This article was downloaded by: [Universiteit Twente]
On: 14 July 2015, At: 06:05
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: 5 Howick Place, London, SW1P 1WG

Click for updates

Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/terg20

Network measures for characterising team adaptation processes

Susanne Barth[a], Jan Maarten Schraagen[bc] & Martin Schmettow[b]

[a] Department of Communication Science - Corporate and Marketing Communication, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

[b] Department of Cognitive Psychology and Ergonomics, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

[c] TNO Earth, Life and Social Sciences, P.O. Box 23, 3769 ZG Soesterberg, The Netherlands

Accepted author version posted online: 13 Feb 2015.Published online: 19 Feb 2015.

To cite this article: Susanne Barth, Jan Maarten Schraagen & Martin Schmettow (2015) Network measures for characterising team adaptation processes, Ergonomics, 58:8, 1287-1302, DOI: 10.1080/00140139.2015.1009951

To link to this article: http://dx.doi.org/10.1080/00140139.2015.1009951

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Ergonomics, 2015
Vol. 58, No. 8, 1287–1302, http://dx.doi.org/10.1080/00140139.2015.1009951

Network measures for characterising team adaptation processes

Susanne Barth[a1], Jan Maarten Schraagen[b,c]* and Martin Schmettow[b2]

[a]*Department of Communication Science – Corporate and Marketing Communication, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands;* [b]*Department of Cognitive Psychology and Ergonomics, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands;* [c]*TNO Earth, Life and Social Sciences, P.O. Box 23, 3769 ZG Soesterberg, The Netherlands*

(*Received 16 December 2013; accepted 9 January 2015*)

The aim of this study was to advance the conceptualisation of team adaptation by applying social network analysis (SNA) measures in a field study of a paediatric cardiac surgical team adapting to changes in task complexity and ongoing dynamic complexity. Forty surgical procedures were observed by trained human factors researchers, and communication processes amongst team members were recorded. Focusing on who talked to whom, team communication structures, in response to changing task demands, were characterised by various network measures. Results showed that in complex procedures, the communication patterns were more decentralised and flatter. Also, in critical transition phases of the procedure, communication was characterised by higher information sharing and participation. We discuss implications for team adaptation theory and teamwork observation methods.

Practitioner Summary: The reasons for this study were to advance our conceptualisation of team adaptation processes and to further quantify team observation methods. We found that the surgical team studied adapted to complexity of surgical procedures by adopting flatter communication patterns. We quantified team observation methods by applying SNA techniques.

Keywords: teamwork; adaptability; social network analysis; surgery; task complexity

1. Introduction

Teams operating in dynamic, time-pressured environments frequently need to deal with novelty, unpredictability and complexity (Burke et al. 2006; Kozlowski et al. 1999). This requires teams to adapt themselves to these challenges. Although team adaptability is frequently viewed as a core component of teamwork (Salas, Sims, and Burke 2005), the construct has been difficult to define and measure. In a recent review on performance adaptation, Baard, Rench, and Kozlowski (2014, 81) conclude that the conceptualisation of adaptation has been diverse, with the result being 'a vibrant, yet chaotic, line of inquiry; progress has been stymied'. Moreover, the above authors identified '(. . .) a scarcity of research that has systematically investigated the impact of contextual factors on adaptive performance (. . .)' (54).

The aim of this study is to address this gap in the research literature by exploring adaptation in team communication processes using a novel set of network measures. In a field study, it was observed how a paediatric cardiac surgical team adapts to changes in task complexity and ongoing dynamic complexity. First, we will position our research in the conceptual architecture recently proposed by Baard, Rench, and Kozlowski (2014). Second, we will justify our approach of applying social network analysis (SNA) measures to the communication processes employed by the team under study. Third, based on previous research on characterising communication patterns, we will develop our research questions.

2. Conceptual architecture for adaptation

Baard, Rench, and Kozlowski (2014) argue that it is important for any study on adaptation to specify (a) what it is to which an entity is adapting, (b) what level(s) of the organisational system(s) are implicated and (c) what mechanisms underlie that particular form of adaptation at that level or at multiple levels. Our approach to adaptation focuses on the processes teams use to respond to changes necessitating adaptation. We view these processes as domain-specific rather than generic, but assume that they can be characterised qualitatively and quantitatively through measurement. This assumption is in line with work of Houghton et al. (2006) and Walker et al. (2010) who showed that command and control structures and distributed cognition in complex systems can be effectively illustrated by network analysis, which enables a qualitative as well as a quantitative approach of the question. In terms of the typology of task complexity developed by Wood (1986), we focus on dynamic complexity or volatility in the rate of change. According to Walker et al. (2009), the ongoing interchange of

---

*Corresponding author. Email: jan_maarten.schraagen@tno.nl; j.m.c.schraagen@utwente.nl information usage and sharing depends strongly on the dynamic complexity and change in the environment. Teams, especially those operating in high-risk situations (for instance paediatric cardiac surgery, PCS) with very low error tolerance, are frequently confronted with novel situations full of complexity and uncertainty. In order to properly act upon these requirements, such teams rely to a great extent on teamwork, and the adoption of appropriate communication structures depends heavily on the task requirements and other environmental factors (Salas, Rosen, and King 2007). In such dynamic environments, the time to reflect on the situation is often sparse and situation awareness (SA) plays an important role. SA here can be seen as a continuous process which functions as a pre-assumption for adaptation to the complexity of the situation (Gorman, Cooke, and Winner 2006) and should be seen as a phenomenon at the system level (Stanton et al. 2006). According to Salas, Rosen, and DiazGranados (2010), individual experts are usually able to adapt properly to novel, complex situations, but this task is considerably more difficult for expert teams as a whole, especially in multi-professional teams (as in an OR). In the particular case of a paediatric cardiac surgical team, two types of dynamic complexity can be distinguished: (1) ongoing dynamic complexity that is imposed by the different phases of the surgical procedure and (2) one-time changes in complexity that are imposed by the nature of the surgical procedure. The second, relatively slow-moving change in complexity, is due to the specific surgical procedures, for instance closing a hole between the aorta and the pulmonary artery is much simpler than crafting a major blood vessel to the body (aorta). The ongoing dynamic complexity applies to all surgical procedures, and is the result of phases such as going on and off cardio-pulmonary bypass and all the coordinative complexity this involves.

The focal level of adaptation is explicitly on the team level, for several reasons, as described next. To date, team processes have usually been examined by means of fixed behavioural rating schemes that exclusively focus on individual team members' cognitive processes to the neglect of interactive team cognition (Cooke et al. 2013; Salmon et al. 2008; Stanton et al. 2006). Within such behavioural rating schemes, the use of relatively abstract concepts such as 'leadership', 'situation awareness' and 'decision making' (see Flin, O'Connor, and Crighton 2008 for a review) makes it difficult to diagnose precisely during what stage teamwork failed. Furthermore, most research conducted observation of team processes at brief intervals during the team operation, and frequently classified teamwork behaviour afterwards (Schraagen et al. 2010). Lack of covering the whole situation, the risk of missing information and hindsight bias (Fischhoff 1975) could bias the outcomes of these research approaches. They therefore seem to be less useful for providing practical guidance on team training. In contrast, we observed team adaptation processes in real time, for the entire surgical procedure, and over an extended period of time.

Finally, in terms of the mechanisms underlying adaptive performance, we will focus on behavioural mechanisms in terms of skilled communicative action. This is in line with contingency theory as the properties of the organisational structure and the changing environment influence the team performance, and a successful team should be able to adapt to environmental requirements (Borgatti and Li 2009; Katz and Kahn 1978). Consequently, teams operating in high-risk environments often develop highly differentiated structures, cohesive by means of communication.

The importance of adapting team communication structures to environmental demands has been shown in earlier studies by Leavitt (1951) and Bavelas (1950): strong *centralisation*, defined as to what extent there is a central actor as in the hub-and-spokes structure shown in Figure 1,[3] was beneficial for performance on simple tasks, but counterproductive if dealing with complex tasks. Also, when the provided information is ambiguous and more information gathering is requested for problem solving, decentralised communication patterns are beneficial as group members would then be allowed to approach the task from several perspectives, such as displayed in a circle network. These findings imply that the benefits and effects of a social network structure (such as a command and control team) depend on the degree of task difficulty and environmental demands (Houghton et al. 2006).

This study aims at examining the patterns of communication, in terms of degrees of centralisation, within a paediatric cardiac surgical team, with the overall goal of diagnosing team performance and providing practical guidelines for improving team performance. In line with contingency theory, we focus on the different stages and the critical

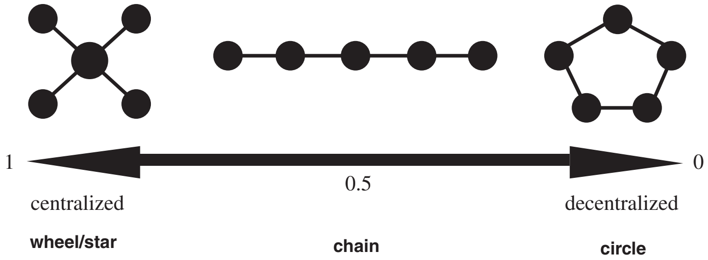


Figure 1. Examples of simple network structures.

transitional processes from one phase to the next as well as on environmental constraints such as the overall complexity of the surgical procedures. Structured observation methods together with analysis of communicative interactions are used to illustrate whether and how the paediatric cardiac surgical team adapts to the environment (see Walker et al. 2006 for a related approach).

2.1. Capturing adaptive communication structures in the operating room

Healthcare teams are frequently confronted with novel and complex situations (Healey and Vincent 2007; Salas, Rosen, and King 2007), making seamless integration of multi-professional task fulfilment necessary. Particularly, non-technical skills such as communication skills are important to inform team members about surrounding tasks and events that lie in the responsibility of other members (Artman 2000; Artman and Garbis 1998).

Recent research in the operating room arena has shown that good teamwork is associated with fewer adverse events, shorter duration of the overall procedure and lower postoperative morbidity (Schmutz and Manser 2013). In cases of emergency, team members must integrate their individual perspectives and skills in order to get the complete picture of the situation (Burtscher and Manser 2012; Burtscher et al. 2010; Manser, Howard, and Gaba 2008; Manser et al. 2009). This is mostly achieved by explicit communication, of which the patterns can be observed and analysed (Cooke et al. 2013; Gorman, Cooke, and Winner 2006; Gutwin and Greenberg 2004; Walker et al. 2006). Taken together, effective team communication structures are a precondition for cohesive teamwork and are therefore highly desirable for patient safety (Gillespie et al. 2010).

The interactive team cognition approach (Cooke et al. 2013) provides a theoretical alternative to existing approaches that exclusively focus on individual team members' cognitive processes to the neglect of interactive team cognition. Interactive team cognition views team cognition as context-dependent team interaction rather than a monolithic entity that a team can either have or not have. Rather than viewing team cognition as something that is shared among team members and then aggregated, it is viewed as an interdependent network that should be studied at the team level. Team cognition arises as an emergent property as team members communicate with each other (Walker et al. 2006). Fortunately, team communication is easily observable. Rather than classifying this communication in various static categories such as 'situation awareness' and 'decision making', there is a need to maintain the network properties of teamwork and characterise skilled communicative action.

2.2. Social network analysis

In line with the distributed cognition approach and 'systemic situation awareness', the influence of the network structure, skills and communication on team performance is of great importance (Borgatti et al. 2009; Garbis and Artman 1998; Stanton et al. 2006; Walker et al. 2009).

A promising approach for studying real-time team interaction at the team level is SNA (Wasserman and Faust 1994). SNA basically conceives a network as a set of actors (or nodes) and the relationships (or edges) between them. These elements of SNA are often easy to observe and record, without the necessity of highly trained raters (Alba 1982). Starting with a *sociomatrix* defining which units have a 'communicates with' relationship, SNA is able to move beyond simply counting the number of events. More specifically, the centralisation aspects of communication (Goldhaber 1993; Lawrence and Lorsch 1967; Tushman 1979) can be assessed by measures of *centrality*, which may be either defined at the actor or team level (Pfautz and Pfautz 2009). This approach should be distinguished from, and is complementary to, recent structural or network approaches to shared team knowledge (e.g. Avnet and Weigel 2013; Espinosa and Clark 2014). We focus on real-time team communication, while the latter approaches use surveys to capture team knowledge network structures.

In this study, degree centralisation, density, closeness centralisation, betweenness centralisation and reciprocity were chosen as the metrics of centralisation, in order to capture context-dependency of communicative behaviour within a medical team (see Table 1). Compared to classical behavioural rating schemes, these metrics of centralisation are not influenced by hindsight bias as they are based on real-time communication and not established immediately after the surgical procedure.

2.3. Dynamic adaptation to phases of the surgical procedure

Multi-professional teams, such as in an OR, need to perform highly context dependent behaviour. The effective goal accomplishment of such a medical team is related to its ability of adapting behaviour to the environment and the individual requirements in the different phases of the surgical procedure as presented in Table 2 (Howell, Windahl, and Seidel 2010).

Table 1. Description of constructs of centralisation within a network.

Metric	Core measurement	Definition	Functional relevance	References
Degree of centralisation Closeness centralisation	Measures the degree of centralisation	Degree of centralisation is measured by the comparison of the centrality scores of the most central point with the scores of all other points,[1] whereas closeness centralisation is based on the compactness of a given network.[2]	A high centralised communicative network is based on the information flow of a few individuals.[3] In a decentralised network, the information flow is more equally spread among team members. Degree of centralisation has a value of 1 when all actors in the network interact with only one central actor. A minimum value of 0 implies that all actors have the same degree of centrality.[4] Networks with a high degree in centralisation often score high on closeness centralisation. The distances between connections and the time frame of information distribution are small.[5,6]	[1]Scott (2000) [2,6]Everett and Borgatti (1999) [3]Bavelas (1950) [4]Kang (2007) [5]Sabidussi (1966)
Density Betweenness centralisation	Measures the level of cohesion	Density measurement compares the actual links in a given network to all possible links, and describes the level of interrelatedness between members.[1,7] Betweenness centralisation measures the cohesion and describes the individual abilities to broker or bridge the information flow between actors that are not directly connected in the network.[1,8,9]	Teams that score high on density have many ties to each other and can reach higher levels of information sharing, which is essential for collaboration and task completion.[8,10] A high score on betweenness centralisation can be an indication of high participation and information sharing.[11]	[7]Balkundi and Harrison (2006) [8]Benham-Hutchins and Effken (2010) [9]Burt (1992) [10]Hansen (1999) [11]Freeman (1977)
Reciprocity	Measures the degree of symmetry in sending and receiving messages	The measurement of reciprocal relationships is an extension of the degree of hierarchy. It reflects the degree of relationships which are reciprocal, thus, members can reach each other directly.	Teams who score high on reciprocity might be better in problem solving than teams low in reciprocity.[12]	[12]Ahuja and Carley (1999)

Table 2. Successive phases of a paediatric cardiac surgical procedure.

Phase	Process flow	Domain	N	A	S	P	Comment
1	Patient in surgical holding area. Pre-operative events and medication. Patient transported to OR	Transport to OR					*Not* applicable in this study
2	Patient is in OR. Induction of anaesthesia, insertion of lines. Preparing for surgery.	Pre-surgery/anaesth. Induction	+[1]	+	−[2]	−	*Not* applicable in this study
3	Incision, dissection, canulation	Surgery/pre-bypass	+	+	+	+	Applicable in this study
4	Go on cardiopulmonary bypass. Identification of structure, surgical repair.	Surgery/bypass	+	−	+	+	Applicable in this study
5	Off CPB, heparin reversed, homeostasis	Surgery/post bypass	+	+	+	−	*Partly* applicable in this study
6	Chest closed. Prepared for move and update ICU, team leaves with patient to ICU.	Transport to ICU	+	+	+	−	*Not* applicable in this study
7	Arrival at ICU. Nurses take over, anaesthetist/surgeon inform ICU.	Handoff	−	+	+	−	*Not* applicable in this study

Note: N, nurse; A, anaesthetist; S, surgeon; P, perfusionist; +[1], present, −[2], not present.

These findings are in line with contingency theory and the work by Kozlowski, Gully, Nason, and Smith (1999) who concluded that team processes, consisting of complex skills such as communication, enable flexible and adaptive team performance related to the environmental demands, resulting in different communication patterns during a surgical procedure.

One may argue that in the high-risk transitional phases of a surgical procedure, the workload becomes larger and the situation could become more ambiguous and complex. In such situations, fast information sharing and collaboration among team members are essential. Team members who have many ties to one another can reach a higher level of information sharing. This indicates that dense networks should be better at problem solving than loose networks (Balkundi and Harrison 2006; Hansen 1999).

From a communication point of view, a team performs best if the network is still hierarchical and somewhat centralised (Ahuja and Carley 1999). During complex tasks, hierarchies are well suited because they need less information exchange. They are more resistant to communication errors and beneficial in situations in which members change (Carley 1992; Carley and Lin 1995). This is especially true during the transitional phases of a surgical procedure. Parting members have to complete their job fully, providing updates to still involved members. The members who are still involved, mostly those highest in the authority level, have to introduce newly arriving members to the situation. Consequently, the first research question addressed in this study is:

RQ1: What adaptive behaviours of a medical team can be ascertained by analysing the communication patterns of such a team during the various phases of a surgical procedure?

2.4. One-time adaptation to complexity of surgical procedure

Team members usually make choices in their communication patterns, which affects the function of the group and the information sharing within the team (Schraagen, Huis in 't Veld, and de Koning 2010; Stanton, Walker, and Sorensen 2012; Walker et al. 2012). Two of the most common communication structures are the classical hierarchy and the network structure, whereby the degree of centralisation has an important effect on group performance and individual functioning such as the availability of information in problem-solving situations (Bavelas 1950; Leavitt 1951). However, centralisation of information flow is not the only parameter that influences group performance. The complexity of the task seems to be an additional influencer. For instance, Cummings and Cross (2003) found that groups with decentralised communication patterns performed better on complex tasks than teams with a centralised structure, because they were better protected from cognitive overload. Especially in non-routine situations with complex task requirements, team members need more information processing and a more flexible problem-solving strategy. A decentralised set-up provides coherent decision-making and extensive information sharing and wider participation (Brown and Miller 2000). In particular, teams dealing with time pressure and stress tend to reduce their communication and decision-making to fewer members of the team, especially to members higher in the authority level. Consequently, communication patterns will become more centralised (Brown and Miller 2000; Xiao et al. 2003). Furthermore, networks with a high degree of centralisation often score high on compactness. This means that the distances between connections and the time frame of information distribution among the network members are small, which is beneficial for team success (Borgatti and Everett 2000).

In conclusion, the second research question of this study is:

RQ2: What adaptive behaviours of a medical team can be ascertained by analysing the communication patterns of such a team across various degrees of surgical task complexity?

3. Method

The observational study of a PCS team was conducted at the Wilhelmina Children's Hospital, which is part of the University Medical Centre Utrecht, The Netherlands. The structured, real-time observations of the surgical personnel took place during the successive phases of the surgical procedures going from anaesthesia to handover in the intensive care. A complete cardiac surgical procedure consists of seven successive phases. Initially, the current study concentrated on the most central phases during the surgical procedure (phases 2–5), which include pre-surgery (anaesthesia induction), starting surgery (phase 3: pre-bypass), main surgery (phase 4: bypass) and finishing surgery (phase 5: post bypass). After consultation with the anaesthetist of the PCS team, we decided to focus solely on the most critical phases, which are phases 3 and 4 and the beginning of phase 5, as these are most likely to yield meaningful conclusions with regard to possible changes in communication patterns. The pre- and postoperative phase (phases 1, 2, 6 and 7), which cover the transport to the operating room (OR), anaesthesia induction, transport to the intensive care and handoff, were omitted. For a detailed overview of the division of phases, see Table 2.

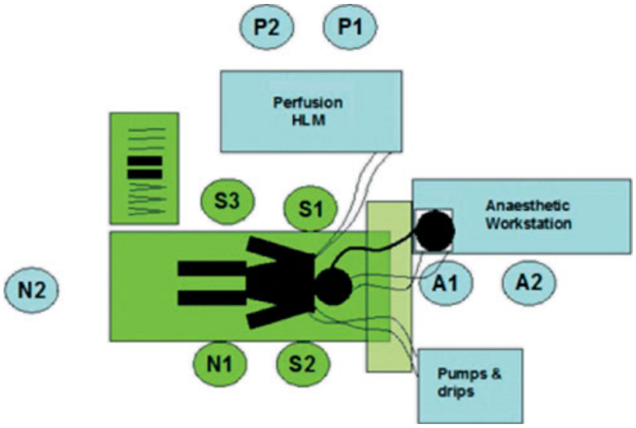
3.1. *Sample: the PCS team*

The PCS team consisted of eight to nine members, involving anaesthesiology providers, perfusionists, surgeons and nurses and in some cases also the cardiologist. Members belonging to the observed surgical team were relatively stable over time, but the exact team composition could somewhat vary from one surgical procedure to the next. For a detailed team composition of the PCS team, see Figure 2.

The surgical personnel gave their informed consent for participating in the observational study. They were fully informed about the purpose of the study. It was ensured that all data would be obtained confidentially and stored anonymously. The study was approved by the IRB ethics committee.

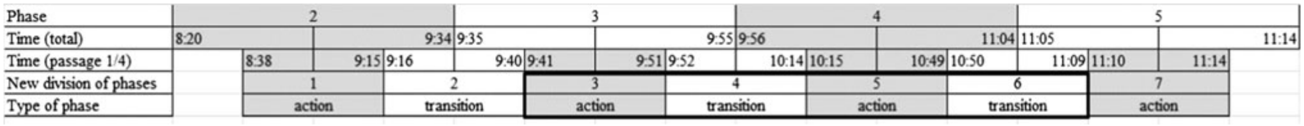
3.2. *Procedure and material*

The observational time schedule was divided into two parts. The first part occurred in the time period of December 2008 until March 2009. The second part took place from September 2009 until November 2009, resulting in a final sample of 40 live observations. The procedure from 28 January 2009 was excluded from the data-set due to insufficient data obtained from the observation. The communication among the team members of the PCS was documented in real time by two trained



S1=Surgeon, S2=Surgical Assistant 1, S3=Surgical Assistant 2
A1=Anaesthetist, A2=Anaesthetic Assistant
P1=Perfusionist1, P2=Perfusionist 2
N1=Instrument Nurse, N2=Circulating Nurse

Figure 2. Composition of PCS team.



Phase	2				3				4				5			
Time (total)	8:20		9:34		9:35		9:55		9:56		11:04		11:05		11:14	
Time (passage 1/4)		8:38	9:15	9:16	9:40	9:41	9:51	9:52	10:14	10:15	10:49	10:50	11:09	11:10	11:14	
New division of phases		1		2		3		4		5		6		7		
Type of phase		action		transition		action		transition		action		transition		action		

Figure 3. Example of division of phases.

human factors observers. The observational protocols concentrated on the social network aspects of the PCS such as *who talks to, works with and reports to whom.*

The complexity of the 40 procedures was measured using the basic Aristotle® risk assessment scoring system, developed by the Aristotle Executive Committee (Lacour-Gayet et al. 2004). This system is widely used to characterise the complexity of various paediatric cardiac surgical procedures. The scoring criteria were based on the difficulty of a given procedure, the potential morbidity and mortality (Schraagen 2011). The basic Aristotle scale ranges from 1.5 to 15 and reflects only the procedure complexity; the comprehensive score ranges from 1.5 to 25 and includes also complexity factors related to the patient (Lacour-Gayet et al. 2004). In this study, the values of the Aristotle® score were only used for the classification of complexity. Based on these ratings, procedures were split into half. The non-complex procedures had an Aristotle® score of 1.0–7.9 and the complex procedures had an Aristotle® score of 8.0–15.0. The division resulted in a set of 12 non-complex and 27 complex procedures.[4] For more information about the observational methods and tools applied, see Schraagen et al. (2010).

In order to narrow down the high-risk transitional processes at the intersection of two successive phases, the whole phases of the surgical procedures were divided into quarter phases, based on the actual duration of each phase, resulting in a division of seven phases. These seven phases were divided into action phases and transition phases: for instance, phase 2 starts with an action phase, then moves into a transition phase covering the last quarter of phase 2 and the first quarter of phase 3, which is then succeeded by action phase 3, etc. For an example of the division of phases, see Figure 3.

3.3. *Measures of centralisation*

In order to convert the verbal protocols to centralisation metrics, the verbal protocols were first coded and transcribed and subsequently analysed with the Organisational Risk Analyzer (ORA) version ORA NetScenes 3.0.0.2©[5] (Carley and Reminga 2004). In contrast to many other SNA tools, ORA can compute centralisation scores at the team level (Carley et al. 2007). To explore the dynamics and changes of the communication networks of the PCS team, the data were analysed in ORA at the team level according to the standard network analysis functions. In order to detect possible differences in the successive phases of the surgical procedures, the data were analysed per action phase and transitional phase (Diesner, Frantz, and Carley 2005). Using ORA, network-level degree centralisation, density, closeness centralisation, betweenness centralisation and reciprocity were calculated. Although these metrics have been a major focus in SNA, they also have weaknesses in terms of correlation to each other. According to Valente et al. (2008), in cases of very strong correlations, these must be considered redundant. Pearson's product–moment correlations showed that there is a strong negative correlation between hierarchy and reciprocity, $r^2 = -0.901$. Therefore, we chose to proceed with the measure of reciprocity and disregard hierarchy. Correlations among the other centralisation measures varied between small and moderate. The average of the correlations for all measures excluding reciprocity was 0.10 with a standard deviation of 0.22.

4. Results

This section discusses the results of the data analysis, addressing differences discovered in the communication patterns with regard to the progression of phases and the degree of complexity. Furthermore, we focus on the differences between the action phases and the high-risk transitional phases at the intersection of two successive phases.

4.1. *Frequency of communication events*

Concentrating on phases 3–6, during the 39 procedures a total of 1868 communication events were produced, of which 1443 (mean = 53.4) communication events took place in the complex procedures and 425 (mean = 35.4) in the non-complex procedures. Because complex procedures took longer than non-complex procedures, we decided to control for the duration by using the frequency (events per minute) instead of the raw counts. A total frequency of 76.24 events accounted for the non-complex procedures and 39.29 events per minute for the complex procedures. Whereas complex procedures have more total message exchange, this happens at a lower frequency. Apparently, complex procedures also contained much longer periods of silence.

With regard to non-complex procedures, the highest event frequency was observed in phase 5 (23.51), followed by phase 6 (18.49), phase 4 (18.07) and phase 3 (16.16). During complex procedures, the event frequency was distributed somewhat differently across phases: in phase 4 most events took place (12.62), followed by phase 3 (11.41), phase 6 (9.19) and phase 5 (6.07). Almost all communication was directed to individual members of the team. The events directed to the whole team were omitted. Furthermore, the link strength between almost all actor pairs was symmetric, indicating a considerable degree of reciprocity in the team. In non-complex procedures, most communication events took place between P1 and S1 (13.32% and 9.79%, respectively), followed by A1 and S1 (8.88% and 6.98%, respectively) and P1 and A1 (7.26% and 6.42%, respectively). In complex procedures, again the highest amount of communication took place between P1 and S1 (11.94% and 9.82%, respectively), followed by A1 and S1 (6.48% and 4.88%, respectively), as in the non-complex procedures. But different to the non-complex procedures, the remaining events are not concentrated around P1 and A1 (3.85% and 2.91%, respectively), but more equally distributed around other parties such as S1 and S2 (3.85% and 3.49%, respectively) and P1 and S2 (not reciprocal at 3.16%). For a top 10 of frequency of events, see Table 3.

4.2. *Direction of communication*

Analysis of the sender and receiver role with regard to communication between team members revealed that both S1 and P1 are the most frequent senders, whereas S1 alone clearly functioned most often in the receiver role. This can be explained by the fact that S1 asked quite often for explicit feedback from more than one team member. These findings hold for both non-complex and complex procedures. A1 was also intensively involved in the communication during procedures, with a stronger sender than receiver role (for a complete overview, see Table 4).

4.3. *Content of communication*

The communication events obtained during the 39 procedures were categorised into nine major types of communication utterance: answer, command, confirmation, control, discussion, explanation, question, request and statement. The categorisation was based on the work of Santos et al. (2012) and inspired by the work on command and control networks (Walker et al. 2012). During non-complex procedures, slightly more *answers* were given (15.06%) than during complex procedures (12.68%). The *command* and *control* structures were equally developed in non-complex and complex procedures (± 14.35% and ± 9.65%, respectively). There is a tendency for more *confirmation* (15.80%) and *discussion* (7.62%) in complex procedures than in non-complex procedures (13.44% and 1.88%, respectively). Distributed by percentage, no differences could be found with regard to *explanation, question, request* and *statements* in non-complex and complex procedures.

Concentrating on the top three of actors, S1's communication involved mainly command and control but also statements meant to inform the team about the state of affairs. P1 was more likely to give an answer or confirmation but also to inform the team about progression by making explicit statements. The same is true for A1 (for a complete overview of all types of communication of the nine team members, see Table 5).

4.4. *Centralisation of communication*

Analysis of the centralisation in phases 3–6 shows that the degree of centralisation varies from 0.16 to 0.20 in the non-complex procedures and from 0.16 to 0.27 in the complex procedures. This means that the communication networks are

Table 3. Top 10 of frequency of communication links of PCS team members.

	Non-complex				Complex		
Rank	Involved members	Frequency	Percentage	Rank	Involved members	Frequency	Percentage
1	P1-S1	10.16	13.32	1	P1-S1	4.72	11.94
2	S1-P1	7.47	9.79	2	S1-P1	3.88	9.82
3	A1-S1	6.77	8.88	3	A1-S1	2.56	6.48
4	P1-A1	5.54	7.26	4	S1-A1	1.93	4.88
5	S1-A1	5.32	6.98	5	P1-A1	1.52	3.85
6	A1-P1	4.90	6.42	6	S1-S2	1.52	3.85
7	S2-S1	2.99	3.92	7	S2-S1	1.38	3.49
8	A2-S1	2.60	3.41	8	P1-S2	1.25	3.16
9	S1-S2	1.95	2.56	9	A1-P1	1.15	2.91
10	P1-S2	1.86	2.44	10	A2-S1	0.26	0.66

Table 4. Percentage of sender and receiver role.

	Non-complex		Complex	
Member	Sender (%)	Receiver (%)	Sender (%)	Receiver (%)
S1	23.47	34.18	25.45	29.32
P1	25.57	19.69	20.54	17.20
A1	19.51	18.15	17.23	15.15
S2	10.76	10.74	11.79	15.28
A2	7.68	6.95	4.86	5.99
P2	2.52	2.77	9.64	7.69
S3	4.30	4.01	3.04	5.26
N1	3.19	1.77	4.96	2.63
N2	3.00	1.74	2.50	1.47
Total	100	100	100	100

overall decentralised but often with some actors ‘in the know’. In most phases, the network is still organised around a central point, but surrounded by other members who are themselves highly connected to the network.

With regard to the non-complex procedures, in (action) phase 3, S1, A1 and P1 are clearly the central actors, as they have more connections than others. Also, Figure 4 shows that most of the communication took place between these three actors, followed by events between S1 and S2, in which S3 supports S2 and S1. N1 and N2 function in a supporting role for S1 and have little connections to the rest of the network. The situation changes in (transition) phase 4 with the network mostly concentrating around S1 and P1 (going on cardiopulmonary bypass (CPB)). In this phase, A1 and S2 support mainly S1 and P1, and N1 supports S1. The other members are still part of the network, but not strongly connected to the inner circle of S1 and P1. This situation is still present in (action) phase 5, where S1 has a central role, again. Most of the communication takes place between S1, P1 and A1 but S2 and N1 are involved as well. The other members are still part of the network but not strongly connected to the inner circle. In (transition) phase 6, the triad of S1, A1 and P1 is still prevalent but S2, A2 and P2 are also part of the inner circle of the network whereas S3, N1 and N2 are left somewhat outside.

Looking at the complex procedures, the network plot shows that in (action) phase 3 of the complex procedures, S1 is also the most central point in the network. However, the network is more equally spread around different actors such as P1 and A1, but also P2, A2 and S3 are more strongly connected than in the non-complex procedures. N1 and N2 again play a subordinate role. As in the non-complex procedures, in (transition) phase 4 of the complex procedures, the network is mainly concentrated around S1 and P1. However, A1, S2 and P2 are also somewhat integrated which is different compared to the non-complex procedures. In (action) phase 5, the network becomes flatter and a chain formation arises, going from A1 to P1 and from S1 to N1, in which S2 functions in a supporting role to S1 and P1. All other team members are arranged around this chain formation but do not play a primary role. In (transition) phase 6, the situation changes again as the ‘golden triangle’ of S1, P1 and A1 is prevalent, but actively connected to S2, P2 and A2.

4.5. Metrics of centralisation

Analysis shows that the *density* of the network seems to be stronger in complex procedures than in non-complex procedures. A high score on density implies that team members have many ties to each other and can reach higher levels of information sharing, which could be especially important in complex situations. In contrast, the scores on *closeness* centralisation seem to be higher in non-complex procedures, which indicate flatter structures in complex procedures. In other words, in complex procedures, the network seems to have more events to each other in order to guarantee faster information sharing and consultation with different members of the team but the structures are flatter than non-complex procedures. Furthermore, results show that the score on *betweenness* centralisation increases in both non-complex and complex procedures during the course of the procedures. The score on *reciprocity* is somewhat lower in the non-complex procedures, which indicates that an explicit feedback loop is more present during complex procedures. For a detailed overview of the centralisation scores, see Table 6.

5. Discussion

The aim of this study was to advance our conceptualisation of team adaptation by exploring team communication patterns using a novel set of network measures. Data were obtained in a field study on a paediatric cardiac surgical team confronted with changes in task complexity and ongoing dynamic complexity.

Table 5. Type of communication of team members.

	Answer			Command			Confirmation			Control			Discussion			Explanation			Question			Request			Statement			
	Non-complex	Complex	Total	Non-complex	Complex	Total	Non-complex	Complex	Total	Non-complex	Complex	Total	Non-complex	Complex	Total	Non-complex	Complex	Total	Non-complex	Complex	Total	Non-complex	Complex	Total	Non-complex	Complex	Total	Total
S1	17	40	57	44	134	178	14	29	43	21	74	95	1	39	40	2	7	9	18	59	77	12	35	47	25	110	135	681
P1	22	71	93	5	23	28	16	69	85	8	23	31	2	5	7	–	2	2	7	39	46	1	11	12	22	95	117	421
A1	8	31	39	6	8	14	15	32	47	4	11	15	3	12	15	–	22	14	12	26	3	8	11	26	62	88	257	–
S2	–	11	11	4	31	35	3	12	15	2	23	25	1	27	28	1	3	4	8	27	35	4	13	17	12	31	43	213
A2	4	4	8	–	1	1	3	11	14	2	–	2	–	7	7	1	1	–	1	3	4	2	2	4	11	20	31	72
P2	2	8	10	1	5	6	4	8	12	3	5	8	1	5	6	2	–	2	3	8	11	3	1	4	5	12	17	76
S3	1	4	5	1	3	4	–	3	3	1	6	7	–	8	8	–	–	0	1	3	4	2	3	5	2	12	14	50
N1	4	8	12	–	5	5	1	2	3	–	1	1	–	6	6	–	1	1	2	8	10	1	10	11	1	12	13	62
N2	6	6	12	–	1	1	1	5	6	–	–	0	–	1	1	–	2	2	–	1	1	–	2	2	2	9	11	36
Total	64	183	247	61	211	272	57	171	228	41	143	184	8	110	118	6	17	23	54	160	214	28	85	113	106	363	469	1868

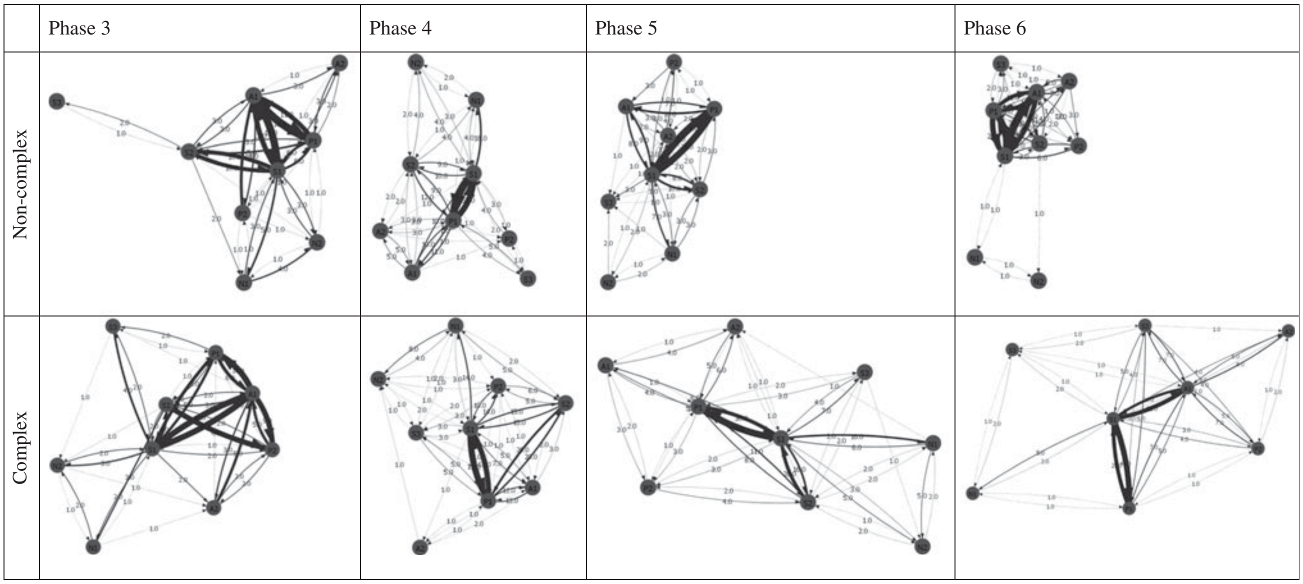


Figure 4. Network plots of phases 3–6 of non-complex and complex procedures.

Due to the criticality associated with complex procedures, we argued that especially during these procedures more specialised knowledge and teamwork would be required. In order to fulfil these requirements, in complex procedures flatter and more decentralised communication structures are needed, which are an indication for teamwork and interdependence (Ahuja and Carley 1999). These assumptions were confirmed. First and foremost, this particular observed medical team adapted its communication behaviour to the degree of complexity of the surgical procedure. Results showed that in complex procedures, the network structures were flatter, enabling higher levels of information sharing. This was reflected by higher density and lower closeness scores in complex procedures. Second, analysis of communication content showed more discussion during complex procedures than during non-complex procedures. Third, frequency of communication events per minute was lower in complex procedures.

These findings are in line with Duncan (1973) who found that teams confronted with complex task requirements need more decentralised communication patterns to be able to be more flexible in problem solving and reciprocal consultancy. Teams that are confronted with complex challenges benefit from spreading knowledge and skills among team members (Arrow and Henry 2010). The intriguing finding that the number of communication events was lower in complex procedures may be explained by the higher workload involved in such procedures, making the team more quiet overall, whilst interspersed with brief bursts of information sharing.

Focusing next on dynamic, within-procedure complexity, one may argue that the transitional phases rather than the action phases are most critical during surgery, resulting in an increase in workload and communication. This is particularly the case when going on and off cardio-pulmonary bypass, the episodes we focused on. Shared SA is required and centralised structures are beneficial as a few individuals can give direct information to other members. We therefore hypothesised that the verbal communication patterns would change according to urgency, particularly at the high-risk transitional processes. According to Balkundi, Barsness, and Michael (2009) and Wolf et al. (2009), dense networks are more able to distribute knowledge and coordinate tasks. However, dense networks may also have the tendency to restrict

Table 6. Metrics of centralisation.

	Non-complex				Complex			
	Phase 3	Phase 4	Phase 5	Phase 6	Phase 3	Phase 4	Phase 5	Phase 6
Density	0.53	0.58	0.59	0.57	0.58	0.68	0.61	0.69
Reciprocity	0.81	0.83	0.72	0.86	0.68	0.89	0.83	0.95
Degree centralisation	0.19	0.16	0.20	0.20	0.27	0.16	0.19	0.22
Betweenness centralisation	0.21	0.17	0.52	0.54	0.19	0.19	0.19	0.32
Closeness centralisation	0.33	0.28	0.53	0.54	0.35	0.22	0.47	0.29

each other in task fulfilment as too many opinions can be constraining. Thus, density should always be considered within the context the team operates in (Wasserman and Faust 1994). Hence, it may be concluded that in the transitional phases in which fast decision-making is required, a less dense team could be beneficial. As a consequence, more team members are probably needed who are able to broker or bridge the information to other team members who are not directly connected to the core team.

The results showed that density and reciprocity were higher in the transition phases than in the action phases (with the effects being more pronounced in the complex than in the non-complex procedures), with the other measures showing little variation across phases. Betweenness centralisation was only higher in transition phase 6, not in transition phase 4, and in particular during complex procedures. This means that in the critical transitional phase 6 (going off CPB), central actors P1, S1 and A1 may control the information flow and the transmission of information. This in turn may lead to higher participation and information sharing (Burt 1992). This pattern of results makes sense, as going off CPB is even more critical than going on CPB, and requires active team participation. Taken together, the results on density and betweenness centralisation indicate higher levels of information sharing during the transition phases than during the action phases. Higher scores on reciprocity indicate more closed-loop communication during transition phases. Again, differences between action and transition phases were more pronounced during complex than during non-complex procedures, confirming overall effects of complexity.

The results thus show that the medical team adapted its team structure and communication behaviour according to the overall degree of task complexity as well as to the degree of dynamic complexity. It seems that the medical team was able to be flexible in the adaptation of communication patterns to the situational demands. The team did not stick rigidly to hierarchical communication but involved the team as a whole in case of overall complex procedures, as well as during critical transitional phases in the surgical procedure. Such findings on the team level could not have been made by using common behavioural rating schemes, analysing the individual team member. These results also further corroborate previous results on the same team reported by Schraagen (2011). As those results were based on a qualitative analysis of a few selected surgical procedures, the current results, covering the complete data-set, quantitatively strengthen the previous results. This study showed that an observation on the team level including all communication events displayed by the team provides a unique insight into the interaction among medical team members in the complex social micro-system of a paediatric cardiac surgical team.

5.1. Theoretical implications

The current research has advanced the understanding of team adaptability in various ways. First, we have captured the adaptation process through quantitative measurement of communication patterns. In this sense, we have begun to unpack the black box of the performance adaptation process, as recommended by Baard et al. (2014). More specifically, it was argued that the mechanisms of the adaptation process should not be phrased in static, componential terms such as ‘situation assessment’, ‘leadership’, ‘diagnosis’ or ‘decision making.’ These are highly abstract concepts that mean different things to different people, as has been noted before (e.g. Rothrock, Harvey, and Burns 2005). Rather, we propose using the refined and quantitative measures well known in SNA to characterise the change of communication processes.

Second, we found that a team, knowing in advance a particular task may be very complex, may anticipate this complexity and adapt its communication processes to involve more team members. Phrased more generally, this particular medical team achieved adaptive and reliable performance by melding bureaucratic communication structures with flexibility-enhancing processes, such as ‘heedful interrelating’ (Schraagen 2011). In this sense, the structure adopted by the medical team resembles a ‘small world network’ (Watts and Strogatz 1998), as it represents a transition region between a fully ordered network and a network that is heavily biased towards one node (*cf.* Stanton, Walker, and Sorenseon 2012). Although the surgeon was arguably the central node, there always was a liaison with either the perfusionist, the anaesthetist, the assisting surgeon and the nurse, or any combination of these. We have shown that these liaisons were in fact stronger during complex procedures and during transitional phases of the procedure.

Team adaptation is best viewed, then, as an emergent phenomenon created from cycles of performance, where individuals utilise resources to meet changing demands (Burke et al. 2006). Resources are recognitional knowledge of typical cue-action patterns, but may also be knowledge of typical communication patterns or ‘protocols’, such as ‘heedful interrelating’ or ‘backup behaviour’. In our previous work, we were able to demonstrate the importance of recognitional knowledge to deal with both routine and non-routine events (Schraagen 2011). At that time, it was not possible to quantitatively demonstrate the importance of protocols, as we had not employed SNA techniques yet. This study, by using these techniques, advanced this knowledge by demonstrating that a team may also adapt to changes in dynamic task complexity by dynamically switching communication processes from hierarchical to flatter structures and vice versa.

5.2. Practical implications, limitations and future research suggestions

This study showed that team research should move beyond general labels of teamwork indications such as ‘leadership’ or ‘situation awareness’. Rather, the focus should be on the adaptive team processes in a given context and at the team level. SNA is a promising approach to match such requirements. SNA enables the analysis of team processes such as real-time communication behaviour at the fine-grained level of the team. In this regard, SNA provides support for the interactive team cognition concept, as the individual performance depends on the network’s structure and vice versa (Cooke et al. 2013).

SNA can be used to narrow team behaviour down to a limited time frame. Such an analysis provides answers to the question of what kind of behaviour was displayed and in which manner within a specific time frame. The conclusions, drawn on such specific results of SNA, can be used for behavioural change and modification according to situational and environmental requirements and could be used, for instance, as a basis for team training through specific interventions (see Schraagen and Post 2014 for an application in the naval domain).

Although the approach of SNA has many advantages, the study is not unbiased and a few limitations should be mentioned. First of all, the SNA of this study was based on observational data, obtained during live sessions that could not all be video-recorded due to privacy considerations. Although the observations were conducted by trained human factors specialists, the observational data could suffer from low inter-rater reliability and subjectivity of the observer (Schraagen et al. 2010). This was countered by establishing a rigorous training programme, based on extensive life observations and structured testing of inter-rater reliability based on video clips of life surgical procedures. Furthermore, live surgical procedures can be characterised by a relatively large team and fast on-going processes and actions. Therefore, it can be argued that some events might have been missed by the observers, particularly as the surgical procedures were not video-taped on all occasions.

Furthermore, data were obtained from one surgical team only. Therefore, the analysis took place within the communication structures of a specific team. A comparison with another team was not possible for practical and financial reasons, and the generalisation of the results will therefore be less strong. The method and procedure for data analysis may, however, be more widely applied to other teams, both in healthcare settings and beyond. As automatic speaker identification techniques become more widely available, identifying who speaks to whom may become easier in the future. As this is the primary input to SNA, and this type of analysis can be automated, feedback of results to the teams may become much faster in the future. This will allow for more specific, targeted feedback and interventions.

Acknowledgements

The authors express their sincere gratitude to the paediatric cardiac surgical team involved for their openness to be observed. In particular, thanks to Ton Schouten, anaesthesiologist, and Felix Haas, surgeon, for their numerous contributions. Thanks also to the TNO observers Josine van de Ven and Dolf van der Beek. We gratefully acknowledge the comments by two anonymous reviewers. This study is based on the first author’s Master thesis in partial fulfilment of the degree of Master of Psychology.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was funded by TNO under the programmes ‘Human Factors in Patient Safety’ (data collection) and the Enabling Technology Program ‘Behaviour and Innovation’ (SNA).

Notes

1. Email: s.barth@utwente.nl
2. Email: m.schmettow@utwente.nl
3. Formally, centralisation is a collective term for various measures on social network structure. The statement made, as well as Figure 1, refers to *degree centralisation*, strictly. See Table 1 for an overview of centralisation measures.
4. A further attempt to use the single Aristotle® score as a scale weight variable revealed no differences compared to the split half method and was therefore omitted for this study.
5. COPYRIGHT (c) 2001–2013 Kathleen M. Carley – Center for Computational Analysis of Social and Organisational Systems (CASOS), Institute for Software Research International (ISRI), School of Computer Science, Carnegie Mellon University, 5000 Forbes Avenue – Pittsburgh, PA 15213-3890 – ALL RIGHTS RESERVED.

References

Ahuja, M. K., and K. M. Carley. 1999. “Network Structure in Virtual Organizations.” *Organisation Science* 10 (6): 741–757. doi:10.1287/orsc.10.6.741.

Alba, R. D. 1982. “Taking Stock of Network Analysis: A Decade’s Results.” In *Research in the Sociology of Organizations*, edited by S. B. Bacharach, 39–74. Greenwich, CT: JAI Press.

Arrow, H., and K. B. Henry. 2010. “Using Complexity to Promote Group Learning in Health Care.” *Journal of Evaluation in Clinical Practice* 16 (4): 861–866. doi:10.1111/j.1365-2753.2010.01500.x.

Artman, H. 2000. “Team Situation Assessment and Information Distribution.” *Ergonomics* 43 (8): 1111–1128. doi:10.1080/00140130050084905.

Artman, H., and C. Garbis. 1998. “Situation Awareness as Distributed Cognition.” In *ECCE 9: Proceedings of the 9th European Conference on Cognitive Ergonomics*, edited by T. R. G. Green, L. Bannon, C. P. Warren, and J. Buckley, 151–156. Le Chesnay: European Association of Cognitive Ergonomics.

Avnet, M. S., and A. L. Weigel. 2013. “The Structural Approach to Shared Knowledge: An Application to Engineering Design Teams.” *Human Factors: The Journal of the Human Factors and Ergonomics Society* 55 (3): 581–594. doi:10.1177/0018720812462388.

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

Balkundi, P., Z. Barsness, and J. H. Michael. 2009. “Unlocking the Influence of Leadership Network Structures on Team Conflict and Viability.” *Small Group Research* 40 (3): 301–322. doi:10.1177/1046496409333404.

Balkundi, P., and D. A. Harrison. 2006. “Ties, Leaders, and Time in Teams: Strong Inference About Network Structure’s Effects on Team Viability and Performance.” *Academy of Management Journal* 49 (1): 49–68. doi:10.5465/AMJ.2006.20785500.

Bavelas, A. 1950. “Communication Patterns in Task-Oriented Groups.” *Journal of the Acoustical Society of America* 22 (6): 725–730. doi:10.1121/1.1906679.

Benham-Hutchins, M. M., and J. A. Effken. 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.

Borgatti, S. P., and M. G. Everett. 2000. “Models of Core/Periphery Structures.” *Social Networks* 21 (4): 375–395. doi:10.1016/S0378-8733(99)00019-2.

Borgatti, S. P., and X. Li. 2009. “On Social Network Analysis in a Supply Chain Context.” *Journal of Supply Chain Management* 45 (2): 5–22. doi:10.1111/j.1745-493X.2009.03166.x.

Borgatti, S. P., A. Mehra, D. J. Brass, and G. Labianca. 2009. “Network Analysis in the Social Sciences.” *Science* 323 (5916): 892–895. doi:10.1126/science.1165821.

Brown, T. M., and C. E. Miller. 2000. “Communication Networks in Task-Performing Groups: Effects of Task Complexity, Time Pressure, and Interpersonal Dominance.” *Small Group Research* 31 (2): 131–157. doi:10.1177/104649640003100201.

Burke, C. S., K. C. Stagl, E. Salas, L. Pierce, and D. Kendall. 2006. “Understanding Team Adaptation: A Conceptual Analysis and Model.” *Journal of Applied Pscyhology* 91 (6): 1189–1207. doi:10.1037/0021-9010.91.6.1189.

Burt, R. S. 1992. *Structural Holes: The Social Structure of Competition*. Cambridge, MA: Harvard University Press.

Burtscher, M. J., and T. Manser. 2012. “Team Mental Models and Their Potential to Improve Teamwork and Safety: A Review and Implications for Future Research in Healthcare.” *Safety Science* 50 (5): 1344–1354. doi:10.1016/j.ssci.2011.12.033.

Burtscher, M. J., J. Wacker, G. Grote, and T. Manser. 2010. “Managing Nonroutine Events in Anesthesia: The Role of Adaptive Coordination.” *Human Factors* 52 (2): 282–294. doi:10.1177/0018720809359178.

Carley, K. M. 1992. “Organizational Learning and Personnel Turnover.” *Organisational Science* 3 (1): 20–46. doi:10.1287/orsc.3.1.20.

Carley, K. M., J. Diesner, J. Reminga, and M. Tsvetovat. 2007. “Toward an Interoperable Dynamic Network Analysis Toolkit.” *Decision Support Systems* 43 (4): 1324–1347. doi:10.1016/j.dss.2006.04.003.

Carley, K. M., and J. Reminga. 2004. *ORA: Organisation Risk Analyzer. CASOS Technical Report* (CMU-ISRI-04-106). Pittsburgh, PA: Carnegie Mellon University.

Carley, K. M., and Z. Lin Lin. 1995. “Organizational Designs Suited to High Performance Under Stress.” *IEEE Transactions on Systems, Man and Cybernetics* 25 (2): 221–230. doi:10.1109/21.364841.

Cooke, N. J., J. C. Gorman, C. W. Myers, and J. L. Duran. 2013. “Interactive Team Cognition.” *Cognitive Science* 37 (2): 255–285. doi:10.1111/cogs.12009.

Cummings, J. N., and R. Cross. 2003. “Structural Properties of Work Groups and Their Consequences for Performance.” *Social Networks* 25 (3): 197–210. doi:10.1016/S0378-8733(02)00049-7.

Diesner, J., T. L. Frantz, and K. M. Carley. 2005. “Communication Networks from the Enron Email Corpus ‘It’s Always About the People. Enron Is No Different’.” *Computational & Mathematical Organization Theory* 11 (3): 201–228. doi:10.1007/s10588-005-5377-0.

Duncan, R. B. 1973. “Multiple Decision-Making Structures in Adapting to Environmental Uncertainty: The Impact on Organizational Effectiveness.” *Human Relations* 26 (3): 273–291. doi:10.1177/001872677302600301.

Espinosa, J. A., and M. A. Clark. 2014. “Team Knowledge Representation: A Network Perspective.” *Human Factors* 56 (2): 333–348. doi:10.1177/0018720813494093.

Everett, M. G., and S. P. Borgatti. 1999. “The Centrality of Groups and Classes.” *Journal of Mathematical Sociology* 23 (3): 181–201. doi:10.1080/0022250X.1999.9990219.

Fischhoff, B. 1975. “Hindsight Is Not Equal to Foresight: The Effect of Outcome Knowledge on Judgment Under Uncertainty.” *Journal of Experimental Psychology: Human Perception and Performance* 1 (3): 288–299. doi:10.1037/0096-1523.1.3.288.

Flin, R., P. O’Connor, and M. Crighton. 2008. *Safety at the Sharp End: A Guide to Non-Technical Skills*. Farnham: Ashgate Publishing Limited.

Freeman, L. C. 1977. “A Set of Measures of Centrality Based on Betweenness.” *Sociometry* 40 (1): 35–41. doi:10.2307/3033543.

Garbis, C., and H. Artman. 1998. “Team Communication and Coordination as Distributed Cognition.” In *Proceedings of 9th Conference of Cognitive Ergonomics: Cognition and Cooperation*, edited by T. Green, L. Bannon, C. Warren and Buckley, 151–156. Limerick: European Association of Cognitive Ergonomics.

Gillespie, B. M., W. Chaboyer, P. Longbottom, and M. Wallis. 2010. “The Impact of Organisational and Individual Factors on Team Communication in Surgery: A Qualitative Study.” *International Journal of Nursing Studies* 47 (6): 732–741. doi:10.1016/j.ijnurstu.2009.11.001.

Goldhaber, G. M. 1993. *Organisational Communication*. New York: McGraw Hill.

Gorman, J. C., N. J. Cooke, and J. L. Winner. 2006. “Measuring Team Situation Awareness in Decentralized Command and Control Environments.” *Ergonomics* 49 (12–13): 1312–1325. doi:10.1080/00140130600612788.

Gutwin, C., and S. Greenberg. 2004. “The Importance of Awareness for Team Cognition in Distributed Collaboration.” In *Team Cognition: Understanding the Factors That Drive Processes and Performance*, edited by E. Salas and S. M. Fiore, 177–201. Washington, DC: APA Press.

Hansen, M. T. 1999. “The Search-Transfer Problem: The Role of Weak Ties in Sharing Knowledge Across Organization Subunits.” *Administrative Science Quarterly* 44 (1): 82–111. doi:10.2307/2667032.

Healey, A. N., and C. A. Vincent. 2007. “The Systems of Surgery.” *Theoretical Issues in Ergonomics Science* 8 (5): 429–443. doi:10.1080/14639220701193314.

Houghton, R. J., C. Baber, R. McMaster, N. A. Stanton, P. Salmon, R. Stewart, and G. Walker. 2006. “Command and Control in Emergency Services Operations: A Social Network Analysis.” *Ergonomics* 49 (12–13): 1204–1225.

Howell, D., C. Windahl, and R. Seidel. 2010. “A Project Contingency Framework Based on Uncertainty and its Consequences.” *International Journal of Project Management* 28 (3): 256–264. doi:10.1016/j.ijproman.2009.06.002.

Kang, S. M. 2007. “Equicentrality and Network Centralization: A Micro–Macro Linkage.” *Social Networks* 29 (4): 585–601. doi:10.1016/j.socnet.2007.07.004.

Katz, D., and R. L. Kahn. 1978. *The Social Psychology of Organisations*. 2nd ed. New York: Wiley.

Kozlowski, S. W. J., S. M. Gully, E. R. Nason, and E. M. Smith. 1999. “Developing Adaptive Teams: A Theory of Compilation and Performance Across Levels and Time.” In *The Changing Nature of Work Performance: Implications for Staffing, Personnel Actions, and Development*, edited by D. R. Ilgen and E. D. Pulakos, 240–292. San Francisco, CA: Jossey-Bass.

Lacour-Gayet, F., D. Clarke, J. Jacobs, J. Comas, S. S. Daebritz, W. W. Daenen, W. W. Gaynor, L. Hamilton, M. Jacobs, and B. Maruszsewski. 2004. “The Aristotle Score: A Complexity-Adjusted Method to Evaluate Surgical Results.” *European Journal of Cardiothoracic Surgery* 25 (6): 911–924. doi:10.1016/j.ejcts.2004.03.027.

Lacour-Gayet, F., D. Clarke, J. Jacobs, W. Gaynor, L. Hamilton, M. Jacobs, B. Maruszewski, M. Pozzi, T. Spray, C. Tchervenkov, and C. Mavroudis. 2004. “The Aristotle Score for Congenital Heart Surgery.” *Pediatric Cardiac Surgery Annual of the Seminars in Thoracic and Cardiovascular Surgery* 7 (1): 185–191. doi:10.1053/j.pcsu.2004.02.011.

Lawrence, P. R., and J. W. Lorsch. 1967. “Differentiation and Integration in Complex Organizations.” *Administrative Science Quarterly* 12 (1): 1–47. doi:10.2307/2391211.

Leavitt, H. J. 1951. “Some Effects of Certain Communication Patterns on Group Performance.” *Journal of Abnormal and Social Psychology* 46 (1): 38–50. doi:10.1037/h0057189.

Manser, T., T. K. Harrison, D. M. Gaba, and S. K. Howard. 2009. “Coordination Patterns Related to High Clinical Performance in a Simulated Anesthetic Crisis.” *Anesthesia & Analgesia* 108 (5): 1606–1615. doi:10.1213/ane.0b013e3181981d36.

Manser, T., S. K. Howard, and D. M. Gaba. 2008. “Adaptive Coordination in Cardiac Anaesthesia: A Study of Situational Changes in Coordination Patterns Using a New Observation System.” *Ergonomics* 51 (8): 1153–1178. doi:10.1080/00140130801961919.

Pfautz, J. D., and S. L. Pfautz. 2009. “Methods for the Analysis of Social and Organizational Aspects of the Work Domain.” In *Applications of Cognitive Work Analysis*, edited by A. M. Bisantz and C. M. Burns, 175–228. Boca Raton, FL: CRC Press.

Rothrock, L., C. M. Harvey, and J. Burns. 2005. “A Theoretical Framework and Quantitative Architecture to Assess Team Task Complexity in Dynamic Environments.” *Theoretical Issues in Ergonomics Science* 6 (2): 157–171. doi:10.1080/1463922042000295678.

Sabidussi, G. 1966. “The Centrality Index of a Graph.” *Psychometrika* 31 (4): 581–603. doi:10.1007/BF02289527.

Salas, E., M. A. Rosen, and D. DiazGranados. 2010. “Expertise-Based Intuition and Decision Making in Organizations.” *Journal of Management* 36 (4): 941–973. doi:10.1177/0149206309350084.

Salas, E., M. A. Rosen, and H. King. 2007. “Managing Teams Managing Crises: Principles of Teamwork to Improve Patient Safety in the Emergency Room and Beyond.” *Theoretical Issues in Ergonomics Science* 8 (5): 381–394. doi:10.1080/14639220701317764.

Salas, E., D. E. Sims, and C. S. Burke. 2005. “Is There a ‘Big Five’ in Teamwork?” *Small Group Research* 36 (5): 555–599. doi:10.1177/1046496405277134.

Salmon, P. M., N. A. Stanton, G. H. Walker, C. Baber, D. P. Jenkins, R. McMaster, and M. S. Young. 2008. “What Really Is Going On? Review of Situation Awareness Models for Individuals and Teams.” *Theoretical Issues in Ergonomics Science* 9 (4): 297–323. doi:10.1080/14639220701561775.

Santos, R., L. Bakero, P. Franco, C. Alves, I. Fragata, and J. Fragata. 2012. “Characterization of Non-Technical Skills in Paediatric Cardiac Surgery: Communication Patterns.” *European Journal of Cardio-Thoracic Surgery* 41 (5): 1005–1012. doi:10.1093/ejcts/ezs068.

Schmutz, J., and T. Manser. 2013. “Do Team Processes Really Have an Effect on Clinical Performance? A Systematic Literature Review.” *British Journal of Anaesthesia* 110 (4): 529–544. doi:10.1093/bja/aes513.

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. doi:10.1080/1464536X.2011.564481.

Schraagen, J. M., T. Schouten, M. Smit, F. Haas, D. van der Beek, J. van de Ven, and P. Barach. 2010. “Assessing and Improving Teamwork in Cardiac Surgery.” *Quality and Safety in Health Care* 19: 1–6. doi:10.1136./qshc.2009.040105.

Schraagen, J. M., and W. M. Post. 2014. “Characterizing Naval Team Readiness Through Social Network Analysis.” In *Proceedings of the Human Factors and Ergonomics Society 58th Annual Meeting*, Chicago, IL, October 27–31, 325–329. Santa Monica, CA: Human Factors and Ergonomics Society.

Schraagen, J. M., M. Huis in 't Veld, and L. de Koning. 2010. "Information Sharing During Crisis Management in Hierarchical vs. Network Teams." *Journal of Contingencies and Crisis Management* 18 (2): 117–127. doi:10.1111/j.1468-5973.2010.00604.x.

Scott, J. 2000. *Social Network Analysis. A Handbook*. 2nd ed. London: Sage Publications.

Stanton, N. A., R. Stewart, D. Harris, R. J. Houghton, C. C. Baber, R. McMaster, P. Salmon, G. Hoyle, G. Walker, M. S. Young, M. Linsell, R. Dymott, and D. Green. 2006. "Distributed Situation Awareness in Dynamic Systems: Theoretical Development and Application of an Ergonomics Methodology." *Ergonomics* 49 (12–13): 1288–1311. doi:10.1080/00140130600612762.

Stanton, N. A., G. H. Walker, and L. J. Sorensen. 2012. "It's a Small World After All: Contrasting Hierarchical and Edge Networks in a Simulated Intelligence Analysis Task." *Ergonomics* 55 (3): 265–281. doi:10.1080/00140139.2011.642006.

Tushman, M. L. 1979. "Work Characteristics and Subunit Communication Structure: A Contingency Analysis." *Administrative Science Quarterly* 24 (1): 82–98. doi:10.2307/2989877.

Valente, T. W., K. Coronges, C. Lakon, and E. Costenbader. 2008. "How Correlated Are Network Centrality Measures?" *Connect (Tor.)* 1 (28): 16–26.

Walker, G. H., H. Gibson, N. A. Stanton, C. Baber, P. Salmon, and D. Green. 2006. "Event Analysis of Systemic Teamwork (EAST): A Novel Integration of Ergonomics Methods to Analyse C4i Activity." *Ergonomics* 49 (12–13): 1345–1369. doi:10.1080/00140130600612846.

Walker, G. H., N. A. Stanton, C. Baber, L. Wells, H. Gibson, P. Salmon, and D. Jenkins. 2010. "From Ethnography to the EAST Method: A Tractable Approach for Representing Distributed Cognition in Air Traffic Control." *Ergonomics* 53 (2): 184–197. doi:10.1080/00140130903171672.

Walker, G. H., N. A. Stanton, P. M. Salmon, D. P. Jenkins, S. Monnan, and S. Handy. 2012. "Communications and Cohesion: A Comparison Between Two Command and Control Paradigms." *Theoretical Issues in Ergonomics Science* 13 (5): 508–527. doi:10.1080/1463922X.2010.544340.

Walker, G. H., N. A. Stanton, R. Stewart, D. Jenkins, L. Wells, P. Salmon, and C. Baber. 2009. "Using an Integrated Methods Approach to Analyse the Emergent Properties of Military Command and Control." *Applied Ergonomics* 40 (4): 636–647. doi:10.1016/j.apergo.2008.05.003.

Wasserman, S., and K. Faust. 1994. *Social Network Analysis: Methods and Applications*. New York: Cambridge University Press.

Watts, D. J., and S. H. Strogatz. 1998. "Collective Dynamics of 'Small-World' Networks." *Nature* 393 (6684): 440–442. doi:10.1038/30918.

Wolf, T., A. Schröter, D. Damian, and T. Nguyen. 2009. "Predicting Build Failures Using Social Network Analysis on Developer Communication." *Proceedings of the 31st International Conference on Software Engineering, Canada* 31: 1–11. doi:10.1109/ICSE.2009.5070503.

Wood, R. E. 1986. "Task Complexity: Definition of the Construct." *Organizational Behavior and Human Decision Processes* 37 (1): 60–82. doi:10.1016/0749-5978(86)90044-0.

Xiao, Y., J. F. Seagull, C. Mackenzie, J. Ziegert, and K. J. Klein. 2003. "Team Communication Patterns as Measures of Team Processes: Exploring the Effects of Task Urgency and Shared Team Experience." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 47 (12): 1502–1506. doi:10.1177/154193120304701228.