) in communication. An advantage is that it can be used for real-time analysis of team communication to detect anomalies or breakdowns, if it proves to be computationally efficient enough (Grimm et al., 2017). A similar framework is the Flow Analysis of Utterance Events in Teams (FAUCET), which measures the regularities and structure in a team's communication flow but does not characterize specific patterns (Weil et al., 2008). Ngo et al. (2014) used the Hurwicz Alpha Criterion to investigate variability in completion times of communication processes. These results were then compared to the opinions of actors in the communication process to link communication process completion times with situational awareness and external influences. However, this framework also does not measure specific patterns. Some studies solely measured communication frequency. For example, Dunn et al. (2002) found that communication frequency was influenced by critical events as well as following temporal cycles. Zhang et al. (2016) linked the frequency of certain communication patterns to the workload capacity of air traffic control teams. Xiao et al. (2003) found that the proportion of communication from a team leader grew under higher task urgency. They combined their frequency analysis with a content analysis, finding that during critical situations fewer questions were asked and more instructions were given. While communication frequency adapts in critical situations, these frameworks cannot give insight into changes of communication patterns. Multiple other studies used frameworks to code and analyze the content of communication events, such as the Model of Team Collaboration (Hutchins et al., 2007), the Closed-Loop Communication Framework (Davis et al., 2017), the “Big Five” framework (Bellury et al., 2016), Fairclough’s Critical Discourse Analytic Framework (Liu et al., 2012), and the Categorization System for Complex Problem Solving (Bierhals et al., 2007). Stainback et al. (2011) developed a novel framework for analyzing content: The Communication Productivity Model, which measured the density of content related to the productivity of a team. Manser (2009) also developed a novel coding framework, which Weller et al. (2014) and Manser et al. (2013) used in combinations with ANOVAs to find relations between communication patterns, criticality, and performance. Lastly, Boies and Fiset (2018) developed a novel coding framework to study shared mental models. However, these content related models are context dependent, meaning they must be adapted for each context they are applied in. Furthermore, human coders are needed, which is time intensive and introduces a possibility of bias. On the other hand, the content of communication contains most information and is the reason communication exists. Foregoing the analysis of it means loss of information. Some frameworks focus on content qualitatively rather than quantitatively. For example, Jahn and Johansson (2018) applied the Structurational Model to study communication in crisis response team meetings during a wildfire. Using this model, they found that reflexive self-structuring is important for the adaptive capacity of teams. Schraagen (2011) used the NOTECHS system (Mishra, Catchpole, & McCulloch, 2009) to code transcripts for qualitative analysis in addition to a quantitative analysis of the same surgical team that was also studied in the current study. A few studies applied qualitative analysis without mentioning a predeveloped framework (Gorman, Cooke, & Winner, 2006; McKinney & Smith, 2005; Salem, 2008).

REM has advantages and disadvantages in comparison to other frameworks. Firstly, it can be used to study fine-grained temporal communication patterns, as opposed to SNA (Quintane et al., 2014). Besides that, it lends itself well for extensions, facilitating improvement. Furthermore, it is less computationally intensive than previous approaches and scales to networks of arbitrary size (Vu et al., 2017). Lastly, it is possible to study multiple patterns, as Pilny et al. (2016) stated: *"Perhaps the greatest utility of REM lies in the wide range of sufficient statistics that can be derived from event sequences."* A disadvantage of REM is that, because it does not consider communication content, it lacks some depth in comparison to models that take the content of communication in consideration, such as the Structurational Model of Jahn and Johansson (2018) and content analyses as applied by Siassakos et al. (2009). Furthermore, because of the necessity for timestamped, dyadic data it requires rigid data acquisition. As follows, studies that applied REM have not included relational events such as nonverbal communication or communication through non-timestamped or recorded channels. One disadvantage it has in comparison with SNA is that SNA provides comprehensive network views of social structures with insight into links between nodes, while REM only gives tables and graphs for information per pattern. Because of REM's context independence and range of sufficient statistics, it lends itself well for the statistical analysis of differences in communication between critical and non-critical situations.

Applications of REM

Fifteen of the reviewed studies implemented REM in various contexts with different extensions. The first use of the original model was applied to multiple teams in the critical situation of the 9/11 first response (Butts, 2008). David and Schraagen (2018) applied it to compare one team in a critical and a non-critical situation. Pilny et al. (2016) and Leenders et al. (2016) used REM to study the communication of military multi-team systems. Others used REM to study email networks (Quintane & Carnabuci, 2016), hospital patient transfers (Amati et al., 2019), internet forum discussions (Liang, 2014), online learning environments (Vu et al., 2017), and collaborative work on Wikipedia articles (Lerner & Lomi, 2018, 2019). Multiple extensions to REM have been proposed. Four studies applied REM with a two-node extension, making it possible to apply REM to different sets of actors (Brandenberger, 2018; Lerner & Lomi, 2018; Quintane & Carnabuci, 2016; Quintane et al., 2014), for example, humans and parliamentary bills (Brandenberger, 2018). Lerner and Lomi (2019) developed a software program for REM with a two-node extension. A stratification of REM was proposed by Vu et al. (2015), which allows for the analysis of more complex data structures with many types of nodes and events. Amati et al. (2019) and Vu et al. (2017) used a multivariate point process extension, which makes it possible to code events with one sender but multiple receivers and to reveal time-specific variations in communication patterns. Lastly, DuBois et al. (2013) developed a hierarchical extension, making it possible to aggregate relational events from multiple datasets and groups. Schecter et al. (2018) applied DuBois et al.'s (2013) extension to study 55 four-person teams in critical situations. An advantage of the original REM is that it was developed to study teams in critical situations and comes with a set of patterns that are fit for studying human team communication (Butts, 2008). A hierarchical or multivariate point process extension may add some flexibility to the framework in studying teams in critical and non-critical situations. However, when using these extensions, the mathematical formulas for the communication patterns must be developed anew. Rather than re-inventing the wheel with a few extra spokes, the original REM was used in the current study.

Communication patterns

Summarizing the reviewed literature, this section discusses previously studied communication patterns measurable with REM and how these patterns may differ between critical and non-critical situations. In context independent frameworks, a communication pattern is a short array of ordered relational events that may represent an overall interaction sequence (Gorman et al., 2012).

Participation Shifts

An often studied set of patterns are Participation shifts, or P-shifts. A simple example is the pattern of actor A sending to actor B and B responding to A (PSAB-BA). This pattern can be used to estimate the likelihood of B sending to A when A has sent to B. It is a Turn Receiving P-shift called ‘ Reciprocity’ (Gibson, 2003). Reciprocity (PSAB-BA) is important in various contexts, both in critical and non-critical situations (Barth et al., 2015; Butts, 2008; David & Schraagen, 2018) and may increase somewhat in critical situations (Butts, 2008). David and Schraagen (2018) indeed found that Reciprocity somewhat increased in critical situations, linking this to increased reliance on the immediately preceding communication pattern rather than conscious decisions. On the other hand, Pilny et al. (2016) found that Reciprocity had no significant effect on the communication of two co-operating military teams in a critical situation. However, Leenders et al. (2016) found Reciprocity to play an important role in military teams in critical situations. Higher Reciprocity was related to higher levels of coordination and effective information sharing in critical situations (Schecter et al., 2018) and closed-loop communication (Davis et al., 2017). Less closing of loops may have a negative influence on performance (Bellury et al., 2016). Reciprocity is expected to be positive and may increase somewhat in critical situations. Another pattern in the Turn Receiving group is “handing off” of communication (PSAB-BY); B receives the turn from A and talks to Y. David and Schraagen (2018) saw an increase of this pattern in a team going from a non-critical to a critical situation, relating this to more reliance on basic conversational norms rather than institutionalized communication procedures. Butts (2008) also saw positive effects for this pattern in critical situations.

“Handing off” is also expected to be positive and increase somewhat in critical situations. Such increase may be due to less closing of loops (Davis et al., 2017) and more switching in communication partners (Butts, 2008).

Two other groups of Participation Shifts are: Turn Usurping and Turn Continuing. The Turn Usurping group involves interruptions of conversations and consists of the P-shifts PSAB-XA, PSAB-XB, and PSAB-XY (Butts, 2008). Turn Continuing means a speaker continues their turn, targeting a new receiver and consists of the pattern PSAB-AY. David and Schraagen (2018) saw negative effects in non-critical situations in both Turn Usurping and Turn Continuing patterns and positive effects in critical situations, connecting this to an increase of dependence on simple conversational rules rather than institutionally determined communication patterns. Butts (2008) also observed positive effects for these patterns in a critical situation. However, Liang (2014) observed positive effects for these patterns in non-critical situations between people that . Since the current study focusses on teams that know each other, Turn Continuing and Turn Usurping patterns are expected to be negative in non-critical situations and positive in critical situations.

Recency

Recency reflects a more general impact on future communication than the direct, turn-taking patterns of P-shifts (Butts, 2008). When it is positive, actors exhibit a tendency to address those with whom they have had recent contact. This can be in sending to the same actor one has recently sent to before (Recency Sending) or sending to an actor one has recently received from before (Recency Receiving). There may be interruptions after which people respond, which is visible in lower Reciprocity and higher Recency Receiving (Butts, 2008). This adaptation means a team keeps displaying closed-loop communication (Davis et al., 2017). A greater presence of Recency Receiving in critical situations may suggest a greater dependency on short-term memory (David & Schraagen, 2018). In a non-critical situation, Liang (2014) observed a positive effect of Recency Receiving (having recently received from an actor) and a negative effect for Recency Sending (having recently sent to an actor). It is expected that the patterns of Recency in the current study will be in line with the findings of Liang (2014), showing that conversations may be interrupted but loops are closed (positive Recency Receiving), while actors will talk with multiple others rather than keeping the same targets (negative Recency Sending). Recency Receiving may increase in critical situations, because there may be more interruption in conversations higher dependence on short-term memory.

Triadic Effects

Triadic effects describe the communication between three actors and comes in two forms: Two Paths and Shared Partners (Butts, 2008). Similar to Recency, both can happen in two directions: Incoming and outgoing. Two Paths describes the likelihood of actor A sending to actor B if there is a third actor X who often acts as a "broker" between A and B (Brandenberger, 2018; Quintane & Carnabuci, 2016). Shared Partners describes the likelihood of actor A sending to actor B if both have had contact with X. Actors may be motivated to contact others based on shared interactions with third parties (Butts, 2008). Studies found that Triadic Effects hovered around 0 in critical situations (Butts, 2008; David & Schraagen, 2018) and non-critical situations (David & Schraagen, 2018). There may be a small positive effect of Incoming Shared Partners and a negative effect for incoming Two Paths in critical situations (Butts, 2008). However, both David & Schraagen's (2018) and Butts' research (2008) stated that their data did not provide sufficient evidence for a statement for or against the presence of Triadic Effects. Schecter et al. (2018) linked higher levels of Outgoing Two Paths to better coordination. Brandenberger (2018) found a negative effect for Outgoing Two Paths in a non-critical situation. Increases in Triadic Effects may indicate improvements in the efficiency of communication, as communication changes to direct between actor A and B instead of via a broker (Quintane & Carnabuci, 2016). MacKellar (2012) suggest that, in a non-critical situation, teams with communication brokers were more successful than teams without. In conclusion, Triadic Effects may differ between critical and non-critical situations, but this is uncertain. However, they are linked to communication efficiency and coordination, which are of importance in critical situations because they require rapid decision making (Hutchins, 2007).

Inertia

Inertia reflects the degree to which group members' past contacts tend to be their future contacts. Similar to Recency, this can be in sending to the same actor one has often sent to before (Inertia Sending) or sending to an actor one has often received from before (Inertia Receiving). A positive effect may indicate routinized communication, while a negative effect may indicate partner switching and a search process. Both can be beneficial to the performance of teams (Butts, 2008). Information seeking behavior may be a compensation for complexity, and thus be more present in critical situations (Manser et al., 2013). A positive Inertia Sending effect may also indicate that all actors communicated evenly with everybody else (Leenders et al., 2016). Schecter et al. (2018) found positive relationships between Inertia and coordination and information sharing and linked lower Inertia to more uncertainty and entropy. However, Inertia Sending may also indicate a dependence on cognitive factors such as short-term memory rather than following institutional regulations (David & Schraagen, 2018). Quintane and Carnabuci (2016) observed small positive effects for both Inertia Sending and Receiving in non-critical situations. Multiple studies have only studied Inertia Sending and made the inference that this reflects all previous contact between actors. Pilny et al. (2016) and Schecter et al. (2018) found a positive effect for Inertia Sending in a military team in a critical situation. David and Schraagen (2018) found that Inertia Sending had a stronger positive effect in critical situations than in non-critical situations, linking this to higher dependence on cognitive factor such as short-term memory. Based on the variety of results, it is uncertain what Inertia effects will be found. However, higher Inertia Sending may be expected in critical situations.

Preferential Attachment

Available actors may become attractive targets for other actors. For example, because they are more available to memory (David & Schraagen, 2018). In a self-strengthening process, actors with more past activity are more likely to be chosen as targets (Butts, 2008). As such, Preferential Attachment causes centrality of a team, making some actors get central roles in the communication structure (Amati et al., 2019; Schecter et al., 2018). A negative Preferential Attachment parameter may indicate a flatter communication distribution (Butts, 2008), which was linked to an adaptation to complexity (Barth et al., 2015) and better shared mental models (Bierhals et al., 2007). On the other hand, negative Preferential Attachment in critical situations while it is positive in non-critical situations, could be linked to reliance on short-term memory rather than institutional communication structures (David & Schraagen, 2018). More Preferential Attachment between central actors may also occur in critical situations (Xiao et al., 2003). Schecter et al. (2018) connected lower Preferential Attachment to better coordination and information sharing in critical situations. In crisis response teams in critical situations, communication was driven more by simple communication rules such as P-shifts and Recency than by Preferential Attachment (Butts, 2008). In non-critical situations, a positive effect of Preferential Attachment was found (Liang, 2014). In teams with existing institutional communication structures, Preferential Attachment may not play a large role. However, since it may indicate changes in the centrality of teams, which is related to adaptation, it is interesting to study. If it does play a role, it is expected to be positive and more so in critical situations.

High Initiator

As an actor sends more events overall, they can become even more likely to send messages (Schecter et al., 2018), which indicates whether particular individuals are exceptionally talkative in comparison to the rest of the team (Leenders et al., 2016). A positive effect of this communication pattern implies centralization, while a negative effect implies flatter communication structures (Schecter et al., 2018). So, it may be used to investigate centralization in teams. Calder et al. (2017) found that some actors initiated much more communication than others in emergency resuscitation teams. Xiao et al. (2003) saw a relative increase of communication of already central actors in critical situations as compared to non-critical situations. However, Barth et al. (2015) found that communication structures flattened out in more complex situations, which may be related to better information sharing. Bierhals et al. (2007) related flatter communication patterns to better shared mental models. Shared mental models, in turn, were related to higher performance (Bellury et al., 2016). It is expected that the High Initiator pattern is positive, but less so in critical situations because teams are expected to assume flatter communication structures to improve information sharing and retain shared mental models.

Fixed Effects

Fixed Effects reflect individual-level differences in the frequency of sending and receiving. Such individual heterogeneity may, for example, be related to context or institutional roles. Unequal Fixed Effects may indicate a hierarchical communication structure (Butts, 2008). Manser (2009) and E. S. Patterson et al. (2004) argue that clear team roles are important for coordination, which may show in Fixed Effects that are in line with institutional roles. Teams often have hierarchical communication structures (Benham-Hutchins & Effken, 2010; Siassakos et al., 2009) but may shift to a more hierarchical structure in critical situations (Au et al., 2009). Sevdalis et al. (2012) found that, in surgical teams in critical situations, surgeons were most likely to send and receive, while nurses were also likely to receive. Correspondingly, Calder et al. (2017) found that doctors and head nurses sent most relational events in emergency resuscitation teams. Barth et al. (2015) found that the first surgeon, first perfusionist, and first anesthetist were the most probable receivers and senders in both critical and non-critical situations, but that these frequencies of communication flattened out slightly in critical situations. Cumin et al. (2017) found that these actors, as well as the first nurse, were most likely to mention crucial information. During surgeries, surgeons were the most common senders and receivers (Greenberg et al., 2007) and responsible for most coordinating behavior (Schraagen, 2011). Weller et al. (2014) found that targets of communication are the same in critical and non-critical situations. In contrast, in teams less built on institutional structures, Fixed Effects may not be in line with institutional roles in critical situations but may actually show small hierarchical groups forming around actors without institutional leading roles (Butts, 2008). Such hub forming may reduce the effectiveness of teams (Salem, 2008). Siassakos et al. (2009) and Manser (2009) linked unclear roles to lower team situational awareness and clarity of responsibilities, causing errors. McKinney and Smith (2005) connected cockpit crew performance to crewmembers' awareness of their communication responsibilities and role. It is expected that the Fixed Effects found in the current study will have a hierarchical structure in line with institutional roles because of its positive influence on performance but may flatten out in critical situations to improve information sharing.

Centrality and Centralization

Centrality is an overall indication of how well connected an actor is within a communication network (Benham-Hutchins & Effken, 2010). The balance of this centrality between actors indicates centralization; if some actors are more central than others, a team has a high degree of centralization (Barth et al., 2015) and a hierarchical communication structure (Benham-Hutchins & Effken, 2010). Closeness centralization is based on the compactness of a network. Higher closeness centralization is linked to fast information distribution. Betweenness centralization describes the interrelatedness of actors. High betweenness centralization is linked to effective information sharing.

Multiple studies of team communication found that centrality and centralization were present in teams. Au et al. (2009) found high levels of centralization around leading officers in an air and space command center team in critical situations. Butts et al. (2007) on the other hand, found some centralization around actors without institutional leading roles in first responder teams in critical situations. Multiple studies found centrality of actors in line with institutional roles in a hospital setting in both critical and non-critical situations (e.g., Barth et al., 2015; Calder et al., 2017; P. D. Patterson et al., 2013). Team communication may become less central in critical situations (Barth et al., 2015), which can be linked to more information sharing (Manser, 2009). Decisions are probably made by these actors, rather than collaboratively (Hutchins et al., 2007). Besides that, centralization varied based on the topics discussed. Medical advice was more often sought from central actors, while general socializing and problem solving was more distributed (P. D. Patterson et al., 2013). Alsamadani et al. (2012) found no relationship between accident rates and the level of centrality in small work crews in non-critical situations, while MacKellar (2012) found that more centralized teams performed better in non-critical situations. Salem (2008) also suggested that levels of centralization influence team performance. Schecter et al. (2018) suggest that low centralization may be advantageous in critical situations because the open-ended nature of tasks requires effective information sharing.

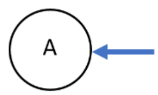
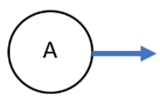
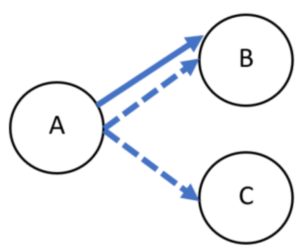
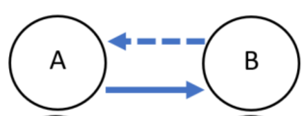
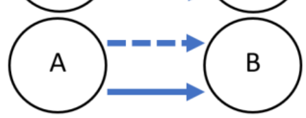
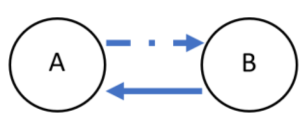
While centrality and centralization cannot be directly measured with REM, they can be measured indirectly with Fixed Effects, Preferential Attachment (Butts, 2008), and High Initiator (Schecter et al., 2018). Unequal Fixed Effects and large effects for Preferential Attachment and High Initiator may indicate centrality of the actors with the most positive Fixed Effects, and thus centralization of the team. It is expected that centrality and centralization are lower in critical situations, thus that Fixed Effects are more equal across actors and High Initiator and Preferential Attachment are lower. Lower centrality and centralization are expected because these are related to better information sharing (Barth et al., 2015), which is advantageous in critical situations (Schecter et al., 2018).

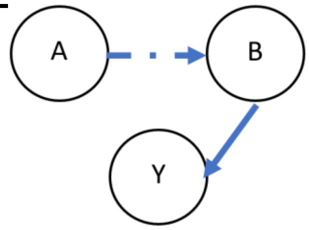
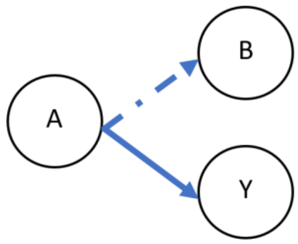
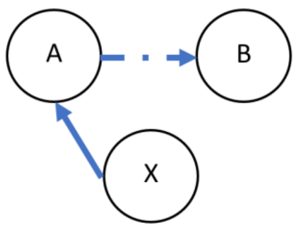
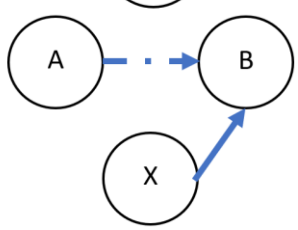
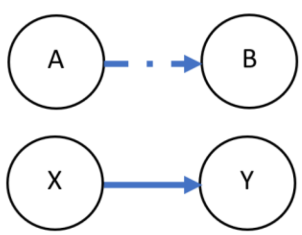
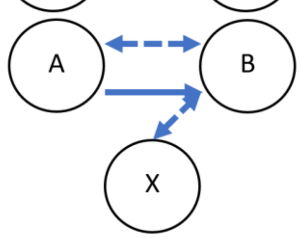
Combinations of patterns

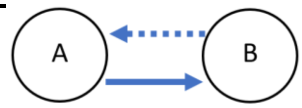
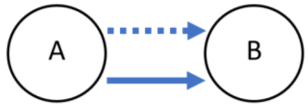
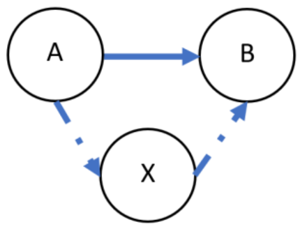
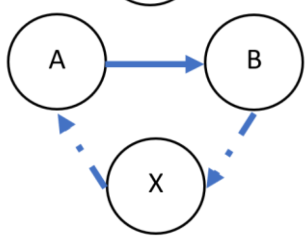
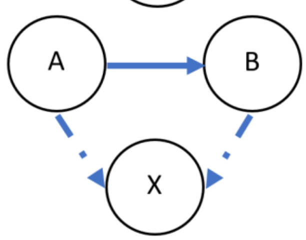
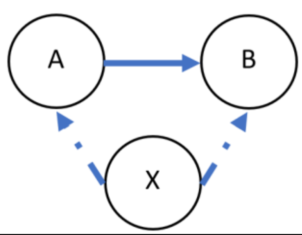
Some studies' findings concerned combinations of communication patterns. For example, Butts (2008) found that a combination of cognitive behavioral effects (Recency Sending and Inertia Sending and P-Shifts) were key drivers in the communication behavior of radio communications during the response to the WTC incident, while Fixed Effects and Preferential Attachment were less important. Similarly, David and Schraagen (2018) found larger effects in critical situations for patterns that are linked to cognitive effects such as dependence on short term memory (Recency Sending and Inertia Sending and P-Shifts). On the other hand, lower Fixed Effects, Preferential Attachment, and High Initiator patterns in critical situations would be in line with the decentralization findings of Barth et al. (2015). Furthermore, Lingard et al. (2002) suggest that communication in operation room teams is subtle and complex, with many socially motivated communication patterns. Communication varied in terms of duration, complexity, and participants, from question-and-response sequences to long discussions engaging various speakers and listeners. Besides that, relational events tend to cluster around certain phases of activity in the OR. Communication patterns found with REM may, therefore, be rather varied. Goguen and Linde (1983) found that planning and explanation were less common in critical situations, while more direct speech was used. Stachowski et al. (2009) also found that higher performing teams exhibited fewer, shorter and simpler interaction patterns in critical situations, as well as fewer established systematic patterns. This may change communication patterns measurable by REM such as fewer Triadic Effects or less Preferential Attachment and Inertia. Similarly, Weil et al. (2008) associated regular communication patterns with high performance. Large variability in communication may result from lack of situational awareness or external factors

(Ngo et al., 2014). Gorman et al. (2012) found that teams that were mixed halfway through an experiment had less rigid coordination patterns than teams that stayed intact, which may imply that teams that always work in the same constituency might only marginally adapt to critical situations. Table 3 sums up the patterns discussed in this section with a visualization, explanation, and the hypothesized difference between critical and non-critical situations.

Table 3. Communication patterns with visualization, explanation and hypothesized difference between critical and non-critical situations.

Pattern	Visualization	Explanation	Hypothesized difference
Fixed Effects (FE)			Expected to be in line with institutional roles
FE Receiving		The likelihood of A receiving the next event	Expected to be more even in critical situations, because teams may adapt by flattening communication structures
FE Sending		The likelihood of A sending the next event	Expected to be more even in critical situations, because teams may adapt by flattening communication structures
High Initiator (HI)		As A sends more overall, A becomes more likely to send the next event	Expected to be lower in critical situations, because teams may adapt by flattening communication structures
Inertia (IN)			Inertia probably plays an important role, but it is uncertain whether these patterns will be positive or negative
Inertia Receiving		As A receives more to B, A becomes more likely to send to B	No directional hypothesis can be supported
Inertia Sending		As A sends more to B, A becomes more likely to send to B	Expected to be higher in critical situations
P-Shifts			
Turn Receiving (TR) PSAB-BA		When A sends to B, B is likely to send to A	Expected to be positive in critical and non-critical situations. May increase somewhat in critical situations

Pattern	Visualization	Explanation	Hypothesized difference
PSAB-BY		When A sends to B, B is likely to send to Y	Expected to be positive in critical and non-critical situations. May increase somewhat in critical situations
Turn Continuing (TC)			Expected to be negative in non-critical situations and positive in critical situations
PSAB-AY		When A sends to B, A is likely to send to A	
Turn Usurping (TU)			Expected to be negative in non-critical situations and positive in critical situations
PSAB-XA		When A sends to B, X is likely to send to A	
PSAB-XB		When A sends to B, X is likely to send to B	
PSAB-XY		When A sends to B, X is likely to send to Y	
Preferential Attachment (PA)		When B has received and sent many of the previous events, B is likely to receive the next event	Expected to be positive in both critical and non-critical situations. May be higher in critical situations
Recency (R)			

Pattern	Visualization	Explanation	Hypothesized difference
Recency Receiving		When A has recently received from B, A is likely to send to B	Expected to be positive but more so in critical situations
Recency Sending		When A has recently sent to B, A is likely to send to B	Expected to be negative in both critical and non-critical situations
Triadic effects (T)			Expected to have little importance. If they differ between critical and non-critical situations, it is uncertain in which direction
Outgoing two-paths		When A sends to X and X sends to B, A is likely to send to B	There may be a small negative effect in non-critical situations
Incoming two-paths		When B sends to X and X sends to A, A is likely to send to B	There may be a small negative effect in critical situations
Outgoing shared partners		When A and B send to X, A is likely to send to B	No hypothesis
Incoming shared partners		When A and B receive from X, A is likely to send to B	There may be a small negative effect in critical situations

Four types of arrows are used in the visualization: (a) Continuous arrows are the next relational event; (b) Long dashes are the total of relational events prior to the current moment; (c) Short dashes are recently sent events; (d) Long-short-long dashes are the immediately prior event. Each pattern's explanation is given in a positive direction. However, the patterns may also happen in a negative direction.

Limitations of the literature review

There may have been an incomplete retrieval of relevant studies. It was difficult to adapt the search string to find a balance between focus and scope, due to some alternative meanings of the search terms of interest that lay outside of the topic of interest. Besides that, the words "framework", "model", and "critical" are used in a wide variety of contexts.

These problems were partly tackled by aiming for a large scope and then focusing by limiting the distance between synonyms of framework and communication, excluding certain terms which were connected to many unwanted search results, and excluding irrelevant subject areas. Nevertheless, seven interesting articles were not captured by the search string and retrieved from alternative sources [Barth et al., 2015; Gorman et al., 2006; Manser, 2009; Schraagen, 2011; Stachowski et al., 2009; Xiao et al., 2003]. There may be other interesting articles that were not captured by the search string. Another limitation is that few studies dealt with specific causal variables in communication patterns. Multiple studies found that patterns may change due to the global cause of increasing criticality. However, Gorman et al. (2012) found that mixing team members influenced the way teams adapted communication patterns in critical situations. The insight of our literature review into such causal variables is limited.

Natural History Study

To achieve our aims (see section "Research aims and outline") a natural history approach was adopted, built upon the literature review. Following a natural history approach, we used data from real-world events in order to ensure strong external validity. However, this goes at the cost of limited insight into causal relationships (Woods & Hollnagel, 2006), as was the case in many publications in the literature review.

Method

Transcripts of real-life situations were used, ensuring the authenticity of data. The communication patterns found to be of interest in the literature review and how these may differ in critical and non-critical situations were used to provide a focus for the analysis. In the following, the considerations in selecting data sources are discussed. Next, the categorization of data into critical and non-critical situations is clarified. Then the data preparation and analysis are explained.

Data sources

For optimal use of REM and generalizability, data sources must (ideally) meet four requirements: (1) The teams consist of at least three agents; (2) There are clear audio recorded interactions between agents in which it is clear who talks to whom; (3) There are recordings of critical as well as non-critical situations; (4) There are recordings of which the chronological order of communication sequences are known and have a duration of at least one hour. Furthermore, to be able to generalize to teams in other fields of work and other situations, data sources from multiple fields of work are sought.

Based on these preconditions, data sources were sought. The United States National Transportation Safety Board (NTSB) databases, with a focus on their marine, railroad, and aviation accidents ("Data & Stats," 2018). Of the marine vessel El Faro incident, extensive mission transcripts are available, however, most of the time the team did not consist of more than two members (Payne, 2016). The few railroad accident transcripts that were found did not cover teams of more than two members, nor encompassed a sufficiently long timescale. Aviation accidents have more interesting data available in the form of comprehensive CVR transcripts ("Cockpit Voice Recorder Database," 2018; "Data & Stats," 2018). However, as mentioned before, teams other than airplane cockpit teams are preferred for generalizability purposes. Moreover, most of these cover timeframes relatively short for satisfactory analysis (30 minutes), as well as not having sufficient team members during parts of the recordings.

Another source we considered was a rich source of real-life team communications, namely the transcripts of communication processes among team members in pediatric cardiac surgical procedures previously studied by Barth et al. (2015) and Schraagen (2011). These transcripts encompass 39 pediatric cardiac procedures conducted at the Wilhelmina Children's Hospital, which is part of the University Medical Centre Utrecht. These transcripts conform to the four preconditions but are subjectively more in the non-critical range than in the critical (most surgeries were not under high levels of both complexity and hazard, relative to the teams' experience),

For generalizability to more teams and situations, the transcripts of the Apollo 13 Flight Director's voice loop, available on http://apollo13realtime.org/ (Tseng, N.D.) were considered for analysis, in addition to the cardiac surgical procedures. These transcripts lend themselves well for insight into team communication, especially in critical situations. However, while more than six hours of transcripts portray a critical situation, of non-critical situations only slightly more than nine minutes before the incident are readily available online. Upon further inquiry, NASA itself could not provide Flight Director's voice loop data of non-critical situations either (J. Stoll, personal communication, November 28, 2018), nor of any of the other Apollo missions ("Apollo Lunar Surface Journal Raw Transcripts," N.D.), or similar missions ("Mercury Through Apollo - Mission Transcripts," 2018). Hence, precondition three is not completely fulfilled by this source. More extensive transcripts are available of the Air-Ground voice loop. However, while this data conforms to all four preconditions, these transcripts are not interesting for this study. Their communication is strongly dependent on fixed effects of organizational structures; CAPCOM dictates to the team members on the spacecraft and the spacecraft reports to CAPCOM. Therefore, Air-Ground voice loop data of Apollo missions is not expected to provide adequate insight into team communication changes in critical situations that are generalizable to other situations than Air-Ground communication during space missions.

Based on this pursuit of sources, we concluded that communication pattern differences are best studied by examining the surgical and Apollo 13 Mission Control center data sources. While each of these sources by themselves does not perfectly fit the four preconditions, the combination does provide adequate insight into communication patterns. The Apollo 13 Flight Director's voice loop transcript gives multiple hours of insight into critical situation communication and a few minutes insight into non-critical situation communication. The surgery transcripts give hours of insight into communication patterns in both non-critical and critical situations but depict only one field of work. So, communication patterns in both the Mission Control center team and surgical team were be studied. In the framework of adaptability (Woods & Hollnagel, 2006), this study seeks to discern general patterns, recurring in fields of work. Therefore, communication patterns are expected to be similar to those found by David and Schraagen (2018) and ought to be researchable in multiple sources at once. As such, it is deemed acceptable if these sources are studied together.

The surgical team did not have the same composition of team members in all surgeries. Therefore, the surgical datasets were split into two groups. One group of surgeries in which three surgeons were present (making nine team members), and one group of surgeries in which the third surgeon was absent (making eight team members). For the rest, the team was identical. For greater reliability, it was decided not to include the three surgeries in which the team had different compositions of members. As such, 36 of the available 39 transcripts of the surgical procedure recordings were used for analysis, split into two groups of datasets; 20 surgeries in which the team had nine team members and 16 surgeries in which the team had eight team members.

Of the Flight Director's voice loop of the Apollo 13 Mission Control center, the full available transcript was used (Tseng, N.D.). This transcript covers slightly more than six hours of communication around the incident, which is sufficient in the frame of the transaction level (Schraagen, 2017) and applicable when using REM Butts (2008). The data starts at about nine minutes before the command center gets notified of the incident through the famous line: *“Houston, we’ve had a problem here.”* (Not “Houston, we have a problem,” as in the film). Of the full elapsed time of the mission, the transcript spans from 55:46:16 to 62:02:04 (hh:mm:ss), of which the command center gets notified about the problem at 55:55:35. The transcript stops with the reason given: *“After six hours of continual crisis, Apollo 13 is now safely back on a trajectory towards Earth, with a stable configuration and no immediate dangers.”* (Tseng, N.D.).

Categorization of data into critical and non-critical situations

The data sources were split into two categories: ‘non-critical’ and ‘critical.’ The Mission Control center data is split at the moment the incident is noticed; everything prior to the incident is considered as a non-critical situation, everything occurring after the incident is considered as a critical situation. With regard to the surgical data, each operation was regarded as an indivisible unit of analysis. Operations were categorized based on post-miniSTAR results, as was suggested by Schraagen (2011). The post-miniSTAR is a five yes/no question survey that was filled out immediately after the surgical procedure by team members of the surgical team under study. According to Schraagen (2011), the post-miniSTAR serves as a total score for surgical teams as a whole for each operation, with scores reflecting the occurrence of major non-routine events and disturbances. Post-miniSTAR scores had a significant correlation with other measures that indicate the criticality of surgeries, such as the Aristotle score, which is an a priori indicator of the complexity of the surgical procedure (Lacour-Gayet et al., 2004), number of non-routine events observed, and observed 30-day post-surgical outcome (Schraagen, 2011). Surgical procedures that received an above average post-miniSTAR score were categorized as critical; below average scores were deemed non-critical. Of the 36 surgeries, post-miniSTAR scores were available of 32 operations. Of the remaining four observations, the non-routine event counts were used to determine the criticality of the situations. Based on this method, transcripts of 18 critical and 20 non-critical situations are studied in three groups of datasets, one group of the Mission Control Team and two groups of datasets of the surgical team (one group of surgeries in which it had nine members and one group of surgeries in which it had eight member). Table 4 summarizes the groups.

Table 4. The groups of datasets studied and how many critical and non-critical situations they contain

Dataset group	Critical situations	Non-critical situations
Apollo 13 Mission Control	1	1
Surgical team with nine members	11	9
Surgical team with eight members	6	10

Data preparation

Transcripts of audio files were received. The original transcripts included timestamps, the identity of senders and verbal communication events, and in the case of the surgery transcripts also the identity of the receiver of each event. Of the Apollo 13 Mission Control center transcripts, the receiver was coded based on the content and/or context of each message. Fortunately, this was rather simple because of their custom of starting messages by addressing the target receiver, which they only neglect when the target is obvious from context. For example, when stating that a message has been received by saying “Roger”. Because only verbal communication was transcribed, analysis considered only verbal relational events. Reliability of the coding of the receivers in the Mission Control center datasets was checked by recoding a randomly selected 10% of the full dataset. A Cohen’s Kappa of 0.971 indicated highly reliable coding. Reliability measures for the original coding of the Mission Control center transcripts were relistening the entire audio and correcting transcripts three times and the possibility for listeners of the transcripts to submit corrections (C. H. Tseng, personal communication, March 13, 2019). Original coding of the transcripts of surgery transcripts is also deemed reliable (Barth et al., 2015; Schraagen, 2011). The identities of the actors were recoded into numbers in alphabetical order. Table 5 shows the actor identities and codes.

Table 5. Coding of the actors

Surgical operations		**Mission Control**	
Actor	**ID**	**Actor**	**ID**
Anesthetist 1	1	AFD	1
Anesthetist 2	2	CAPCOM	2
Nurse 1	3	CONTROL	3
Nurse 2	4	EECOM	4
Perfusionist 1	5	FAO	5
Perfusionist 2	6	FDO	6
Surgeon 1	7	FLIGHT	7
Surgeon 2	8	GNC	8
Surgeon 3	9	GUIDO	9
		INCO	10
		NETWORK	11
		PROCEDURES	12
		RECOVERY	13
		RETRO	14
		SURGEON	15
		TELMU	16

Data was prepared in excel. Transcripts were converted into a format appropriate for relational event models. For each dataset, three columns were generated: ‘Event time’, ‘Sender’, and ‘Receiver’. Table 6 presents an example of one of the transcripts. The ‘Event time’ column depicted the exact time of each relational event as indicated in the transcripts converted to the general format. The ‘Sender’ and ‘Receiver’ columns depicted the actors who sent and received each particular relational event. The coding scheme of the actors is depicted in Table 6. The original transcripts depicted time in the hh:mm:ss format. However, REM requires time to be in the 'general' format. Before converting time to the general format, event times were adapted to be unique to be analyzable with the relational event framework. This was not the case with original timestamps for two reasons: (a) Consecutive events could have the same timestamp during rapid communication; (b) relational events were considered in dyads consisting of one sender and one receiver, meaning that events directed at more than one target could not be analyzed as such. In order to cope with these limitations, the time format was changed from hh:mm:ss to hh:mm:ss.0. For all consecutive dyadic events with duplicate timestamp, events were separated by an offset of 1 ms in chronological order. Non-dyadic events (directed at more than one receiver) were considered separately by giving the same offset of 1 millisecond (ms), in order of targeted recipients. An Offset of 1 ms was chosen to minimize the effect of the adaptation. In the Mission Control center dataset, FLIGHT refers to "all flight controllers" a few times, as well as addressing "everyone" or making general statements. These instances are coded as dyadic events going to each of the flight controllers, in alphabetical order: CONTROL, EECOM, FDO, GNC, GUIDO, INCO, and TELMU (Hutchinson, 2012; C. Tseng, 2017). Other non-dyadic events were coded in the order that actors were addressed. Because in the relational event model event times are understood as relative to the onset of observation (Butts, 2015), time was standardized by fixing the first relational event of each dataset to zero. As such, the null action serves as a placeholder for the onset of events (Butts, 2008).

Table 6. Example of coded transcript

Event time	Sender	Receiver
0	6	5
1.157E-06	5	6
0.0027778	8	3
0.0027789	3	8
0.0131944	5	1

Analysis

All coded files were opened in R (R Core Team, 2018), to be manipulated with the relevant package for Relational Event Modelling (Butts, 2008). To assess communication patterns the following codes from the R package relevent (Butts, 2008) were used: Fixed Effects (FE): FESnd, FERec; Preferential Attachment (PA): NTDegRec; High Initiator (HI): "NTDegSnd"; Triadic Effects (T): OTPSnd, ITPSnd, OSPSnd, ISPSnd; Recency (R): RSndSnd, RRecSnd; Inertia (IN): FrPSndSnd, FrRecSnd; Turn Receiving (TR): PSAB-BA, PSAB-BY; Turn Usurping (TU): PSAB-XA, PSAB-XB, PSAB-XY; Turn Continuing (TC): PSAB-AY. Models of each group of communication patterns were generated (hereafter referred to as marginal models), using the rem.dyad function under interval time maximum likelihood.

Model Selection

Following REM, there is a need to determine which model has the best 'goodness-of-fit' for which the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) are recommended (Pilny et al., 2016). AIC and BIC statistics represent goodness-of-fit by rewarding predictive value and penalizing complexity (Dziak, Coffman, Lanza, Li, & Jermiin, 2019). AIC model selection was chosen over BIC, because AIC penalizes complexity less heavily (Dziak et al., 2019), which in this case is preferable since some marginal models were more complex than others. To find the best fitting model, forward selection was applied (Pilny et al., 2016). This starts by comparing the marginal models. Next, combination models were created by entering one marginal model at a time in order of goodness-of-fit until adding marginal models stopped increasing the goodness-of-fit. Models were compared to each other as well as to a null model, which treats all events as equiprobable and thus serves as a reference for the other models (Butts, 2008). Comparison of the combination models was done based on Akaike weights (W_i) which are a commonly seen method of comparing AIC scores. Akaike weights are a value between 0 and 1, with the sum of the weights of the candidate models being 1. It can be considered as analogous to the probability that a given model is the best approximating model (Symonds and Moussalli, 2011). This process was carried out for the surgical team and the Mission Control center team separately. The selection of the model for the surgical team with eight and nine actors was done in tandem, because it may be interesting to compare communication patterns of the team with a different number of members.

Parameter Estimates

The combination models that had the best AIC scores were selected for further analysis by comparing parameter estimates and 95% confidence intervals on a geom_pointrange() graph (Wickham, 2016). Parameter estimates are indicators of the odds that an interaction will happen given the conditions specified in a communication pattern, for example, a parameter estimate of 2 on PSAB-BA means that if A sends to B, B is 7.39 times more likely to send a message to A, because 7.39 is the exponential function of the estimate (e2 = 7.39) (Pilny et al., 2016).

Categorizing the surgeries into critical and non-critical by splitting the datasets down the middle based on post-miniSTAR scores meant many surgeries were only marginally critical or non-critical. Therefore, the parameter estimates of the three most and least critical surgeries were also compared of both the surgical team with nine and with eight actors. Comparing the most and least critical situations may bring to light more subtle differences in communication patterns.

Pooling of the datasets

Because the data of the surgical team came from multiple datasets, a two-step approach was followed to pool the data. It is assumed that for each surgery there exist true model parameters under the models. Fitting the models yielded parameter estimates for each individual surgery. These estimates are decomposed theoretically as the true parameter values plus a measurement error. The means and variances were pooled across the surgeries to estimate the means and variances of underlying true parameters (Cochran, 1954; Snijders & Baerveldt, 2003). This type of post ex pooling is a limited, but more straightforward, case of hierarchical modeling (Snijders & Baerveldt, 2003) and should give an analogous result as hierarchical modeling given the same modeling assumptions (Schecter et al., 2018). Pooling datasets requires the separate datasets to are sufficiently informative for estimating the parameters in the models (Snijders & Baerveldt, 2003). Since the surgeries last at one hour, this assumption is met. The critical situation dataset of the Mission Control center was split and also pooled because the dataset was too large to compute at once. AIC scores can sensibly be summed across models (Butts, personal communication, March 14, 2019). To pool the standard errors, the Satterthwaite approximation was applied, which is robust against possible heterogeneity of variance (Satterthwaite, 1946).

Results

Premodeling descriptive statistics

As Figure 2 depicts, the critical procedures lasted on average an hour longer (mean = 04:06:19, min = 02:54:00, max = 05:44:00) than the non-critical procedures (mean = 03:04:52, min = 01:40:00, max = 05:51:00). Table 7 depicts the total time of analyzed data for both data sources.

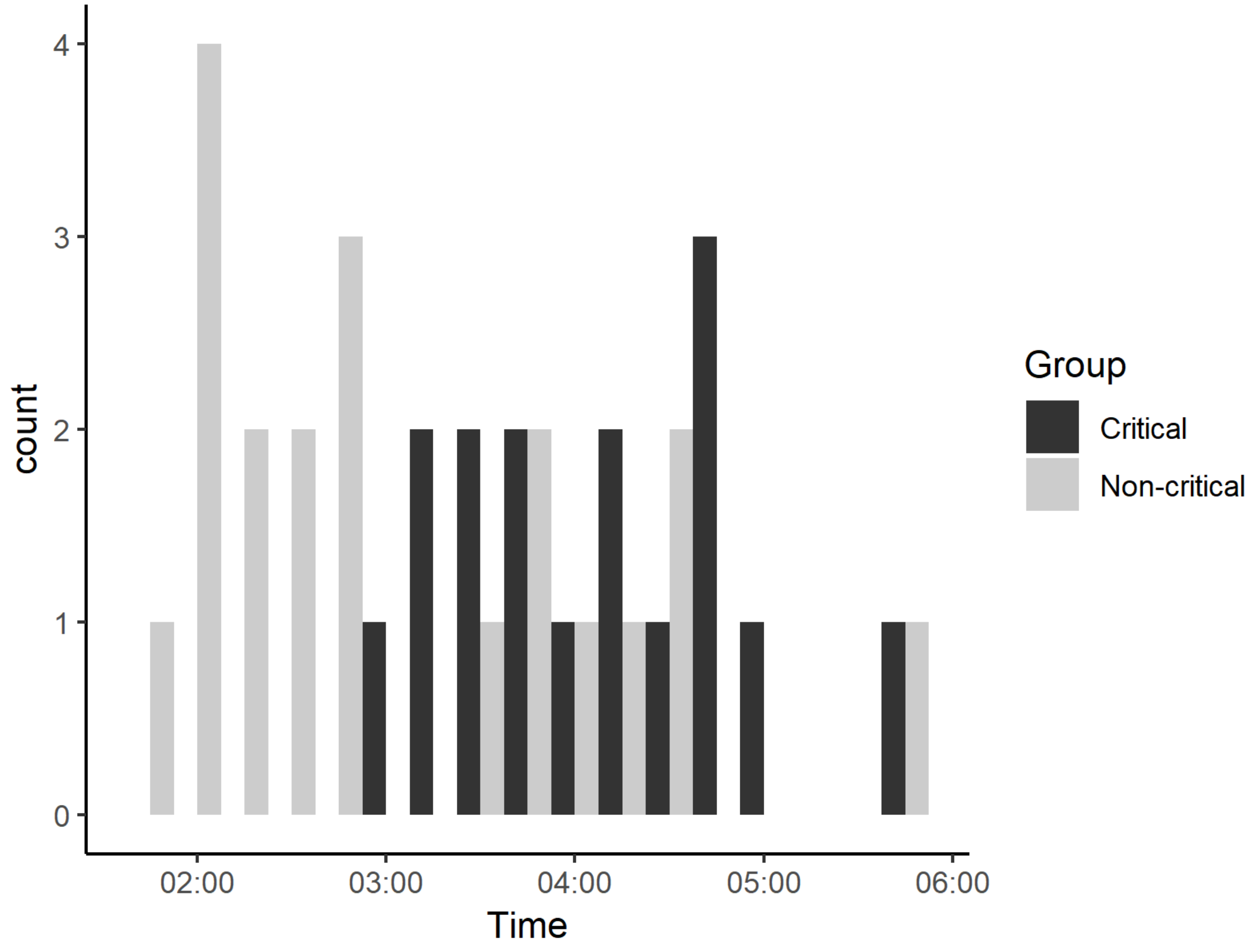


Figure 2. Distribution of the duration of the surgeries (Binwidth = 15 minutes).

Table 7. Time of analyzed data in hh:mm:ss.

Dataset group	Critical situations	Non-critical situations	Total
Apollo 13 Mission Control	6:06:29	0:09:19	6:15:48
Surgical team with nine members	40:09:00	20:43:00	60:52:00
Surgical team with eight members	25:32:00	30:32:00	56:04:00
Total	71:47:29	51:24:19	123:11:48

Model Selection

To determine which model has the highest goodness-of-fit, AIC scores were evaluated for the critical and non-critical situations of the surgical and Mission Control data. Table 8 shows the number of actors (N), number or relational events (M) of the analyzed data, the AIC scores of the models, and the Akaike weights (W_i) of the combined models. Abbreviations of the models are explained in the legend. A lower AIC score indicates a better fit (Anderson & Burnham, 2004) and an Akaike weight closer to 1 indicates a higher probability that a given model is the best approximating model. For example, a W_i of 0.42 means there is a 42% chance that a model is the best approximating model describing the data, as compared to the other models under consideration (Symonds & Moussalli, 2011).

Concerning the surgical data, AIC scores for the critical and non-critical situations were very similar, indicating that patterns have similar explanatory power in both situations. Turn Receiving, Recency, and Fixed Effects had the highest goodness-of-fit. High Initiator and Inertia patterns came after and Preferential Attachment, Triadic Effects, Turn Usurping, and Turn Continuing had the lowest goodness-of-fit, lower than the null model. Combination models with more variables had increasingly higher goodness-of-fit (lower AIC, higher W_i). This increase levelled of around the model TR_R_FE_HI_IN. In the non-critical situation with nine actors it had the strongest Akaike weight ($W_i = 0.99$). The model with one more effect, TR_R_FE_HI_IN_PA had the highest Akaike weight in the critical situation with nine actors ($W_i = 0.98$), the critical situation with eight actors ($W_i = 1$), and the non-critical situation with eight actors $W_i = 0.99$). Both these models seemed to be good approximating models when looking at all situations (Symonds & Moussalli, 2011). To further inform the choice between models, the strength and risk of error of AIC can be considered (Dziak et al., 2018). Applying AIC to large datasets runs the risk of overfitting large models (Dziak et al., 2018), therefore, the smaller model, TR_R_FE_HI_IN, was selected for further analysis of the communication patterns of the surgical team.

The AIC scores of the Mission Control data showed a slightly different hierarchy of goodness-of-fit of the marginal models. Fixed Effects surpassed Turn Receiving and Recency as the best fitting marginal model, meaning the communication of the Mission Control center team was better explained by Fixed Effects than the communication of the surgical team. At the same time, the goodness-of-fit of Triadic Effects was lowest, surpassing Turn Usurping, and Turn Continuing, meaning that Triadic Effects provided the least explanation. While showing similar scores in the critical and non-critical situation, there was more variation than in the surgical data. In the critical situation, Triadic Effects was the only model scoring worse than null, while in the non-critical situation, Turn Continuing, Turn Usurping, and Preferential Attachment also scored worse. When inspecting the combined models, goodness-of-fit again increased with size and FE_TR_R_HI had the highest probability of being the best fitting model in the critical situation ($W_i = 1$). In the non-critical situation, it had the second highest probability of being the best fitting model ($W_i = 0.29$) after FE_TR_R ($W_i = 0.53$). Because the Akaike Weight score of FE_TR_R_HI was so high in the critical situation, this model was chosen for further analysis (Symonds & Moussalli, 2011).

Table 8. Data size, AIC scores, and Akaike Weights (W_i) for the Relational Event Models.

	Surgical team with 9 actors				Surgical team with 8 actors				Apollo 13 Mission Control team			
	Critical	**W_i**	**Non-critical**	**W_i**	**Critical**	**W_i**	**Non-Critical**	**W_i**	**Critical**	**W_i**	**Non-critical**	**W_i**
N	9		9		8		8		16		16	
M	977		481		592		535		4277		98	
null	-2052.69		-714.77		-1315.14		-1280		-24962.29		-619.04	
FE	-3162.01		-1147.08		-1626.01		-1735.85		-47438.13		-1129.94	
PA	-1897.58		-696.5		-1161.49		-1245.23		-25078.71		-591.84	
HI	-2265.23		-842.76		-1290.09		-1287.76		-29345.46		-665.66	
T	-1340.9		-475.13		-737.48		-831.82		-2216.59		10.49	
R	-3328.59		-1346.92		-2408.04		-1974.39		-43433.63		-1082.25	
IN	-2071.47		-850.6		-1170.59		-1315.11		-26246.8		-676.46	
TR	-3384.39		-1439.83		-2011.82		-2147.67		-44234.75		-1085.28	
TU	-53.41		-73.57		-187.02		-131.81		-3714.73		-73.23	
TC	-9.97		-63.41		-69.35		-88.33		-3345.93		-100.12	
TR_R	-237.5	0	-1774.34	6.1065E-56	-2454.39	9.70547E-61	-2569.56	5.7188E-114				
TR_R_FE	-4916.97	3.5818E-40	-1967.28	4.8104E-14	-2661.72	1.01895E-15	-2895.46	3.35422E-43				
TR_R_FE_HI	-4966.65	2.1978E-29	-2004.27	5.1815E-06	-2691.24	2.62024E-09	-2950.53	3.04713E-31				
TR_R_FE_IN	-5042.1	5.3179E-13	-1998.69	3.1825E-07	-2664.98	5.20061E-15	-3034.92	6.4409E-13				
TR_R_FE_HI_IN	**-5090.52**	**0.01737833**	**-2028.59**	**0.98964082**	**-2703.42**	**1.15663E-06**	**-3082.02**	**0.01087881**				
TR_R_FE_HI_IN_PA	-5098.59	0.98262167	-2019.47	0.01035368	-2730.76	0.999998841	-3091.04	0.98912119				
FE_TR									-57251.23	1.8929E-213	-1368.37	0.001287371
FE_TR_R									-58137.38	5.03439E-21	-1380.4	0.526014477
FE_TR_R_HI									**-58230.86**	**1**	**-1379.22**	**0.291687024**
FE_TR_R_IN									-58150.71	3.9509E-18	-1378.26	0.181011128

Top down, the rows represent the number of actors (N); the number of relational events (M); the null model (null); the marginal models: Fixed Effects (FE), Preferential Attachment (PA), High Initiator (HI), Triadic Effects (T), Recency (R), Inertia (IN), Turn Receiving (TR), Turn Usurping (TU), and Turn Continuing (TC); and the combination models in order of goodness-of-fit (e.g., TR_R consists of Turn Receiving and Recency). The models selected for analysis are indicated in bold.

Parameter Estimates

Each of the communication patterns studied can have a positive or negative parameter, indicating whether these patterns were encouraged or discouraged. Therefore, parameter estimates and their 95% confidence intervals were compared. Figure 3, 4, and 5 show, respectively, the parameter estimates of the surgical operations with nine actors and with eight actors and of the Apollo 13 Mission Control center. The Appendix shows the exact parameter estimates underlying the graphs. Actor identities of the surgical team are coded, S stands for surgeon, P for perfusionist, N for Nurse, and A for anesthetist (e.g., S1 is surgeon one). For the Fixed Effects, anesthetist 1 is the reference actor fixed to 0 because actors were coded in alphabetical order, meaning that the FE of all actors are distributed around 0 as relative to Anesthetist 1. The same goes for AFD of the Mission Control team. The actors of the Mission Control team are named by their acronyms as defined by NASA (McDivitt, 1970). In alphabetical order, these are Assistant Flight Director (AFD), Capsule Communicator (CAPCOM), Guidance, Control, and Propulsion Officer for the Landing Module (CONTROL), Electrical, Environmental, Sequential, Systems Engineer for the Command and Service Module (EECOM), Flight Activities Officer (FAO), Flight Dynamics Officer (FDO), Flight Director (FLIGHT), Guidance, Navigation and Control Systems Engineer for the Command and Service Module (GNC), Guidance Officer (GUIDO), Instrumentation and Communication Officer (INCO), Network Controller (NETWORK), Operations and Procedures Officer (PROCEDURES), Recovery Officer (RECOVERY), Retrofire Officer (RETRO), Aeromedical Officer (SURGEON), and Electrical, Environmental, Extra Vehicular Systems Engineer for the Landing Module (TELMU).

The surgical team

First, the differences in communication patterns of the surgical team in critical and non-critical situations were considered. The surgical team with nine actors showed no significant difference in communication patterns between critical and non-critical situations; the 95% confidence intervals of the parameter estimates of the critical and non-critical situations overlap (see Figure 3). However, when the team was with eight actors there were some differences between critical and non-critical situations (see Figure 4). Firstly, Inertia-send (Inertia Sending) is less negative in critical situations, which indicates actors were less unlikely to send to teammates they often sent to in the past. Secondly, a difference appeared in the Inertia-rec (Inertia Receiving) pattern. The team was likely to send to actors they frequently received from, but in the critical situations they were less likely to do so than in non-critical situations.

The last difference is in anesthetist two's Fixed Effect for receiving (FErec-A2). They were unlikely to receive events in non-critical situations, but this effect became neutral in critical situations.

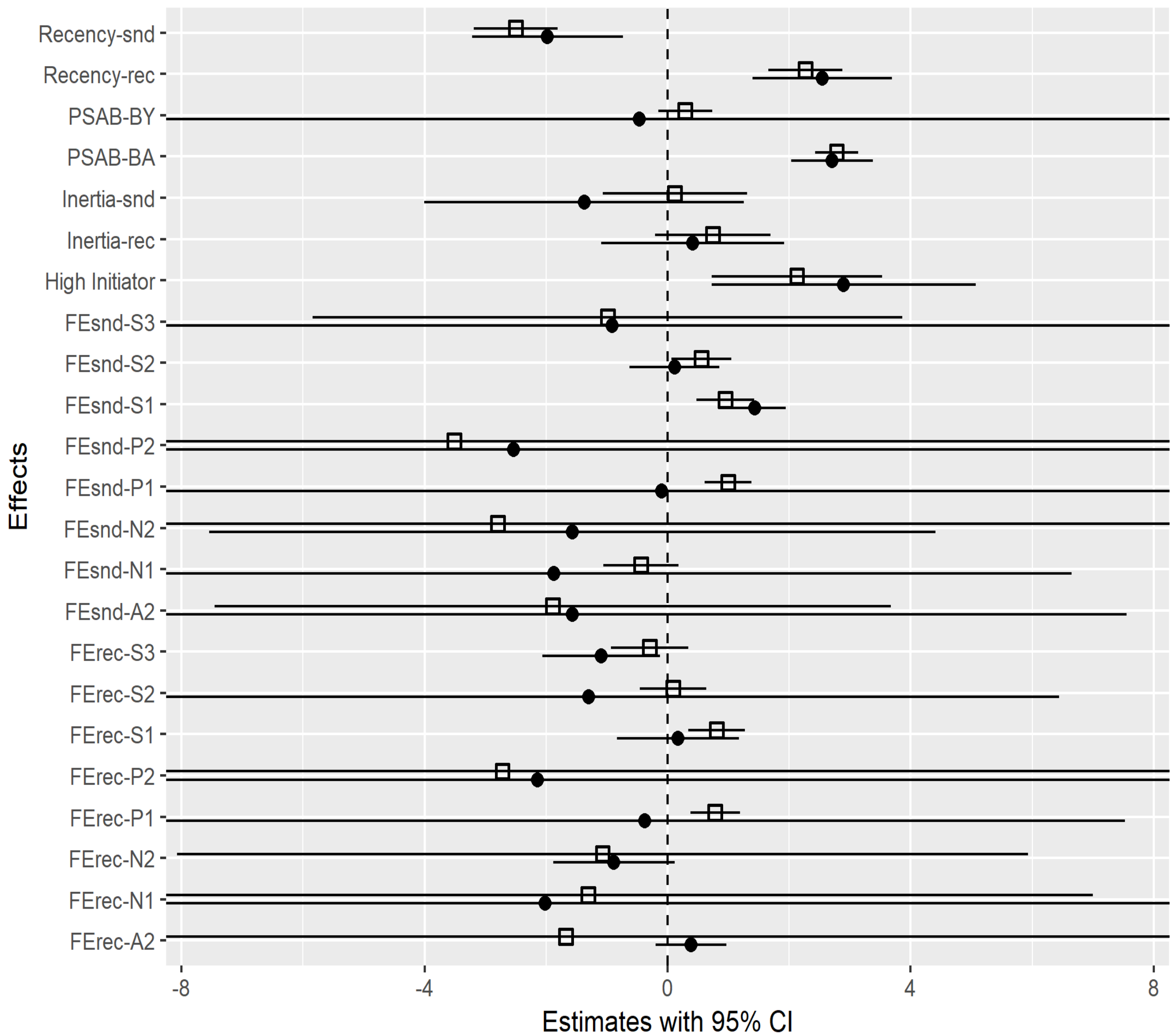


Figure 3. Parameter estimates and 95% confidence intervals of communication patterns of the surgical operations when the team was with nine actors. Squares indicate critical situations, circles indicate non-critical situations, horizontal lines are the confidence intervals. Positive parameter estimates indicate that a relational event will probably happen given the conditions specified in the communication pattern. Negative estimates indicate that a relational event is unlikely to happen.

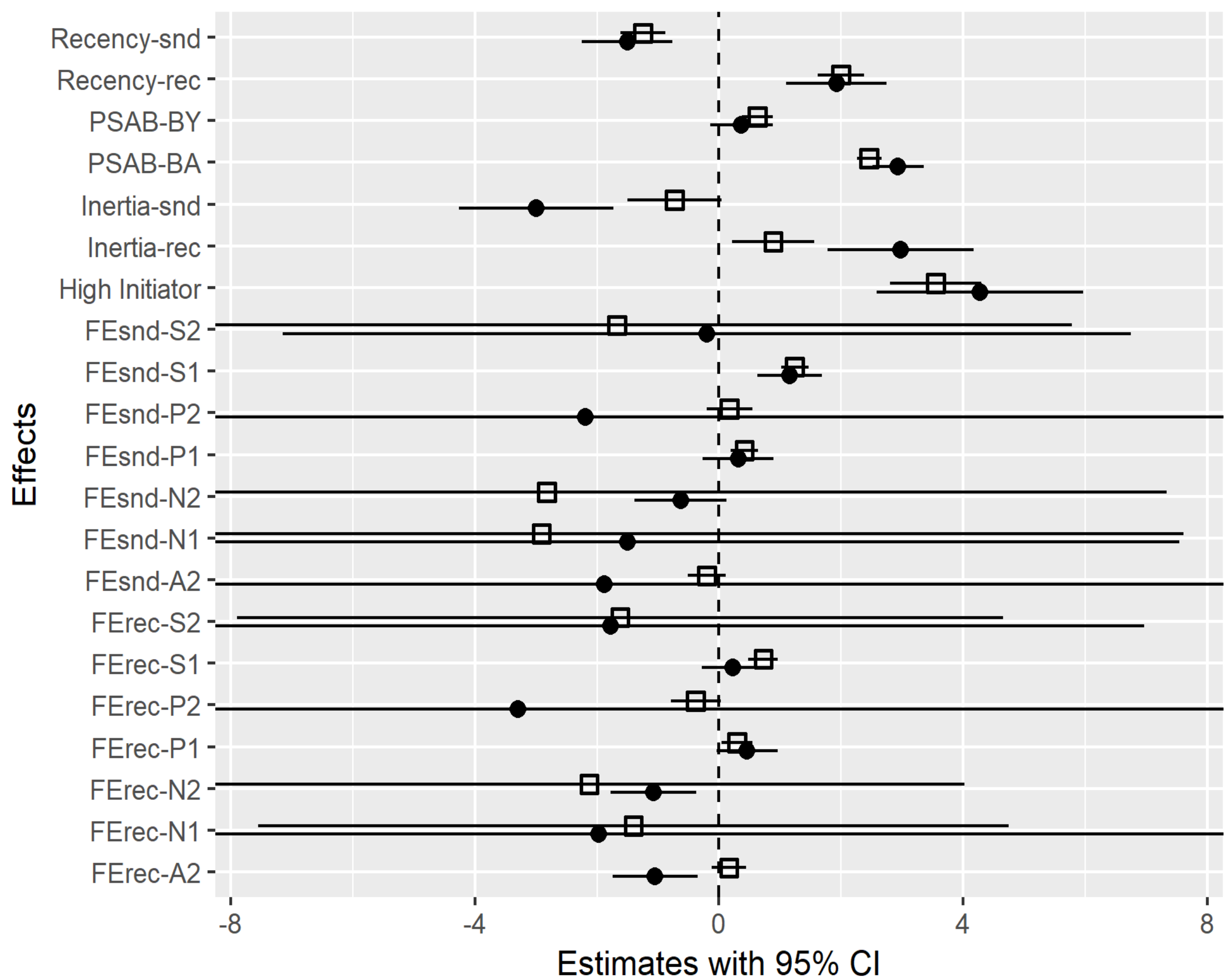


Figure 4. Parameter estimates and 95% confidence intervals of communication patterns of the surgical operations when the team was with eight actors. Squares indicate critical situations, circles indicate non-critical situations, horizontal lines are the confidence intervals. Positive parameter estimates indicate that a relational event will probably happen given the conditions specified in the communication pattern. Negative estimates indicate that a relational event is unlikely to happen.

The Apollo 13 Mission Control team

In the Mission Control team, a few patterns changed significantly, moving from non-critical to critical (see Figure 5). Actors were unlikely to send to actors they recently sent to (Recency-send) in the non-critical situation, however, this effect diminished in the critical situation. The Turn Receiving pattern PSAB-BY indicating “handing off” of communication was negative in non-critical situations and positive in critical situations. Reciprocity (PSAB-BA) had an overall important effect but was slightly less present in critical situations. Some Fixed Effects of the Mission Control team changed as well. GNC was less likely to send in the critical situation than in the non-critical situation and FLIGHT was somewhat less likely to receive events in the critical situation, although he kept his strong receiving role.

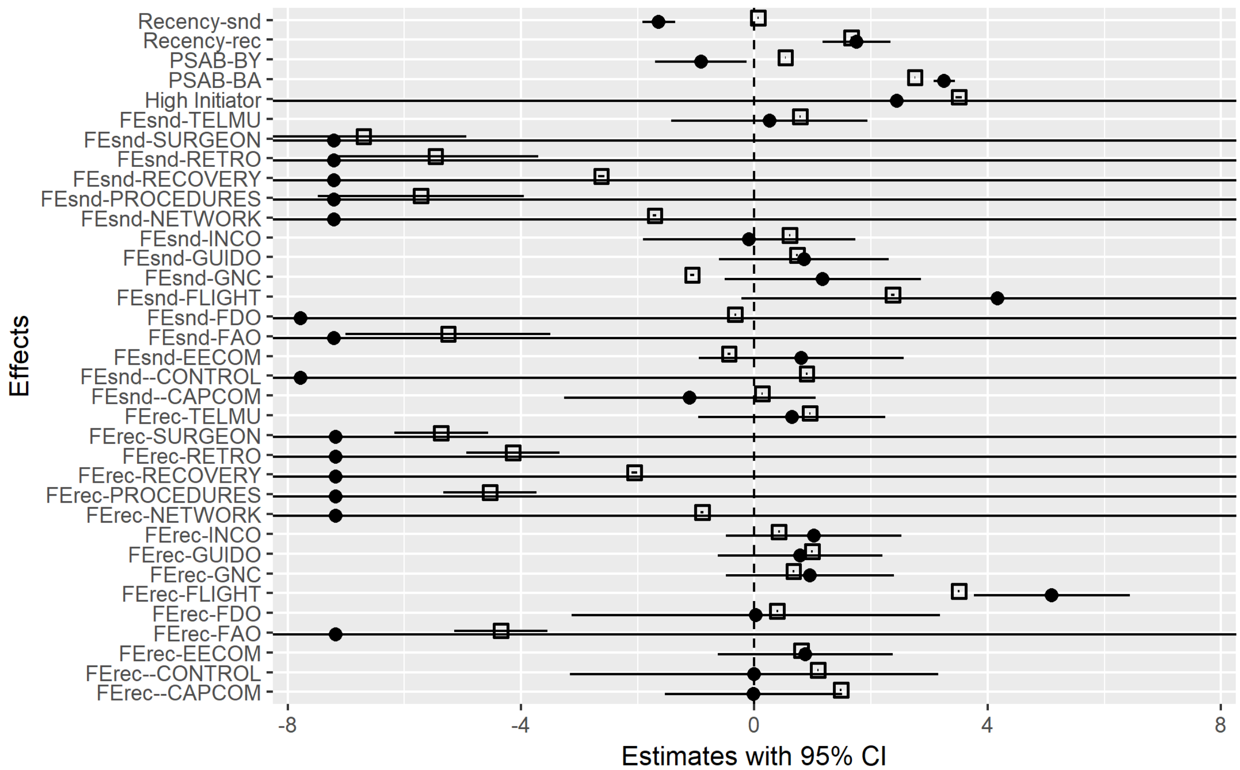


Figure 5. Parameter estimates and 95% confidence intervals of communication patterns the Apollo 13 Mission Control center team. Squares indicate critical situations, circles indicate non-critical situations, horizontal lines are the confidence intervals. Positive parameter estimates indicate that a relational event will probably happen given the conditions specified in the communication pattern. Negative estimates indicate that a relational event is unlikely to happen.

The general presence of communication patterns

Besides the differences between critical and non-critical situations, the general presence of communication patterns is interesting. In both teams, the Turn Receiving pattern Reciprocity (PSAB-BA) was very important, in line with literature (Barth et al., 2015; Butts, 2008; David & Schraagen, 2018; Pilny et al., 2016). Recency Receiving (Recency-rec) also had a strong positive effect, indicating that actors were likely to send to actors they recently received from. In contrast, Recency-send pattern had a negative effect, indicating that actors were unlikely to send to a partner they recently sent to. The Fixed Effects show grouping around important actors. In the surgical team, surgeon one played a central role, as well as Perfusionist one, more clearly so in the critical situation. Anesthetist one, who is the reference actor also played a central role (Barth et al., 2015), which explains the negative Fixed Effects of the other actors. The other actors played less central or fixed roles. A similar structure is visible in the Mission Control center team, where FLIGHT played a particularly central role. The actors whose Fixed Effects were around -7 in the non-critical situation had no or only one relational event. Together with the large 95% confidence intervals, this is a reminder of the limited insight obtained from the short period of the non-critical situation available of the Apollo 13 mission. However, these actors were also very passive in the critical situation, with the exception of CONTROL. When focussing on the critical situation, some actors besides FLIGHT seemed fairly central, such as INCO, GUIDO, CONTROL, and TELMU. Interestingly, GNC and EECOM scored positive on sending, but negative on receiving. The large, positive effect of High Initiator (HI) supports that central actors in both the Mission Control and surgical team were relatively frequent talkers.

Comparison of the communication patterns of the surgical team in extreme situations

For more insight into the differences of communication patterns between critical and non-critical situations, the three most critical and three least critical situations were compared of the surgical team with nine and with eight actors. Figure 6 shows the parameter estimates and 95% confidence intervals of the communication patterns in the three most critical and three least critical situations for the surgical team with nine (left) and with eight (right) actors. The Appendix shows the exact parameter estimates underlying the graphs.

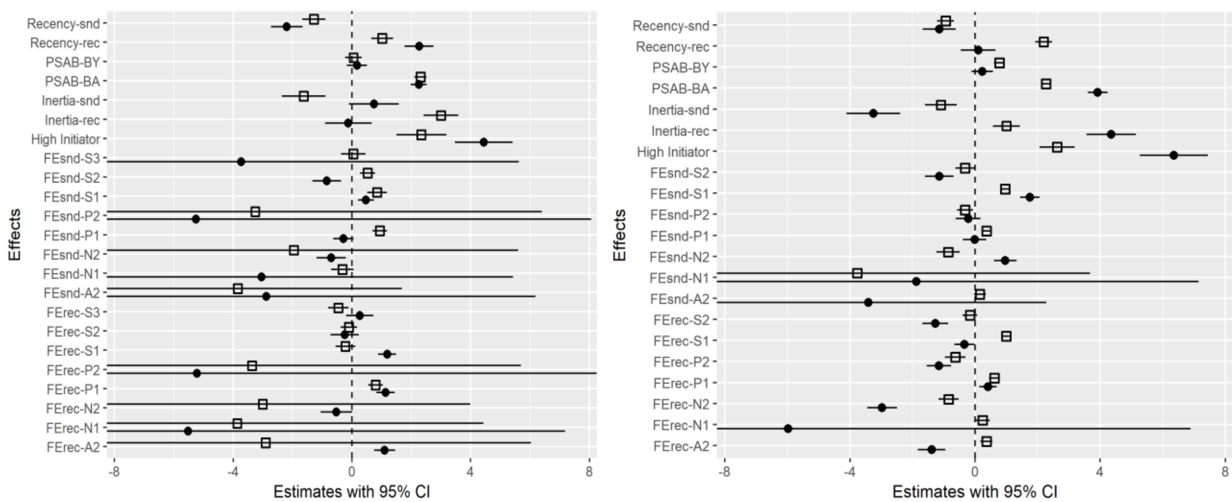


Figure 6. Parameter estimates and 95% confidence intervals of communication patterns of the extremely critical and non-critical surgical operations when the team was with nine actors (left panel) and with eight actors (right panel). Squares indicate critical situations, circles indicate non-critical situations, horizontal lines are the confidence intervals. Positive parameter estimates indicate that a relational event will probably happen given the conditions specified in the communication pattern. Negative estimates indicate that a relational event is unlikely to happen.

Considering the differences between critical and non-critical situations, there are more differences than in the comparison of all critical with all non-critical surgeries, as expected. Interestingly, the differences in communication patterns between the team with nine and with eight actors are also more pronounced. While overall similar, specific patterns are different depending on team size. First, the patterns of the team with nine actors are interpreted, then, the patterns of the team with eight actors. After that, the differences in patterns between the team with nine and with eight actors are discussed.

The surgical team with nine actors

Multiple differences in communication patterns are visible in the team with nine actors. Firstly, there now is a difference visible in the Recency-rec pattern. This indicates that actors in critical situations were less likely to send to actors they recently received from, which indicates more variability in conversation partners. Secondly, a difference became visible in the Inertia-send pattern. In critical situations, actors were more unlikely to send to others they frequently sent to in the past. Thirdly, a difference appeared in the Inertia-rec pattern. In critical situations, the team was likely to send to actors they frequently received from. However, in non-critical situations, there was no significant effect for this pattern. Fourthly, a difference appeared in the High Initiator pattern. While some actors are still more communicative than others (large positive effects) the effect is smaller in critical situations. This indicates less centralized communication structures. Lastly, surgeon two and perfusionist one sent more relational events in critical situations. Together with surgeon one's lower receiving rate in critical situations, this indicates lower centralization around surgeon one than in non-critical situations.

The surgical team with eight actors

In the team with eight actors, the differences between extremely critical and extremely non-critical situations are not the same as those when the team had nine actors. Firstly, the Recency-rec pattern had a positive effect in critical situations and a neutral effect in non-critical situations. This means that actors in critical situations were more likely to send to actors they recently received from. Secondly, with eight actors, there is a very small difference in the PSAB-BY pattern. In critical situations, actors are more likely to "hand-off" communication, in a similar fashion to the Mission Control team. Thirdly, the team displayed less Reciprocity (PSAB-BY) in critical situations. However, the higher Recency-rec pattern may replace these Reciprocity patterns that got interrupted. Fourthly, Inertia-send is more negative in non-critical situations and Inertia-rec is more positive in non-critical situations. The team adapted to critical situations by sending more often to the same target. The Inertia-rec pattern was more strongly positive in non-critical situations. This shows that in critical situations actors were less likely to send to others they have frequently received from in the past. Fifthly, the High Initiator pattern was less positive in critical situations, which indicates that the team adopted flatter communication structures. Sixthly, there are multiple differences in the Fixed Effects. Surgeon one is responsible for a smaller portion of the sent events but remains central. They do become a more important receiver, however. Surgeon two receives more and sends more, possibly taking over some communication from surgeon one. Nurse two sends less in critical situations but receives more. Lastly, anesthetist two receives more in critical situations. Interestingly, the surgical team adapted their communication patterns in a different way when it had eight members than when it had nine. Not only did they adapt more communication patterns, but opposite changes are seen in the Inertia-snd, Inertia-rec, and Recency-rec pattern, which indicates less information searching and routinization. Furthermore, the team showed a decrease in reciprocity (PSAB-AB) and an increase in "handing over" of communication (PSAB-BY), which did not differ when the team had nine actors. Besides these changes, the team adapted by flattening communication structures both with eight and with nine actors.

Differences in adaptation within the surgical team

The surgical team adapted their communication patterns in a different way when it had eight members than when it had nine. Opposite changes are seen in the Inertia-snd, Inertia-rec, and Recency-rec patterns. Furthermore, the team with eight members showed a decrease in reciprocity (PSAB-AB) and an increase in "handing over" of communication (PSAB-BY) in critical situations, which did not differ when the team had nine actors. Besides these changes, the team adapted by flattening communication structures both with eight and with nine actors.

Discussion

In this study, the first aim was to observe whether and how communication patterns captured with REM are different when teams are in critical situations, compared to non-critical situations. The Mission Control team and the surgical team with eight members only marginally adapted their communication patterns to critical situations, while the surgical team with nine members did not adapt their communication patterns. However, when focusing on the most and least critical situations, the surgical team did adapt its communication patterns, both when with nine and with eight actors. In all cases, adaptation happened by a marginal decentralization and flattening of communication structures, but when looking into more detail, differences in adaptation styles are visible. Table 9 shows an overview of the hypothesized and observed differences per communication pattern.

The Apollo 13 Mission Control center team

In the Mission Control center team, there probably were more interruptions of conversations in the critical situation, based on decreasing Reciprocity (PSAB-BA) and increasing Recency-send. The increased Recency-send shows that the team kept closing loops (Davis et al., 2017). Besides that, actors probably changed communication partners more often, because PSAB-BY was negative in the non-critical situation and positive in the critical situation. Together, the changes in the Mission Control team's communication patterns suggest actors were having more conversations simultaneously in the critical situation. This can be linked to higher information sharing to cope with the higher complexity of tasks in critical situations (Schecter et al., 2018). Furthermore, FLIGHT's less central role indicates fewer instructions by FLIGHT and more information sharing by the other actors (Manser et al., 2009). This larger focus on information sharing and lower centralization may be similar to the flattening communication structures found by Barth et al. (2015). In short, the Mission Control team adapted to the critical situation by decentralization and less structured communication. This may be related to a necessity of better information sharing in the search for clues about the cause and solution of the critical situation (Schecter et al., 2018) because the team had to find out what the problem was, what caused it, and how to fix it. Another possible reason that reciprocity decreased in critical situations lies in the voice loop system. Many controllers had one voice loop in one earphone and another voice loop in the other ear. When focusing on one ear, they may miss communication in the other. With more communication in critical situations, this also causes more missed communication and thus less reciprocity.

The surgical team

The surgical team showed some marginal adaptation of communication patterns. When with nine members, communication patterns did not significantly change. When looking at the surgical team with eight members, the more negative estimate on Inertia-send in non-critical situations may be related to a search process (Butts, 2008). The more positive effect of Inertia-rec in non-critical situations may indicate responsiveness and routinization in conversation partners (Leenders et al., 2016) or stricter coordination (Schecter et al., 2018). A negative Inertia-send and a positive Inertia-rec may indicate that the actors who initiate most conversation send to many other actors (negative Inertia-send), while overall, actors are responsive to these high initiators (positive Inertia-rec). If so, these effects being closer to zero in the critical situations suggests that these high initiators address the same targets more often, while the responsiveness decreases. The higher likelihood of receiving in critical situations of anesthetist two (FErec-A2) could reflect that there was more information management between the anesthetists, similar to the findings of Manser et al. (2009).

Turning to the most and least critical situations, the surgical team adapted its communication patterns more, both when it was with nine and with eight actors. When with nine actors, the team had more variability in conversation partners, which may indicate a search process (Butts, 2008). The change in the Inertia-rec may indicate more responsiveness and routinization (Leenders et al., 2016). While some actors are still more communicative than others (large positive Fixed Effects) the difference is smaller in critical situations. This indicates less centralized communication structures (Butts, 2008; Schecter et al., 2018). Lastly, surgeon two and perfusionist one sent more relational events in critical situations. Together with surgeon one's lower receiving rate in critical situations, this indicates lower centrality of surgeon one. When the team was with eight members, the team also decentralized. Lower Reciprocity may indicate less closing of loops (Davis et al., 2017). This is linked to lower process quality and more taking of orders instead of discussing (Schecter et al., 2018) and less routinized communication (Leenders et al., 2016). The higher level of "handing off" of communication fits a picture of less responsiveness. However, the higher Recency-rec pattern may indicate that, at least partly, loops were closed after interruptions of conversations (Butts, 2008). The team adapted to critical situations by sending more often to the same target. The higher Inertia-send could result from enhanced availability to memory (David & Schraagen, 2018) and less searching for information (Butts, 2008). The Inertia-rec pattern was more strongly positive in non-critical situations, which may indicate lower responsiveness and routinization in conversation partners (Leenders et al., 2016).

Interestingly, the surgical team adapted some patterns in a slightly different manner depending on the number of actors. However, no causal relation can be made yet between the number of team members and adaptive behavior. We sought a confounding explanation by comparing the exact differences in criticality of the studied situations. Concerning the difference in adaptation found in the comparison of all surgeries, the larger difference found in the team with eight members may be due to a larger difference in criticality. Critical situations scored 4.3 points higher than non-critical situations on the post-miniSTAR, while for the team with nine members this difference was 3.2. The difference in pattern changes in the most and least critical situations may have a similar explanation. Aristotle scores reveal that the team with nine members was assigned more complex procedures; surgeries had an average of 10.83 for critical situations and 6.27 for non-critical situations, while the team with eight members had an average score of 7.67 in critical situations and 5.17 in non-critical situations.

As visible in Table 9, some hypotheses were not confirmed. Firstly, Inertia played a less important role than expected. This may be the case because these teams had experience working together, negating a tendency towards more inertia, because communication structures were already formed (Butts, 2008). Secondly, Inertia Sending was expected to be higher in critical situations. This was the case for the surgical team with eight members, however, it was lower in critical situations for the surgical team with nine members, possibly because the team was more focused on information seeking and less dependent on short-term memory than the teams studied by the publications on which the hypothesis was based (e.g., David and Schraagen, 2018; Pilny et al., 2016; and Schecter et al., 2018). Thirdly, reciprocity (PSAB-BA) was expected to be slightly more present in critical situations. However, it was equally present in critical and non-critical situations for the surgical team with nine members and slightly less present in the critical situations of the Mission Control team and surgical team with eight members. A possible explanation for this discrepancy with the hypothesis is that the teams had more interruptions of conversations and changes of communication partner (Butts, 2018), rather than being more dependent on short-term memory, as David and Schraagen (2018) suggested.

Table 9. Evaluation of the hypotheses per communication pattern based on both teams.

Pattern	**Hypothesized difference**	**Observed difference**		
		Surgical team with 8 actors	**Surgical team with 9 actors**	**Apollo 13 Mission Control**
Fixed Effects (FE)	Expected to be in line with institutional roles	Strong predictive value according to AIC scores. In line with institutional roles	Strong predictive value according to AIC scores. In line with institutional roles	Strong predictive value according to AIC scores. In line with institutional roles
FE Receiving	Expected to be more even in critical situations, because teams may adapt by flattening communication structures	Uneven, indicating hierarchical communication structures. More even in critical situations, indicating flatter communication structures	Uneven, indicating hierarchical communication structures. More even in critical situations, indicating flatter communication structures	Uneven, indicating hierarchical communication structures. More even in critical situations, indicating flatter communication structures
FE Sending	Expected to be more even in critical situations, because teams may adapt by flattening communication structures	Uneven, indicating hierarchical communication structures. More even in critical situations, indicating flatter communication structures	Uneven, indicating hierarchical communication structures. More even in critical situations, indicating flatter communication structures	Uneven, indicating hierarchical communication structures. More even in critical situations, indicating flatter communication structures
High Initiator (HI)	Expected to be lower in critical situations, because teams may adapt by flattening	High, indicating hierarchical communication structures. Lower in critical situations,	High, indicating hierarchical communication structures. Lower in critical situations,	High, indicating hierarchical communication structures. Lower in critical situations,

Pattern	**Hypothesized difference**	**Observed difference**		
	communication structures	indicating flattening of communication structures	indicating flattening of communication structures	indicating flattening of communication structures
Inertia (IN)	Inertia probably plays an important role, but it is uncertain whether these patterns will be positive or negative	Played a marginally important role	Played a marginally important role	Did not play a very important role
Inertia Receiving	No directional hypothesis can be supported	Positive in critical situations. More positive in non-critical situations	Positive in critical situations. Neutral in non-critical situation	Parameter estimates were not analyzed
Inertia Sending	Expected to be higher in critical situations	More negative in non-critical situations	Negative in critical situations. Neutral in non-critical situations with nine actors	Parameter estimates were not analyzed
P-Shifts				
Turn Receiving (TR)	Probably plays an important role	Strong predictive value according to AIC scores	Strong predictive value according to AIC scores	Strong predictive value according to AIC scores
PSAB-BA	Expected to be positive in critical and non-critical situations. May increase somewhat in critical situations	Positive in both situations. Decreased somewhat in critical situations. This may be due to more interruptions	Positive in both situations	Positive in both situations.
PSAB-BY	Expected to be positive in critical and non-critical situations. May increase somewhat in critical situations	Close to neutral	Close to neutral	Changed from negative to positive when the team entered the critical situation, shows more changes in conversation partners
Turn Continuing (TC)				
PSAB-AY	Expected to be negative in non-critical situations and positive in critical situations	Very low predictive value according to AIC scores. Parameter estimates were not analyzed	Very low predictive value according to AIC scores. Parameter estimates were not analyzed	Very low predictive value according to AIC scores. Parameter estimates were not analyzed
Turn Usurping (TU)	Expected to be negative in non-critical situations and positive in critical situations	Very low predictive value according to AIC scores. Parameter estimates were not analyzed	Very low predictive value according to AIC scores. Parameter estimates were not analyzed	Very low predictive value according to AIC scores. Parameter estimates were not analyzed
PSAB-XA				
PSAB-XB				
PSAB-XY				
Preferential Attachment (PA)	Expected to be positive in both critical and non-critical situations.	Low predictive value according to AIC scores. Parameter	Low predictive value according to AIC scores. Parameter	Low predictive value according to AIC scores. Parameter

Pattern	Hypothesized difference	Observed difference		
	May be higher in critical situations	estimates were not analyzed	estimates were not analyzed	estimates were not analyzed
Recency (R)		Strong predictive value according to AIC scores	Strong predictive value according to AIC scores	Strong predictive value according to AIC scores
Recency Receiving	Expected to be positive but more so in critical situations	Neutral in in non-critical situations, positive in critical situations	Positive but slightly less positive in the in critical situations	Positive
Recency Sending	Expected to be negative in both critical and non-critical situations	Negative	Negative	Negative in the non-critical situation. Neutral in the critical situation
Triadic effects (T)	Expected to have little importance. If they differ between critical and non-critical situations, it is uncertain in which direction	Low predictive value according to AIC scores. Parameter estimates were not analyzed	Low predictive value according to AIC scores. Parameter estimates were not analyzed	Low predictive value according to AIC scores. Parameter estimates were not analyzed
Outgoing two-paths	There may be a small negative effect in non-critical situations			
Incoming two-paths	There may be a small negative effect in critical situations			
Outgoing shared partners	No hypothesis			
Incoming shared partners	There may be a small negative effect in critical situations			

Generalizable changes of communication patterns

The second aim of this study was to evaluate the generalizability of communication patterns of the teams studied as well as those found by David and Schraagen (2018). Both teams had clear hierarchical communication structures that adhered to institutional roles. The well-known communication patterns Reciprocity and Recency did play important roles. Both teams adapted by a marginal decentralization and flattening of communication structures. Such decentralization of communication may be a team driven coping mechanism for critical situations, choosing to share more information about an event which causes criticality. It may also be task driven, caused by more non-routine events of different kinds, necessitating different team members to talk about the tasks they are specialized in. More probably, the flattening of communication structures in response to critical situations is a synthesis of these drives. Those communication and adaptation patterns may be generalizable to other teams as well. However, on a detailed level, the teams adapted in different ways. The surgical team showed variety in adaptation even between eight and nine members. These differences may be due to a variety of reasons, including the complexity of problems and criticality of situations. It may be expected that the adaptation of individual communication patterns in critical situations has low generalizability, which may be because critical situations, by definition, are unique, ambiguous, emergent situations (Stachowski et al., 2009).

The concurrent validity of REM on the transaction level

The third aim of this study was to evaluate the concurrent validity of applying REM to team communication on the transaction level. If the results are consistent and in line with the results of David and Schraagen (2008) support for validity is gained (Spector, 1992).While similar patterns of adaptation are visible in the two teams of the current study, the team studied by David and Schraagen (2018) adapted to a critical situation in a different style. However, both studies did find adaptations. Possibly the structure and adaptation of cockpit crew communication differs from surgical and control room teams because of the vast difference in team members; three versus 8, 9 or 16. Possibly, the type of situation studied is not comparable enough. An out of control airplane in which a problem must be fixed within minutes to save hundreds of lives is not the same as nearly six hours of time to save three lives. Nevertheless, the fact that both studies found changes in communication patterns provides a demonstration for the applicability of REM for studying adaptations of team communication on the transaction level.

Limitations

There are several limitations to this study. Firstly, not all communication channels available to the actors were considered. While non-verbal relational events are common in surgeries (Davis et al., 2017), these were not included in the analysis due to their absence in the transcripts, which may have caused bias. The Apollo 13 Mission Control center actors could communicate through other voice loops as well as personally, besides using the Flight Director's voice loop. A second limitation is the reliability of the coding of the transcripts. Conversion of transcripts and coding of the Mission Control receivers was done by one researcher. While a recoding of 10 percent of the events gave a Cohen's Kappa of 0.971, coding by two coders with inter-rater reliability testing would have given a stronger assurance of reliability. However, reasonable reliability is assumed due to the simplicity of this specific coding task and because previous studies with similar coding tasks that had second coders did not report issues of inter-rater reliability (David & Schraagen, 2018; Davis et al., 2017). Original coding of the Mission Control transcripts was done by Tseng (2017) without traditional scientific reliability measures. However, reliability was checked by two methods:

(a) Thorough checking of the coding was carried out by Tseng; (b) Corrections to the transcript were committed by contributors. Transcripts of the surgical operations were merely converted. These transcripts are assumed to be reliable because they were double-coded by rigorously trained observes followed by testing of inter-rater reliability (Barth et al., 2015; Schraagen, 2011), on top of that, observers were tested multiple times during the observation period to assess whether their rating remained stable. Nevertheless, surgical procedures can be fast processes. In the observation of large teams in such situations, some events may have been missed by observers (Schraagen, 2011). A third limitation of the study is the lack of insight of the researcher into the actual situations. There may be unknown biases. Insight into the actual situations may have improved interpretation of the results because the communication patterns could be connected to concrete events and communication (Davis et al., 2017). A fourth limitation is the fact that no non-dyadic events could be considered due to the dyadic nature of REM. However, very little of the communication was directed at more than one person at a time. The cases in which this happened were coded as series of dyadic events, meaning that at least Fixed Effects and High Initiator patterns probably were not affected greatly. A fifth limitation lies in the data collection of the surgical team. Surgeries over the course of eleven months were observed, so there may be confounding variables in a learning process or due to scrub nurses varying across surgeries. A last limitation is the fact that ex post facto pooling of the data was carried out. Models were fitted to individual datasets and coefficients were pooled. Full hierarchical modelling (see DuBois et al., 2013) would allow for better model selection and may make more precise modelling possible. However, such methods are more complex and effortful, while yielding analog results given the same assumptions (Snijders & Baerveldt, 2003). In the case of the current study, ex post facto pooling is a viable method (Butts, personal communication, March 14, 2019).

Research implications

Evidence accumulates suggesting that teams adapt to critical situations by flattening out communication structures. Besides that, teams members seem to stick to their institutional roles, but may display less closed-loop communication. Information seeking behavior is seen in critical and non-critical situations. Further research into this direction may test whether this is true for more teams and situations or cast a light on the details of team adaptation. REM is an effective method for studying such adaptation of team communication on the transaction level. To find out if, how, and when similar teams adapt communication patterns to critical situations, studying more extreme critical situations may give insight, as well as focussing on smaller timescales. Based on our results, it may be expected that greater effects for the same patterns may be expected during higher criticality. Another research implication lies in team performance. While the findings of the current study suggest that teams adapt to critical situations, no link has been made to team performance. Manser (2009) also stated that, at that time, no link between communication patterns and patient outcome in surgeries had been established. Therefore, it may be interesting to study how communication patterns may influence or predict the success of teams in their endeavors.

Practical implications

Since these teams can be seen as competent, team training may use these patterns. The results of David and Schraagen (2018) may add to such training, focusing on methods for retaining institutionalized procedures. Because REM is not content based, it could be applied rapidly. Automated analysis may be amenable to real-time analysis of communication patterns if REM proves to be computationally efficient enough, which can be used for real-time feedback for training purposes or during work. In a similar vein, Gorman et al. (2019) proposed real-time communication pattern feedback based on a simpler model of communication patterns: the discrete recurrence approach (Gorman, Cooke, Amazeen, & Fouse, 2012), for example in a Perturbation training (Gorman, Cooke, & Amazeen, 2010). Using REM, teams could be given real-time feedback on their communication patterns into more detail than warning for inadequate adaptation to perturbations. For example, when closing of loop patterns are registered less often, or when communication patterns are insufficiently flattened in critical situations. As such, REM can be applied in Perturbation training as well as other forms of team training for critical situations. Before such ad hoc application of REM is realized, REM results can already be applied post hoc. For instance, training could be set up in which teams are confronted with critical situations and discuss communication patterns afterwards, based on REM results. Applicable simulation training is readily available for cockpit crews (McKinney & Smith, 2005), military teams (Schecter et al., 2018), emergency management teams (Dunn, Lewandowsky, & Kirsner, 2002), nuclear power plant teams (Stachowski et al., 2009), and medical teams (Weller et al., 2014). A possible starting point for REM-based feedback would be to manipulate interaction norms, developing structures to normalize when to say what to whom (Schecter et al., 2018).

Conclusion

The findings suggest that teams adapt communication patterns in critical situations. In line with the findings of Barth et al. (2015), teams decentralize communication structures in critical situations, possibly to improve the effectiveness of information sharing (Schecter et al., 2018). However, team members probably stay in line with institutional roles, which was also found in previous research (e.g., Barth et al., 2015; Calder et al., 2017; P. D. Patterson et al., 2013). Furthermore, teams can be expected to display closed-loop communication in both critical and non-critical situations, as suggested by Davis et al. (2017), but may find more difficulty with closing loops in critical situations due to more interruptions and changes of communication partners. Besides that, the findings suggest that teams display information seeking communication patterns in both critical and non-critical situations, which may be a way to deal with complexity (Manser et al., 2013). Lastly, the exact way teams adapt communication patterns to critical situations may differ depending on the team, situation, and possibly even team size. One explanation for this is that critical situations, by definition, are unique, ambiguous, emergent situations (Stachowski et al., 2009). Our study gives some insight into the adaptation of communication patterns. Given our findings more research on the topic is warranted. Team training for critical situations may benefit from using REM-based feedback on communication patterns. With more development of REM, ad hoc feedback may be given during the critical situations.

References

Akama, Y., Cooper, V., & Mees, B. (2016). Beyond transmission: An analysis of communication frameworks in Australian bushfire preparedness. *International Journal of Disaster Resilience in the Built Environment, 7*(1), 49-62. doi:10.1108/IJDRBE-08-2013-0034

Alsamadani, R., Hallowell, M., & Javernick-Will, A. N. (2012). Measuring and modelling safety communication in small work crews in the US using social network analysis. *Construction Management and Economics, 31*(6), 568-579. doi:10.1080/01446193.2012.685486

Amati, V., Lomi, A., & Mascia, D. (2019). Some days are better than others: Examining time-specific variation in the structuring of interorganizational relations. *Social Networks, 57*, 18-33. doi:10.1016/j.socnet.2018.10.001

Anderson, D. R., & Burnham, K. (2004). *Model selection and multi-model inference: A Practical Information-Theoretic Appraoch, Second Edition.* New York, NY: Springer.

Apollo Lunar Surface Journal Raw Transcripts. (N.D.). Retrieved from https://www.hq.nasa.gov/alsj/alsj-rawtrans.html

Au, T. A., Lo, E. H. S., & Hoek, P. J. (2009). *Evaluation of command and control activity for air operations.* Paper presented at the 45th Annual Human Factors and Ergonomics Society of Australia Conference 2009, HFESA 2009, Melbourne, VIC.

Baard, S. K., Rench, T. A., & Kozlowski, S. W. J. (2014). Performance Adaptation: A Theoretical Integration and Review. *Journal of Management, 40*(1), 48-99. doi:10.1177/0149206313488210

Barth, S., Schraagen, J. M., & Schmettow, M. (2015). Network measures for characterising team adaptation processes. *Ergonomics, 58*(8), 1287-1302.

BEA. (2012). *Final report on the accident on 1st June 2009 to the Airbus 330-203 registered F-GZCP operated by Air France flight AF447 Rio de Janeiro Paris*. Retrieved from https://www.bea.aero/docspa/2009/f-cp090601.en/pdf/f-cp090601.en.pdf.

Bellury, L., Hodges, H., Camp, A., & Aduddell, K. (2016). Teamwork in Acute Care: Perceptions of Essential but Unheard Assistive Personnel and the Counterpoint of Perceptions of Registered Nurses. *Research in Nursing and Health, 39*(5), 337-346. doi:10.1002/nur.21737

Benham-Hutchins, M. M., & Effken, J. A. (2010). Multi-professional patterns and methods of communication during patient handoffs. *International Journal of Medical Informatics, 79*(4), 252-267. doi:10.1016/j.ijmedinf.2009.12.005

Bierhals, R., Kohler, P., & Badke-Schaub, P. (2007). *The influence and development of shared mental models in multidisciplinary project teams.* Paper presented at the 16th International Conference on Engineering Design, ICED 2007, Paris.

Boies, K., & Fiset, J. (2018). Leadership and Communication as Antecedents of Shared Mental Models Emergence. *Performance Improvement Quarterly, 31*(3), 293-316. doi:10.1002/piq.21267

Brandenberger, L. (2018). Trading favors—Examining the temporal dynamics of reciprocity in congressional collaborations using relational event models. *Social Networks, 54*, 238-253. doi:10.1016/j.socnet.2018.02.001

Burke, C. S., Stagl, K. C., Salas, E., Pierce, L., & Kendall, D. (2006). Understanding team adaptation: A conceptual analysis and model. *Journal of Applied Psychology, 91*(6), 1189.

Butts, C. T. (2008). A relational event framework for social action. *Sociological Methodology, 38*(1), 155-200. doi:10.1111/j.1467-9531.2008.00203.x

Butts, C. T., Petrescu-Prahova, M., & Cross, B. R. (2007). Responder communication networks in the world trade center disaster: Implications for modeling of communication within emergency settings. *Journal of Mathematical Sociology, 31*(2), 121-147. doi:10.1080/00222500601188056

Calder, L. A., Mastoras, G., Rahimpour, M., Sohmer, B., Weitzman, B., Cwinn, A. A., . . . Parush, A. (2017). Team communication patterns in emergency resuscitation: a mixed methods qualitative analysis. *International Journal of Emergency Medicine, 10*(1). doi:10.1186/s12245-017-0149-4

Cockpit Voice Recorder Database. (2018). Retrieved from https://www.tailstrike.com/database.htm

Cook, T. D., Campbell, D. T., & Shadish, W. (2002). *Experimental and quasi-experimental designs for generalized causal inference*: Houghton Mifflin Boston, MA.

Cumin, D., Skilton, C., & Weller, J. (2017). Information transfer in multidisciplinary operating room teams: A simulation-based observational study. *BMJ Quality and Safety, 26*(3), 209-216. doi:10.1136/bmjqs-2015-005130

Data & Stats. (2018). Retrieved from https://www.ntsb.gov/investigations/data/Pages/Data_Stats.aspx

David, L. Z., & Schraagen, J. M. (2018). Analysing communication dynamics at the transaction level: the case of Air France Flight 447. *Cognition, Technology and Work, 20*(4), 637-649. doi:10.1007/s10111-018-0506-y

Davis, W. A., Jones, S., Crowell-Kuhnberg, A. M., O'Keeffe, D., Boyle, K. M., Klainer, S. B., . . . Yule, S. (2017). Operative team communication during simulated emergencies: Too busy to respond? *Surgery (United States), 161*(5), 1348-1356. doi:10.1016/j.surg.2016.09.027

DuBois, C., Butts, C. T., McFarland, D., & Smyth, P. (2013). Hierarchical models for relational event sequences. *Journal of Mathematical Psychology, 57*(6), 297-309.

Dunn, J. C., Lewandowsky, S., & Kirsner, K. (2002). Dynamics of communication in emergency management. *Applied Cognitive Psychology, 16*(6), 719-737. doi:10.1002/acp.846

Dziak, J. J., Coffman, D. L., Lanza, S. T., Li, R., & Jermiin, L. S. (2019). Sensitivity and specificity of information criteria. *Briefings in Bioinformatics*. https://doi.org/10.1093/bib/bbz016

Fowler, A. J. (2013). A review of recent advances in perioperative patient safety. *Annals of Medicine and Surgery, 2*(1), 10-14. https://doi.org/10.1016/S2049-0801(13)70020-7

Frank, O., & Strauss, D. (1986). Markov graphs. *Journal of the american Statistical association, 81*(395), 832-842.

Gibson, D. R. (2003). Participation Shifts: Order and Differentiation in Group Conversation. *Social Forces, 81*(4), 1335-1380. doi:10.1353/sof.2003.0055

Goguen, J. A., & Linde, C. (1983). *Linguistic Methodology For The Analysis Of Aviation Accidents* (NASA-CR-3741, NAS 1.26:3741). Palo Alto, CA. Retrieved from https://ntrs.nasa.gov/search.jsp?R=19840007067.

Gorman, J. C., Cooke, N. J., & Amazeen, P. G. (2010). Training adaptive teams. *Human factors, 52*(2), 295-307.

Gorman, J. C., Cooke, N. J., Amazeen, P. G., & Fouse, S. (2012). Measuring patterns in team interaction sequences using a discrete recurrence approach. *Human factors, 54*(4), 503-517. https://doi.org/10.1177/0018720811426140.

Gorman, J. C., Cooke, N. J., & Winner, J. L. (2006). Measuring team situation awareness in decentralized command and control environments. *Ergonomics, 49*(12-13), 1312-1325. https://doi.org/10.1080/00140130600612788.

Gorman, J. C., Grimm, D. A., Stevens, R. H., Galloway, T., Willemsen-Dunlap, A. M., & Halpin, D. J. (2019). Measuring Real-Time Team Cognition During Team Training. Human factors, 0018720819852791.

Granlund, R., Granlund, H., Dahlbäck, N., & Johansson, B. (2010). *The effect of a geographical information system on communication in professional emergency response organizations.* Paper presented at the 7th International Conference on Information Systems for Crisis Response and Management, ISCRAM 2010, Seattle, WA.

Greenberg, C. C., Regenbogen, S. E., Studdert, D. M., Lipsitz, S. R., Rogers, S. O., Zinner, M. J., & Gawande, A. A. (2007). Patterns of Communication Breakdowns Resulting in Injury to Surgical Patients. *Journal of the American College of Surgeons, 204*(4), 533-540. doi:10.1016/j.jamcollsurg.2007.01.010.

Grimm, D. A. P., Gorman, J. C., Stevens, R. H., Galloway, T. L., Willemsen-Dunlap, A. M., & Halpin, D. J. (2017). *Demonstration of a method for real-time detection of anomalies in team communication.* Paper presented at the Human Factors and Ergonomics Society 2017 International Annual Meeting, HFES 2017.

Hachour, H. (2008). *A communicational approach to collective knowledge generation: Episteme and praxis.* Paper presented at the 12th World Multi-Conference on Systemics, Cybernetics and Informatics, WMSCI 2008, Jointly with the 14th International Conference on Information Systems Analysis and Synthesis, ISAS 2008, Orlando, FL.

Houghton, R. J., Baber, C., Stanton, N. A., Jenkins, D. P., & Revell, K. (2015). Combining network analysis with Cognitive Work Analysis: insights into social organisational and cooperation analysis. *Ergonomics, 58*(3), 434-449. doi:10.1080/00140139.2014.966770

Hutchins, S. G., Bordetsky, A., Kendall, T., & Garrity, M. (2007). *Evaluating a model of team collaboration via analysis of team communications.* Paper presented at the 51st Annual Meeting of the Human Factors and Ergonomics Society, HFES 2007, Baltimore, MD.

Hutchinson, L. (01-11-2012). Apollo Flight Controller 101: Every console explained. Retrieved from https://arstechnica.com/science/2012/10/apollo-flight-controller-101-every-console-explained/.

Jahn, J. L. S., & Johansson, C. (2018). The communicative constitution of adaptive capacity during Sweden's Västmanland wildfire. *Corporate Communications, 23*(2), 162-179. doi:10.1108/CCIJ-04-2017-0031.

Kozlowski, S., DeShon, R. P., Schmidt, A. M., Chambers, B. A., & Milner, K. R. (2001). *Developing Adaptive Teams: Training Strategies, Learning Processes, and Performance Adaptability* (ADA397319). East Lansing, MI. Retrieved from https://apps.dtic.mil/docs/citations/ADA397319.

Lacour-Gayet, F., Clarke, D., Jacobs, J., Comas, J., Daebritz, S., Daenen, W., . . . Maruszsewski, B. (2004). The Aristotle score: a complexity-adjusted method to evaluate surgical results. *European Journal of Cardio-Thoracic Surgery, 25*(6), 911-924. https://doi.org/10.1016/j.ejcts.2004.03.027.

Leenders, R. T. A. J., Contractor, N. S., & DeChurch, L. A. (2016). Once upon a time: Understanding team processes as relational event networks. *Organizational Psychology Review, 6*(1), 92-115. doi:10.1177/2041386615578312.

Lerner, J., & Lomi, A. (2018). The free encyclopedia that anyone can dispute: An analysis of the micro-structural dynamics of positive and negative relations in the production of contentious Wikipedia articles. *Social Networks*. doi:10.1016/j.socnet.2018.12.003.

Lerner, J., & Lomi, A. (2019) Let's talk about refugees: Network effects drive contributor attention to wikipedia articles about migration-related topics. In*: Vol. 813. 7th International Conference on Complex Networks and their Applications, COMPLEX NETWORKS 2018* (pp. 211-222): Springer Verlag.

Liang, H. (2014). The organizational principles of online political discussion: A relational event stream model for analysis of web forum deliberation. *Human Communication Research, 40*(4), 483-507. doi:10.1111/hcre.12034.

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., . . . Moher, D. (2009). The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions: Explanation and Elaboration. *PLoS Medicine, 6*(7), e1000100. doi:10.1371/journal.pmed.1000100.

Lingard, L., Reznick, R., Espin, S., Regehr, G., & DeVito, I. (2002). Team communications in the operating room: Talk patterns, sites of tension, and implications for novices. *Academic Medicine, 77*(3), 232-237. doi:10.1097/00001888-200203000-00013.

Liu, W., Manias, E., & Gerdtz, M. (2012). Medication communication between nurses and patients during nursing handovers on medical wards: A critical ethnographic study. *International Journal of Nursing Studies, 49*(8), 941-952. doi:10.1016/j.ijnurstu.2012.02.008.

Lomi, A., Mascia, D., Vu, D. Q., Pallotti, F., Conaldi, G., & Iwashyna, T. J. (2014). Quality of care and interhospital collaboration: A study of patient transfers in Italy. *Medical Care, 52*(5), 407-414. doi:10.1097/MLR.0000000000000107.

Lusher, D., Robins, G., & Kremer, P. (2010). The application of social network analysis to team sports. *Measurement in Physical Education and Exercise Science, 14*(4), 211-224. doi:10.1080/1091367X.2010.495559.

MacKellar, B. (2012). *A case study of group communication patterns in a large project software engineering course.* Paper presented at the 2012 25th IEEE Conference on Software Engineering Education and Training, CSEE and T 2012, Nanjing, Jiangsu.

Manser, T. (2009). Teamwork and patient safety in dynamic domains of healthcare: A review of the literature. *Acta Anaesthesiologica Scandinavica, 53*(2), 143-151. doi:10.1111/j.1399-6576.2008.01717.x.

Manser, T., Foster, S., Flin, R., & Patey, R. (2013). Team communication during patient handover from the operating room: More than facts and figures. *Human Factors, 55*(1), 138-156. doi:10.1177/0018720812451594.

Manser, T., Harrison, T. K., Gaba, D. M., & Howard, S. K. (2009). Coordination patterns related to high clinical performance in a simulated anesthetic crisis. *Anesthesia & Analgesia, 108*(5), 1606-1615.

McDivitt, J. A. (1970). Mission Operations Report Apollo 13. Houston, TX Retrieved from https://history.nasa.gov/afj/ap13fj/documents.html.

McKinney, E. H., Jr., & Smith, D. (2005). How swift starting action teams get off the ground: What United Flight 232 and Airline Flight Crews Can Tell Us About Team Communication. *Management Communication Quarterly, 19*(2), 198-237. doi:10.1177/0893318905278539.

Mercury Through Apollo - Mission Transcripts. (2018). Retrieved from https://www.jsc.nasa.gov/history/mission_trans/mission_transcripts.htm.

Mishra, A., Catchpole, K., & McCulloch, P. (2009). The Oxford NOTECHS System: reliability and validity of a tool for measuring teamwork behaviour in the operating theatre. *BMJ Quality & Safety, 18*(2), 104-108.

Moher, D. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Annals of Internal Medicine, 151*(4), 264. doi:10.7326/0003-4819-151-4-200908180-00135.

Musa, N., Abidin, S. Z. Z., & Omar, N. (2016). Multi-dimensional communication model for collaborative group activity. *Indian Journal of Science and Technology, 9*(39). doi:10.17485/ijst/2016/v9i39/92092.

Newell, A. (1990). *Unified theories of cognition:* Harvard University Press.

Ngo, L. V., Walker, K., Holowinsky, A., Knox, G., Shimberg, R., Napoli, N., . . . Barnes, L. E. (2014). *Analysis of communication patterns in critical care environments.* Paper presented at the 2014 IEEE Systems and Information Engineering Design Symposium, SIEDS 2014, Charlottesville, VA.

Patterson, E. S., Cook, R. I., Woods, D. D., & Render, M. L. (2004). Examining the complexity behind a medication error: Generic patterns in communication. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans, 34*(6), 749-756. doi:10.1109/TSMCA.2004.836807.

Patterson, P. D., Pfeiffer, A. J., Weaver, M. D., Krackhardt, D., Arnold, R. M., Yealy, D. M., & Lave, J. R. (2013). Network analysis of team communication in a busy emergency department. *BMC Health Services Research, 13*(1). doi:10.1186/1472-6963-13-109.

Payne, S. (2016). *Voyage Data Recorder - Audio transcript SS El Faro* (DCA16MM001). Washington D.C.: National Transportation Safety Board.

Pilny, A., Schecter, A., Poole, M. S., & Contractor, N. (2016). An illustration of the relational event model to analyze group interaction processes. *Group Dynamics: Theory, Research, and Practice, 20*(3), 181. http://dx.doi.org/10.1037/gdn0000042.

Quintane, E., & Carnabuci, G. (2016). How do brokers broker? Tertius gaudens, tertius iungens, and the temporality of structural holes. *Organization Science, 27*(6), 1343-1360. doi:10.1287/orsc.2016.1091.

Quintane, E., Conaldi, G., Tonellato, M., & Lomi, A. (2014). Modeling Relational Events: A Case Study on an Open Source Software Project. *Organizational Research Methods, 17*(1), 23-50. doi:10.1177/1094428113517007.

R Core Team. (2018). R: A language and environment for statistical computing. In. Vienna, Austria: R Foundation for Statistical Computing.

Redden, E. R., Elliott, L. R., Turner, D. D., & Blackwell, C. L. (2004). Development of a metric for collaborative situation awareness. In D. A. Vincenzi, M. Mouloua, & P. A. Hancock (Eds.) *Human Performance Situation Awareness and Automation: Current Research and Trends* (Vol. 1-2, pp. 72-77): Lawrence Erlbaum Associates.

Roberts, N. C., & Dotterway, K. A. (1995). The Vincennes incident: Another player on the stage? *Defense Analysis, 11*(1), 31-45. https://doi.org/10.1080/07430179508405642.

Salas, E., Sims, D. E., & Burke, C. S. (2005). Is there a "Big Five" in Teamwork? *Small Group Research, 36*(5), 555-599. doi:10.1177/1046496405277134.

Salem, P. (2008). The seven communication reasons organizations do not change. *Corporate Communications, 13*(3), 333-348. doi:10.1108/13563280810893698.

Schecter, A., Pilny, A., Leung, A., Poole, M. S., & Contractor, N. (2018). Step by step: Capturing the dynamics of work team process through relational event sequences. *Journal of Organizational Behavior, 39*(9), 1163-1181. doi:10.1002/job.2247.

Schraagen, J. M. (2011). Dealing with unforeseen complexity in the OR: the role of heedful interrelating in medical teams. *Theoretical issues in ergonomics science, 12*(3), 256-272.

Schraagen, J.M.C. (2017). Beyond Macrocognition: The Transaction Level. In J. Gore & P. Ward (Eds.), NDM13 Naturalistic Decision Making and Uncertainty, Proceedings of the 13th bi-annual international conference on Naturalistic Decision Making, Bath, 20-23 June 2017 (pp. 182-188). Bath: The University of Bath.

Schraagen, J. M., & Verhoeven, F. (2013). Methods for studying medical device technology and practitioner cognition: The case of user-interface issues with infusion pumps. *Journal of biomedical informatics, 46*(1), 181-195. https://doi.org/10.1016/j.jbi.2012.10.005.

Serfaty, D., & Kleinman, D. (1990). *Adaption processes in team decisionmaking and coordination.* Paper presented at the 1990 IEEE International Conference on Systems, Man, and Cybernetics Conference Proceedings.

Sevdalis, N., Wong, H. W. L., Arora, S., Nagpal, K., Healey, A., Hanna, G. B., & Vincent, C. A. (2012). Quantitative analysis of intraoperative communication in open and laparoscopic surgery. *Surgical Endoscopy, 26*(10), 2931-2938. doi:10.1007/s00464-012-2287-3.

Siassakos, D., Draycott, T., Montague, I., & Harris, M. (2009). Content analysis of team communication in an obstetric emergency scenario. *Journal of Obstetrics and Gynaecology, 29*(6), 499-503. doi:10.1080/01443610903039153.

Snijders, T. A., & Baerveldt, C. (2003). A multilevel network study of the effects of delinquent behavior on friendship evolution. *Journal of Mathematical Sociology, 27*(2-3), 123-151.

Snijders, T. A. B. (2001). The statistical evaluation of social network dynamics. *Sociological Methodology, 31*(1), 361-395.

Stachowski, A. A., Kaplan, S. A., & Waller, M. J. (2009). The benefits of flexible team interaction during crises. *Journal of Applied Psychology, 94*(6), 1536.

Stainback, J. R., Sawhney, R., & Aikens, C. H. (2011). *A new lean model: Improving team performance through communications efficacy.* Paper presented at the 61st Annual Conference and Expo of the Institute of Industrial Engineers, Reno, NV.

Spector, P. E. (1992). *Summated rating scale construction: An introduction*: Newbury Park, CA: Sage Publications, Inc.

Svenmarck, P., & Brehmer, B. (1991). D3Fire, an experimental paradigm for the study of distributed decision making. *Distributed Decision Making, Risö National Laboratory, Roskilde*.

Symonds, M. R., & Moussalli, A. (2011). A brief guide to model selection, multimodel inference and model averaging in behavioural ecology using Akaike's information criterion. *Behavioral Ecology and Sociobiology, 65*(1), 13-21.

Tseng, C. (2017). Overview personnel. Retrieved from https://github.com/clint-tseng/apollo13rt/blob/master/exhibits/overview-personnel.md.

Tseng, C. (N.D.). Apollo 13 Real-time. Retrieved from http://apollo13realtime.org/.

Tseng, C. H. (2017). Apollo 13 real-time. Retrieved from https://github.com/clint-tseng/apollo13rt.

Van Diggelen, J., Neerincx, M., Peeters, M., & Schraagen, J. M. (2019). Developing effective and resilient human-agent teamwork using team design patterns. *IEEE Intelligent Systems, 34(2), 15-24*.

Vaughan, D. (2006). NASA Revisited: Theory, Analogy, and Public Sociology. *American Journal of Sociology, 112*(2), 353-393. doi:10.1086/506413.

Vu, D., Lomi, A., Mascia, D., & Pallotti, F. (2017). Relational event models for longitudinal network data with an application to interhospital patient transfers. *Statistics in Medicine, 36*(14), 2265-2287. doi:10.1002/sim.7247.

Vu, D., Pattison, P., & Robins, G. (2015). Relational event models for social learning in MOOCs. *Social Networks, 43*, 121-135. https://doi.org/10.1016/j.socnet.2015.05.001.

Weil, S. A., Duchon, A., Duran, J. L., Cooke, N. J., Gorman, J. C., & Winner, J. L. (2008). *Communications-based performance assessment for air and space operations centers: Preliminary research.* Paper presented at the 52nd Human Factors and Ergonomics Society Annual Meeting, HFES 2008, New York, NY.

Wasserman, S., & Faust, K. (1994). *Social network analysis: Methods and applications* (Vol. 8): Cambridge university press.

Weller, J., Henderson, R., Webster, C. S., Shulruf, B., Torrie, J., Davies, E., . . . Merry, A. F. (2014). Building the evidence on simulation validity: Comparison of anesthesiologists' communication patterns in real and simulated cases. *Anesthesiology, 120*(1), 142-148. doi:10.1097/ALN.0b013e3182a44bc5.

Wickham, H. (2016). ggplot2: elegant graphics for data analysis: Springer.

Woods, D. D., & Hollnagel, E. (2006). *Joint cognitive systems: Patterns in cognitive systems engineering*: Boca Raton, FL: CRC Press.

Xiao, Y., Seagull, F. J., Mackenzie, C., Ziegert, J., & Klein, K. J. (2003). *Team communication patterns as measures of team processes: Exploring the effects of task urgency and shared team experience.* Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting.

Zhang, M., Shan, L., Zhang, M., Liu, K., Yu, H., & Yu, J. (2016). Terminal airspace sector capacity estimation method based on the ATC dynamical model. *Kybernetes, 45*(6), 884-899. doi:10.1108/K-12-2014-0308.

Appendix: Coefficient tables

Table 10. Coefficients of the surgical team with nine members.

	Critical situations				**Non-critical situations**			
	Estimate	**Std.Err**	**Z value**	**Pr(>|z|)**	**Estimate**	**Std.Err**	**Z value**	**Pr(>|z|)**
FErec-A2	-1.67516247222547	5.82814360106069	-0.287426423727892	0.773785831173009	0.384979892982571	0.297032096498112	1.29608852888737	0.194944986552646
FErec-N1	-1.30712991599685	4.23603064449742	-0.308574235102574	0.757645422410304	-2.01234494919667	6.48284852887729	-0.31041060734843	0.756248728765958
FErec-N2	-1.0698220271814	3.57299487026879	-0.299418853378012	0.764620478722622	-0.885326891623171	0.510452310440971	-1.73439687413375	0.0828476893298042
FErec-P1	0.779992489302888	0.207913670296564	3.75152094708502	0.000175765064952982	-0.379930437926901	4.03632433324326	-0.0941278268442861	0.925007615884825
FErec-P2	-2.71838053768399	7.03985608662106	-0.386141492700419	0.699391881622111	-2.1378036575084	6.87016671032502	-0.31117202065789	0.755669852165746
FErec-S1	0.807422982246057	0.237430359473303	3.40067287114075	0.000672202177437908	0.169506980588622	0.512719014282492	0.330604046011115	0.740943589650194
FErec-S2	0.0899068609605395	0.277499804679317	0.323988916188382	0.74594642563679	-1.30113379034786	3.95312222942138	-0.329140794247162	0.742049271115715
FErec-S3	-0.297466168893918	0.325221424972169	-0.914657356658999	0.360371537653097	-1.09486109403309	0.495089998181271	-2.21143852240016	0.0270054846994525
FEsnd-A2	-1.89019581982193	2.83892714463092	-0.665813430047593	0.505530359570955	-1.56677627544743	4.65367994172602	-0.336674695094378	0.736362141215218
FEsnd-N1	-0.438958706740331	0.316802052370258	-1.38559300186384	0.165871216329732	-1.87136147017326	4.34602517027768	-0.43059149380253	0.666765427248098
FEsnd-N2	-2.79535573330267	5.70932769037729	-0.489612067286673	0.62440843570581	-1.56789354962587	3.05026851482681	-0.514018205939778	0.607239262035728
FEsnd-P1	0.992674739112681	0.196857659037525	5.0426015628046	4.59244861028552e-07	-0.102515785292003	4.56267117131851	-0.0224683702688087	0.982074342496766
FEsnd-P2	-3.51242865866672	8.30252755270402	-0.423055345058478	0.672254881655594	-2.53465929282066	7.85258730015996	-0.322780148240953	0.746861748363234
FEsnd-S1	0.949953630046328	0.242272168481508	3.92101839844156	8.81755295485398e-05	1.43411037524661	0.259819747565291	5.51963578090316	3.39703021268178e-08
FEsnd-S2	0.556695572728155	0.250639956854548	2.22109666676658	0.0263444147618581	0.112724366569721	0.375884200557852	0.299891206926031	0.764260141681806
FEsnd-S3	-0.987200046595681	2.47618435399762	-0.398677927595301	0.690130533597037	-0.91692417133172	4.77908000620954	-0.191862067623966	0.847850251031699
HighInitiator	2.12898247974805	0.714724518981932	2.97874554909717	0.00289431019927844	2.89776006210723	1.1075637869115	2.61633695174143	0.00888788011918717
Inertia-rec	0.742235729034076	0.485693975437918	1.52819628525318	0.126463810841399	0.412501744563805	0.769163729277057	0.536299007431772	0.591751916486706
Inertia-snd	0.117856264763833	0.606240724165106	0.194405060673119	0.84585872767002	-1.37517812949981	1.34069407113715	-1.02572104934678	0.305023089560316

	Critical situations				Non-critical situations			
PSAB-BA	2.78279597167217	0.178678345245945	15.5743325686263	0	2.70449633596496	0.344035454144667	7.86109775426728	3.77475828372553e-15
PSAB-BY	0.289116955586755	0.225786251993191	1.28048963581482	0.20037298746739	-0.465696161687414	5.87794835098616	-0.0792276716091394	0.936851535005958
Recency-rec	2.26463284495797	0.311300539102545	7.27474758471902	3.47055717497824e-13	2.54157828435169	0.584751986038594	4.34642095287205	1.38376887266478e-05
Recency-snd	-2.49816952350749	0.351205094643932	-7.11313577623426	1.13442588656198e-12	-1.97720650547388	0.633054390904239	-3.12328061203349	0.00178847143223915

Table 11. Coefficients of the surgical team with eight members.

	Critical situations				Non-critical situations			
	Estimate	**Std.Err**	**Z value**	**Pr(>|z|)**	**Estimate**	**Std.Err**	**Z value**	**Pr(>|z|)**
FErec-A2	0.162693193342137	0.145598861391964	1.11740704416742	0.263820324632388	-1.0522125572254	0.355092885255316	-2.96320371631454	0.00304455002261239
FErec-N1	-1.40493637667254	3.13528091617446	-0.44810542156675	0.654077115477385	-1.97285124017885	6.57255485777121	-0.300165047363006	0.76405126463294
FErec-N2	-2.12906974940643	3.13902913295505	-0.678257403556541	0.497608501694528	-1.07347848494752	0.356465366137757	-3.01145240722396	0.00260001157199885
FErec-P1	0.290251649573334	0.128759683006132	2.25421220988491	0.0241828210332171	0.455237579246608	0.255375006310374	1.78262385902138	0.0746475533031918
FErec-P2	-0.381211526095706	0.208954195096486	-1.82437842858181	0.0680948808763955	-3.29251041667773	6.48432202666902	-0.507764790696104	0.61161830471982
FErec-S1	0.724131660037894	0.122885122455603	5.89275288633509	3.79814202311479e-09	0.228859267576145	0.260981885568483	0.876916292782669	0.380532105949315
FErec-S2	-1.62228787614077	3.20173071247264	-0.506690918702499	0.612371703476332	-1.77870062309388	4.46261222878395	-0.398578350953556	0.690203915992774
FEsnd-A2	-0.198662175359171	0.157948962618816	-1.25776182423312	0.208477905852826	-1.88324885933709	5.29682491785302	-0.355542969334247	0.722182860015797
FEsnd-N1	-2.9108557274155	5.36957525531586	-0.542101672666522	0.587748466507552	-1.50360416533804	4.61391828227848	-0.325884437770216	0.74451179039045
FEsnd-N2	-2.81991965386915	5.17998444727568	-0.544387668065728	0.586174730113615	-0.631698451834489	0.384725945617933	-1.64194398383992	0.100601613457006
FEsnd-P1	0.413534406199346	0.114900283976122	3.59907209877119	0.000319354648023795	0.315561543043381	0.296436783773303	1.06451547283249	0.287095248828532
FEsnd-P2	0.168102413149426	0.190827333697988	0.880913702936668	0.378364530151812	-2.19454991241864	6.97054821376455	-0.31483175284336	0.752889401499364
FEsnd-S1	1.23985641014946	0.114865177649465	10.7940146484877	0	1.15865000928269	0.269502677442907	4.29921520734481	1.71403973847628e-05
FEsnd-S2	-1.67072226872177	3.80460908028856	-0.439131125817282	0.660566526849317	-0.202578119598192	3.5434226159233	-0.0571701830563067	0.954409629773796

	Critical situations				Non-critical situations			
High Initiator	3.54655033315708	0.381627635824127	9.29322197932097	0	4.27437758740605	0.865171425925349	4.9404978705051	7.79233439107685e-07
Inertia-rec	0.886089397783845	0.345305707930572	2.56610121823415	0.0102848811157474	2.97338557715551	0.611773708359896	4.86027028707536	1.17225594697956e-06
Inertia-snd	-0.731545064742312	0.394751928622315	-1.85317667046088	0.0638570403747758	-2.99316386311817	0.644670856008082	-4.64293342133128	3.43497064569931e-06
PSAB-BA	2.45941713282829	0.103274555581575	23.8143569728134	0	2.9309347701886	0.213452172622046	13.7311076958599	0
PSAB-BY	0.624196289529216	0.129116223451827	4.83437536230375	1.33564355775384e-06	0.366435855043259	0.259936873555729	1.40971094262507	0.1586250522983
Recency-rec	1.99233627377201	0.194504421258351	10.2431413172129	0	1.92334832496392	0.420439017082077	4.57461902159391	4.77087330752468e-06
Recency-snd	-1.24493572318587	0.18707846402594	-6.6546180484636	2.84037238174051e-11	-1.50570156634089	0.380098546363879	-3.96134523729391	7.45286816550284e-05

Table 12. Coefficients of the Apollo 13 Mission Control center team.

	Critical situations				Non-critical situations			
	Estimate	**Std.Err**	**Estimate**	**Pr(>|z|)**	**Estimate**	**Std.Err**	**Estimate**	**Pr(>|z|)**
FErec--CAPCOM	1.48199817839503	0.00606900601583777	244.191252163466	0	-0.017966381399259	0.775848192825481	-0.023157083518915	0.981524971809028
FErec--CONTROL	1.09287955459043	0.00621626737574141	175.809611866973	0	-0.00451333148535717	1.61142623103207	-0.0028008303442265	0.997765263632701
FErec-EECOM	0.803010911203482	0.00715020845472297	112.305944125736	0	0.871291367597098	0.765788033872461	1.13777093537375	0.255216144335979
FErec-FAO	-4.34568084716254	0.409219111516012	-10.619447442382	0	-7.17853115154176	1044.17426406659	-0.00687484014745257	0.994514714397293
FErec-FDO	0.390215861416105	0.00766354288443374	50.9184677766618	0	0.0217748539398901	1.61018202811856	0.0135232250513522	0.989210356384316
FErec-FLIGHT	3.50475600476366	0.00653057239295515	536.669038160332	0	5.10016468436987	0.682277951314031	7.47520079543421	7.70494779089859e-14
FErec-GNC	0.671444051829168	0.00744967995785529	90.1305902572588	0	0.949899853940503	0.735689902827042	1.29116880670825	0.196645149032231
FErec-GUIDO	0.988382985954382	0.00643390043555854	153.621119234584	0	0.784984913304097	0.71988591009889	1.09042961154256	0.275523943829117
FErec-INCO	0.422082674314127	0.0066078620412455	63.8758302881531	0	1.0183503733244	0.766646914135004	1.32831731863603	0.184073300773665
FErec-NETWORK	-0.89451981511152	0.0129620771974622	-69.0105298313342	0	-7.17879581908982	1044.05020537684	-0.00687591054732729	0.994513860361945
FErec-PROCEDURES	-4.53215212468558	0.409352782473937	-11.0715068242492	0	-7.17887321048858	1043.95553085306	-0.00687660824462744	0.994513303693202
FErec-RECOVERY	-2.06026654156644	0.0247969654470756	-83.0854301895806	0	-7.17853299137964	1044.11184534088	-0.00687525289882714	0.994514385077127

	Critical situations				Non-critical situations			
FErec-RETRO	-4.13772616036755	0.408855489274038	-10.1202656413259	0	-7.17861856591932	1043.98741507703	-0.00687615431206101	0.994513665870425
FErec-SURGEON	-5.37067925481002	0.409668714627753	-13.1098105933964	0	-7.17890849742751	1044.1740323697	-0.00687520305512225	0.99451442484571
FErec-TELMU	0.952057806186455	0.00634095202192712	150.14430055522	0	0.643559885735966	0.817037980532964	0.787674381203385	0.430887194472012
FEsnd--CAPCOM	0.134114966557111	0.00667361275740155	20.096306368446	0	-1.10559332532521	1.10054761341943	-1.00458472840635	0.315096853897098
FEsnd--CONTROL	0.89879289544813	0.00642817210560346	139.820913423374	0	-7.78150140207268	607.601740087372	-0.0128069109890201	0.989781842776244
FEsnd-EECOM	-0.434318482035329	0.0116385062824877	-37.3173731657336	0	0.805924322292537	0.896433581894969	0.899034059599703	0.368634519105462
FEsnd-FAO	-5.24987434467287	0.895626060230633	-5.86168109413986	4.58204385545002e-09	-7.20283316291472	1070.02862192562	-0.00673143971602601	0.994629128739709
FEsnd-FDO	-0.327639265027075	0.00858095906326472	-38.1821265678456	0	-7.78128588550873	607.800771969915	-0.0128023626233464	0.989785471549495
FEsnd-FLIGHT	2.37400611122312	0.0142800214184618	166.246677204133	0	4.1723747914195	2.23993230440031	1.86272361143368	0.062501162148078
FEsnd-GNC	-1.0646352230769	0.0166198393508762	-64.0580934990066	0	1.17247274875477	0.859389487752615	1.36430892565477	0.172470357904104
FEsnd-GUIDO	0.732342322704494	0.00663114314858632	110.439830100881	0	0.849998781157938	0.740699598322658	1.1475620927604	0.251149386188615
FEsnd-INCO	0.607896489709377	0.0067830898575806	89.6194068592515	0	-0.0911816551251306	0.929042799717216	-0.0981458067947835	0.92181651451699
FEsnd-NETWORK	-1.70797878047007	0.0157293007605344	-108.585804701216	0	-7.20336484037401	1070.45060439329	-0.00672928279998192	0.994630849670742
FEsnd-PROCEDURES	-5.71880415080996	0.900432701090278	-6.35117332354258	2.13678852389876e-10	-7.20304226187665	1070.12626914153	-0.00673102088004536	0.994629462914901
FEsnd-RECOVERY	-2.62272318339352	0.0270937043880048	-96.8019413600263	0	-7.20345596637904	1070.3863817772	-0.00672977168713495	0.994630459604063
FEsnd-RETRO	-5.46494168788069	0.899432917687106	-6.07598585777114	1.23228272030929e-09	-7.20324050963876	1070.15837514575	-0.00673100419240069	0.994629476229413
FEsnd-SURGEON	-6.69788551274479	0.89710572006575	-7.46610501185289	8.26005930321116e-14	-7.20370595680543	1070.25495028065	-0.00673083170969351	0.994629613847585
FEsnd-TELMU	0.782842421054999	0.00646264599136232	121.133421527546	0	0.258666325324551	0.859094715650628	0.301091742985117	0.763344537201473
High Initiator	3.50469807078444	0.0266656043039792	131.431413698037	0	2.43735929745471	6.35143050315721	0.383749660213259	0.701164001850884
PSAB-BA	2.75133685518755	0.00187943357448994	1463.91811476191	0	3.25487099590097	0.0939346026982952	34.6503940231179	0
PSAB-BY	0.533486318609659	0.00307574700333678	173.449350037859	0	-0.916133625953353	0.401377872338198	-2.28247167841237	0.022461507714127
Recency-rec	1.66311999856226	0.00441484627776896	376.710737797811	0	1.751050350668	0.296798107471466	5.89980295220159	3.63935948044514e-09

	Critical situations				Non-critical situations			
Recency-snd	0.0654423802426236	0.00339683104579961	19.2657154154155	0	-1.63767292120098	0.141060989033369	-11.6096798443231	0

Table 13. Coefficients of the Surgical team with nine members in the most and least critical situations.

	Critical situations				Non-critical situations			
	Estimate	**Std.Err**	**Z value**	**Pr(>|z|)**	**Estimate**	**Std.Err**	**Z value**	**Pr(>|z|)**
High Initiator	2.33889972104604	0.427576233035943	5.47013500829788	4.49692889592512e-08	4.44235081948965	0.496940673900333	8.93939871056038	0
Inertia-snd	-1.62604431465687	0.374112088541065	-4.34640944375255	1.38384144698911e-05	0.741834921540962	0.430113741121836	1.72474127333408	0.084574109387151
Inertia-rec	2.99575011586981	0.298246450008095	10.0445457633729	0	-0.122380398364653	0.400297123845396	-0.305723901258703	0.759814873521382
Recency-rec	1.01929431854648	0.185923423459476	5.48233406840558	4.19750638691596e-08	2.26137713622067	0.247309864258963	9.14390189407385	0
Recency-snd	-1.28257650859153	0.200561070181183	-6.39494248526332	1.60607749322139e-10	-2.19363592607938	0.271965565666892	-8.06585907557937	6.66133814775094e-16
FEsnd-A2	-3.84811256138699	2.82294832636449	-1.36315373733488	0.172834063879056	-2.88429915986119	4.62266014986072	-0.623947914481253	0.532661791847947
FEsnd-N1	-0.322128373048417	0.192169426590638	-1.67627274933083	0.0936847800869522	-3.03930057215548	4.31948557501383	-0.703625586744955	0.481665972702502
FEsnd-N2	-1.95495146438252	3.85122087074226	-0.507618630557985	0.611720822481396	-0.700563868079243	0.25046603578559	-2.79704138679688	0.00515729265179443
FEsnd-P1	0.936918222872802	0.12265991892494	7.63834047082762	2.19824158875781e-14	-0.287531423245604	0.175183832785423	-1.64131254964487	0.100732552346845
FEsnd-P2	-3.2577561788798	4.92739279575481	-0.661152117137184	0.508514765158972	-5.25215123510875	6.79035912492813	-0.773471791179282	0.439243216970312
FEsnd-S1	0.845811599030955	0.167310767968008	5.0553327158996	4.29641082488885e-07	0.475244319353439	0.139987408829953	3.39490760866024	0.00068651763577221
FEsnd-S2	0.526008682314258	0.130877846840794	4.01908111274262	5.84255560167612e-05	-0.850903532357177	0.246027618214088	-3.45856915794201	0.000543052833898994
FEsnd-S3	0.0446205555156454	0.211798120302562	0.210674936358752	0.833140933541373	-3.72828664707162	4.77139330962825	-0.781383215579457	0.434577139878145
FErec-A2	-2.90844219728401	4.55906354310489	-0.63794728232791	0.523507997546709	1.10172739025445	0.181794551799605	6.06028827238398	1.3587779790214e-09
FErec-N1	-3.86357156704451	4.22973244764635	-0.91343166851946	0.361015556288973	-5.52061234090502	6.47799840266037	-0.852209586627534	0.39409777676601
FErec-N2	-3.00340731981656	3.56390944336553	-0.842728292495651	0.399380420126192	-0.52316661110262	0.270286547787618	-1.93559988606502	0.0529167243464872
FErec-P1	0.796290808305918	0.126295076837019	6.30500276217032	2.88188806152334e-10	1.1376257493035	0.15832929345354	7.18518806273415	6.7124084068837e-13

	Critical situations				Non-critical situations			
FErec-P2	-3.36248272107551	4.61870462854627	-0.728014235916586	0.466604871868618	-5.21468573095685	6.86366471024397	-0.759752399206502	0.447402600889475
FErec-S1	-0.222181876267706	0.169771033726104	-1.30871486961761	0.190630952915558	1.18677221332533	0.154046264981062	7.70399862321377	1.31006316905768e-14
FErec-S2	-0.104440889681685	0.140721289978083	-0.742182577333902	0.457976723132544	-0.244545166849161	0.242480594115169	-1.00851438335313	0.313207586234611
FErec-S3	-0.461289285130258	0.175912916088425	-2.62225932800969	0.00873489374135672	0.259955058629884	0.233477326488777	1.11340601050774	0.265534094752516
PSAB-BA	2.3095678852097	0.101091220146786	22.8463746095473	0	2.25417581382222	0.137084628046254	16.4436804180672	0
PSAB-BY	0.0534814454446748	0.142297738857038	0.375841850153401	0.707034473009223	0.170211066132076	0.172129941508985	0.988852169703378	0.322735475085012

Table 14. Coefficients of the Surgical team with eight members in the most and least critical situations.

	Critical situations				Non-critical situations			
	Estimate	**Std.Err**	**Estimate**	**Pr(>|z|)**	**Estimate**	**Std.Err**	**Estimate**	**Pr(>|z|)**
High Initiator	2.61923446257471	0.284950700710852	9.19188637206591	0	6.34890140867153	0.555396432120537	11.4312967125681	0
Inertia-snd	-1.0921467488376	0.259073481490299	-4.21558680014303	2.49129545004667e-05	-3.2501036647814	0.43895205934914	-7.40423377805887	1.31894495325469e-13
Inertia-rec	1.00220033168424	0.218959019519582	4.57711371690997	4.71435218241112e-06	4.34668837724749	0.403913862725772	10.7614241014515	0
Recency-rec	2.19094010737953	0.136250649046812	16.0802177656179	0	0.098072722529533	0.282477332417047	0.347187937843944	0.728450132114087
Recency-snd	-0.941576017087727	0.136963661131805	-6.87464112237488	6.21458440264178e-12	-1.14655073434047	0.269821195406209	-4.24929825329091	2.14441243067132e-05
FEsnd-A2	0.155640505065117	0.0962503293200562	1.61703867575947	0.105869932709845	-3.41452141713271	2.90340200785427	-1.17604155673095	0.239578270196673
FEsnd-N1	-3.76616351869361	3.79643503266755	-0.992026331620728	0.321184680679689	-1.87638579047032	4.60137943575755	-0.407787668169426	0.683429567959904
FEsnd-N2	-0.861922739613536	0.189865974261352	-4.53963772585758	5.63509629847303e-06	0.966708599635381	0.184841020254213	5.22994624410677	1.69559336793412e-07
FEsnd-P1	0.369878501788231	0.0810946075203574	4.56107394928053	5.08926524034337e-06	-0.0119384173766787	0.189753149669352	-0.0629155162772348	0.949833779120601
FEsnd-P2	-0.318057868172142	0.129306105623874	-2.45972815156393	0.0139042290439486	-0.222486155662734	0.199041344176377	-1.11778865131448	0.263657269587447
FEsnd-S1	0.962897807490544	0.0770254838262186	12.5010290057118	0	1.75157502775579	0.160152516542049	10.9369185422441	0
FEsnd-S2	-0.318702841510234	0.156051960134871	-2.04228669242468	0.0411231013597968	-1.14264155460471	0.234561581824718	-4.87139260281155	1.10814393283754e-06

	Critical situations				**Non-critical situations**			
FErec-A2	0.364186974751662	0.0958728813581167	3.79864430475709	0.000145489712203517	-1.38886364630682	0.226436142499499	-6.13357757721865	8.59244897455369e-10
FErec-N1	0.239077126218228	0.114693933618863	2.08447926298091	0.0371165945681253	-5.97741956893103	6.56740882677723	-0.910164073319048	0.362735987898767
FErec-N2	-0.846309069249071	0.165062752808047	-5.12719589884249	2.94089466112979e-07	-2.97460428164695	0.242977220236398	-12.2423175257042	0
FErec-P1	0.620617107908532	0.0867582926353809	7.15340388862653	8.46434033974219e-13	0.408357909628085	0.139648373462848	2.92418665181749	0.00345357592667916
FErec-P2	-0.632107585524919	0.165675030111767	-3.81534613332189	0.000135992173704302	-1.15598403690679	0.195679510125269	-5.90753746351247	3.47259376809461e-09
FErec-S1	0.996882216792742	0.0835086316372095	11.9374751717109	0	-0.340254303095515	0.163722909123577	-2.07823269765316	0.0376879318664389
FErec-S2	-0.163449749319322	0.1193581589472	-1.36940575123672	0.170872477495465	-1.27379328468922	0.211374310313564	-6.02624454598863	1.67813207774259e-09
PSAB-BA	2.26937181198289	0.0670554042226414	33.8432351320705	0	3.92036097690371	0.159312869228828	24.6079365457459	0
PSAB-BY	0.776292613592504	0.085367259672938	9.09356369838581	0	0.231130344839165	0.176633108615101	1.30853352834784	0.190692410098841