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ARTICLE

Naturalistic observations of multiteam interaction networks: Implications for cognition in crisis management teams

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ABSTRACT
Interaction has been recognised as an essential lens to understand how cognition is formed in a complex adaptive team such as a multidisciplinary crisis management team (CMT). However, little is known about how interactions within and across CMTs give rise to the multi-team system's overall cognitive functioning, which is essential to avoid breakdowns in coordination. To address this gap, we characterise and compare the component CMTs' role-as-intended (RAI) and role-as-observed (RAO) in adapting to the complexity of managing informational needs. To characterise RAI, we conducted semi-structured interviews with subject matter experts and then made a qualitative synthesis using a thematic analysis method. To characterise RAO, we observed multi-team interaction networks in real-time at a simulated training environment and then analysed the component CMTs' relative importance using node centrality measures. The resulting inconsistencies between RAI and RAO imply the need to investigate cognition in multiple CMTs through the lens of interaction.

Practitioner summary: When a disaster occurs, multidisciplinary CMTs are expected to serve their roles as described in written or verbal guidelines. However, according to our naturalistic observations of multiteam interaction networks, such descriptions may be (necessary but) insufficient for designing, training, and evaluating CMTs in the complexity of managing informational needs together.

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Crisis management; team cognition; multiteam; network analysis; adaptive coordination

1. Introduction

Natural and human-made disasters in 2019 caused global economic losses of around $133 billion and $7 billion, respectively (Swiss Re 2019). Additionally, the recent coronavirus pandemic (COVID-19) has called attention to biological disasters and their socioeconomic implications (Nicola et al. 2020; World Health Organization 2020). When a disaster occurs, crisis management teams (CMTs), involving multiple disciplines such as firefighting, law enforcement, and emergency medical service, are charged to process relevant information and create effective plans as efficiently as possible (Bharosa, Lee, and Janssen 2010; Bigley and Roberts 2001; Militello et al. 2007). Failing to coordinate within and across CMTs can lead to considerable consequences such as delays in response times and subsequent increases in damages (Bearman et al. 2015; Grunwald and Bearman 2017). For instance, in response to the 2005 Hurricane Katrina—a category three storm—communication and coordination failures occurred among four separate command structures and likely contributed to the estimated damage of $125 billion and 1,833 deaths being larger than it would have otherwise (Gheytanchi et al. 2007).

In investigating several disasters, *team cognition* has been explored as a theoretical foundation to explain why team coordination and performance deteriorate under cognitively demanding environments (e.g. Cooke, Gorman, and Winner 2007; Fiore and Salas 2004; Hutchins 1995). Since the seminal theorisation of team cognition as team member interaction by Cooke and her colleagues (Cooke et al. 2013; Cooke and Gorman 2009), interaction has received growing recognition as an essential lens through which cognition can be assessed in a multidisciplinary CMT (e.g. Gorman et al. 2020). However, to date, little is known about how multiple CMTs from multiple disciplines cognitively function as an integrated system despite their often-limited experience of working together under elevated uncertainty and time pressure (e.g. Fleştea et al. 2017; Moon 2019; Son et al. 2018).

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Given the documented issues related to team communication and alignment in response to Hurricane Katrina, multi-team system (MTS) researchers have highlighted the importance of studying *cognition in multiple CMTs*; they argue that these investigations should consider not only within-team interactions (which occur for a single CMT) but also between-team interactions (DeChurch and Zaccaro 2010; Shuffler, Jiménez-Rodríguez, and Kramer 2015).

To address this gap, this study investigates within-team and between-team interaction as evidence of the MTS's cognitive functioning. The remainder of the introduction explains how this study is grounded theoretically, practically, and methodologically.

1.1. Theoretical background: interaction as a lens

Cognition in teams (Wildman, Salas, and Scott 2014) has been conceptualised as the shared knowledge among team members and/or interactions that enable the knowledge to be shared. Knowledge-based cognition theory's advocates argue that a team should function as an aggregated group of individuals with shared (i.e. overlapped and/or distributed) knowledge structures (Cannon-Bowers and Salas 2001; Mohammed, Ferzandi, and Hamilton 2010). According to the theorists of the *interactive team cognition* (ITC; Cooke et al. 2013), conceptualising the shared knowledge per se (without clarifying the role of interaction in the team's cognitive functioning) may lack practical relevance to the teams working in today's complex collaborative environments, such as CMTs. ITC theorists posit that coordinating information across team members with specified but complementary tasks requires team-level cognitive activity represented in the form of interactions (Cooke et al. 2013). Likewise, coordinating information across multiple and multidisciplinary CMTs in adaptation to the complexity of managing crisis informational needs (referred to as 'adaptive coordination') requires multi-team-level cognitive activities in the form of interactions within and between those CMTs. Therefore, following and expanding the ITC theorists' view, we conceptualise cognition in CMTs as interactions.

In the context of crisis management, ITC research has been motivated by a general interest in assessing the adaptive coordination (Burtscher et al. 2010). This emphasis on adaptive coordination has been reflected in the prevalent use of behaviour observation methodology (e.g. Gorman et al. 2020; Pfaff 2012; Stachowski, Kaplan, and Waller 2009; Uitdewilligen and Waller 2018), the purpose of which is to examine work-as-done (WAD; i.e. 'descriptions of how something is actually done, either in a specific case or routinely') rather than work-as-imagined (WAI; i.e. 'the various assumptions, explicit or implicit, that people have about how work should be done') in response to simulated crisis events (Hollnagel 2017, 10). Such emphasis on adaptive coordination is in line with a recent trend in safety management literature to move from a safety-I approach to a safety-II approach. While a safety-I approach minimises the gap between WAD and WAI, a safety-II approach views WAD's deviation from WAI as a lens to identify positive adaptations and improvisations which can be used to improve work (Hollnagel, Robert, and Jefferey 2015; Hollnagel 2017). Yet, despite the prevalent use of behaviour observation methodology that facilitates WAD characterisations, ITC research has rarely been studied at the multiteam level, in the context of multiple multidisciplinary CMTs.

In summary, according to the ITC theory, a CMT is a cognitive system for which cognition—particularly cognitive WAD with an emphasis on adaptive coordination—needs to be understood through the lens of interaction among the system components. Such understanding is necessary for assessing how multiple CMTs adaptively reorganise themselves for their overall cognitive functioning in today's complex response settings (Moon et al. 2019). Therefore, this study explores the unfulfilled potential of ITC's scalability to a MTS. Our investigation is conducted within a narrowed scope of incident action planning, a specific context where multiple CMTs adapt to each other to manage crisis informational needs.

1.2. Practical background: teams and their roles in incident action planning

Incident action planning is a collective cognitive process to manage informational needs when a large-scale incident occurs with its demands exceeding one jurisdiction or organisation's capabilities. After responding to the 9/11 terrorist attacks (Comfort 2002; Comfort and Kapucu 2006), the Department of Homeland Security launched the national incident management system (NIMS), a standardised approach to converge the efforts of all players involved in the response. Following the NIMS guidelines, incident action planning creates 'a consistent rhythm and structure' for inter-jurisdictional and inter-organisational coordination in response to various types and sizes of incidents; it first establishes an initial understanding of the situation and then repeats the following four phases in each operational period: (1) establish incident objectives, (2) develop an incident action plan, (3) prepare and disseminate the plan, and (4) execute, evaluate, and revise the plan (Federal Emergency Management Agency 2015, 3–5). Such a cyclic nature of incident action planning has been widely acknowledged to provide discipline as well as flexibility in making coordinated decisions.

Our investigation centres around an incident management team (IMT): a specific system of CMTs that collectively adapts to the complexity of incident action planning with the delegated authority to act on behalf of the affected jurisdictions. To provide an incident action plan to the field, multiple and multidisciplinary CMTs comprising an IMT need to coordinate with each other in adaptation to complex and dynamic informational needs. The IMT's staffing size can vary from 12 to over 40 personnel, depending on the incident's scale and severity (Federal Emergency Management Agency 2017). As shown in Figure 1, the IMT is a system comprised of five functionally different component sections (i.e. command, plans, operations, logistics, and finance/admin), each of which is also a system comprised of functionally different component units. Since an ITC investigation requires an operationalizable scope and unit of analysis, we further narrowed our investigation scope to the plans section that gathers, evaluates, and shares various informational needs for the effective and timely provision of objectives and courses of action to be taken. Like the overall IMT, the plans section is also a system of CMTs—namely, info/intel (information/intelligence), situation, and section chief units, each of which is comprised of three to five individuals with multidisciplinary experience, knowledge, and cultural backgrounds to handle divergent information demands.

Driven by the ITC theory, an IMT's plans section with a nested organisational structure can be viewed as *a cognitive system-of-systems* (Maier 1998), and its cognition—particularly cognitive WAD with an emphasis on adaptive coordination—can be assessed through the lens of interaction within and across its component cognitive systems, i.e. info/intel, situation, and section chief units. However, there is a practical gap in understanding the cognitive roles of these units through the lens of interaction.

Overall, an IMT's plans section has been designed and trained around the *functional* role descriptions of its component units and their constituting individuals. The NIMS guidelines, for instance, state that 'when each member plays his or her [functional] part correctly, the [incident action planning] process can bring order to the often-chaotic world of managing complex incidents' (Federal Emergency Management Agency 2015, 6). This study refers to the functional role prescribed through written or verbal forms as *role-as-intended* (RAI). Although the necessity of the RAI descriptions has been acknowledged in designing and training an IMT's plans section, their sufficiency has not been demonstrated through the lens of interaction. This study refers to the behavioural role identified from adaptive self-organising interaction patterns as *role-as-observed* (RAO). Practically, the NIMS guidelines may benefit from an enriched understanding of RAO in addition to RAI. Understanding RAO in addition to RAI (and their deviation) can be viewed as a source of information necessary to improve the role descriptions in the NIMS guidelines and the subsequent design and training of CMTs working in the complex context of incident action planning. This is in line with the safety-II approach that views understanding WAD in addition to WAI (and their deviation) as a source of information to improve work. Put simply, the relationship between RAI and RAO can be analogous to the relationship between WAI and WAD.

Therefore, this study investigates both RAO and RAI of info/intel, situation, and section chief units. We investigate RAO, in particular, by observing the plans section's interactions in real-time at a simulated training environment of incident action planning and building the actual interaction networks of the overall MTS. Our characterisation of each unit's RAO was based on the analysis of centrality measures which quantifies their relative and characteristic importance in the overall network.

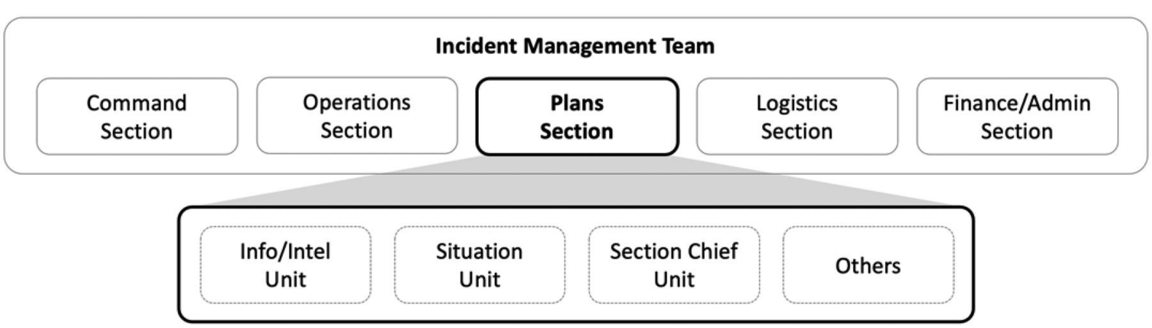


Figure 1. The nested organisational structure of an incident management team (IMT)'s plans section.

1.3. Methodological background: centrality measures in interaction networks

A network refers to 'a set of nodes and the set of ties representing some relationship, or a lack of relationship, between the nodes' (Brass et al. 2004, 795). Network theory has been crucial to conceptualising a complex adaptive system as a network and understanding how system elements' interactions lead to system-level adaptive behaviours or properties (Kolaczyk and Csárdi 2014). One of the most common ways to analyse a complex adaptive system is a descriptive analysis of its network data, i.e. visualising and characterising the properties of nodes, edges, subnetworks, or the overall network as a whole through various numerical summaries.

Teamwork researchers have adopted network theory since at least the 1950s to complement their understanding of team dynamics and processes (Balkundi and Harrison 2006; Brass, Borgatti, and Borgatti 2019). Human factors and ergonomics researchers, in particular, have utilised network theory to investigate adaptive coordination in teams across multiple safety-critical disciplines, including crisis management (e.g. Giordano et al. 2017; Gomes et al. 2014; Klimek et al. 2019), military command and control (e.g. Baber et al. 2013; Houghton et al. 2006; Stanton and Roberts 2020), and healthcare (e.g. Barth, Schraagen, and Schmettow 2015; Salwei et al. 2019). According to a recent review of team network studies between 1994 and 2018 (Park et al. 2020), network theory has been used to investigate constructs at not only the within-team level but also the between-team level (e.g. Heavey and Simsek 2015; Oh, Chung, and Labianca 2004; Shah, Dirks, and Chervany 2006; Sosa, Eppinger, and Rowles 2004; Venkataramani, Richter, and Clarke 2014; Wong 2008; Zaheer and Soda 2009).

With a particular interest in characterising the RAO of info/intel, situation, and section chief units, we used *centrality measures* to quantify each unit's influence over other units and sections. Centrality measures capture the relative importance of system elements (i.e. individual nodes, edges, or subnetworks) in a complex adaptive system (i.e. the overall network as a whole). In other words, centrality measures are important for understanding the system elements' contributing roles for the system's overall cognitive functioning. We used *node centrality measures* to capture the relative importance of each unit in a *coarsened* network where its nodes represent multidisciplinary units/sections and edges represent interactions among them. In the visual representation of the coarsened network, the size of a node represents the unit/section's node centrality, so the unit/section with the highest node centrality can be easily identified by picking the node with the largest size. The thickness of an edge between two nodes represents the frequency of interactions occurring between the two units/sections (that serve as the weights in calculating the node centrality), so the most frequently interacting units/sections can be easily identified by picking the thickest edge.

The importance or influence of a node has different meanings in different types of node centrality measures. Therefore, utilising multiple types of node centrality measures informs the characterisation of the component units' RAO for the plans section's overall cognitive functioning. Our investigation is centred around four classic types of node centrality measures that quantify which nodes are more 'central' or 'important' than other nodes in a network: *degree*, *closeness*, *betweenness*, and *eigenvector* centrality measures (Kolaczyk and Csárdi 2014; Newman 2010). The *degree* centrality of a node captures how involved the node is in its embedded network, which can be measured as the number of nodes it's connected to (called neighbour nodes). The *closeness* centrality of a node captures how close the node is to many other nodes in its embedded network, which can be measured as the inverse sum of its shortest distances to all other nodes. While degree centrality considers only the local structure of a network (only the neighbour nodes), closeness centrality considers the global structure of a network to see how quickly a node of interest can reach other nodes and access their information. The *betweenness* centrality of a node captures how controlling the node is over the flow (e.g. communication flow) between other pairs of nodes in its embedded network, which can be measured as the number of times the node is sitting on the shortest paths between other pairs of nodes. The *eigenvector* centrality of a node captures how influential the node is in its embedded network, which can be measured as the relative score of the node assigned proportionally to the sum of its neighbour nodes' relative scores. The more influential its neighbour nodes are, the more influential the node itself is. Table 1 shows the centrality measures' definitions and associated equations for normalised calculation.

2. Method

We used mixed methods to characterise and compare the component units' RAI and RAO for the plans section's overall cognitive functioning. To characterise RAI, we reviewed the NIMS guidelines, conducted semi-structured interviews with subject matter experts, and then made a qualitative synthesis using a thematic

Table 1. Centrality measures used to characterise the role-as-observed (RAO) of multidisciplinary units.

Types	Definitions and interpretations	Associated equations for normalised calculation
Degree centrality	• The number of its connected nodes (called neighbour nodes) • HOW involved the node is in its embedded network (considering only the local structure, i.e. the neighbour nodes)	$d_i = \frac{1}{2(n-1)}\sum(d_i^{in} + d_i^{out})$ i = the index for the node of interest d_i = the degree centrality of i d_i^{in} = the number of edges pointing in towards i d_i^{out} = the number of edges pointing out from i n = the total number of nodes
Closeness centrality	• The inverse sum of its shortest distances to all other nodes • How close the node is to many other nodes in its embedded network (considering the global structure) • How quickly a node of interest can reach other nodes and access their information	$c_i = \frac{n-1}{\sum_{j\in N} shortest_{distance}(i,j)}$ i = the index for the node of interest c_i = the closeness centrality of i n = the total number of nodes N = the set of all nodes j = the index for other nodes $\in N$ shortest_distance (i, j) = the geodesic distance between i and j
Betweenness centrality	• The number of times the node is sitting on the shortest paths between other pairs of nodes • How controlling the node is over the flow (e.g. communication flow) between other pairs of nodes in its embedded network	$b_i = \frac{2}{(n-1)(n-2)}\sum_{i\neq s\neq t\in N}\frac{num_{shortest}path(s,t\|i)}{num_{shortest}path(s,t)}$ i = the index for the node of interest b_i = the betweenness centrality of i n = the total number of nodes N = the set of all nodes s = the index for the source node $\in N$ t = the index for the target node $\in N$ num_shortest_path (s, t | i) = the total number of shortest paths between s and t that pass through i num_shortest_path (s, t) = the total number of shortest paths between s and t (regardless of passing through i)
Eigenvector centrality	• The relative score of the node assigned proportional to the sum of the relative scores of its neighbour nodes • How influential the node is in its embedded network • The more influential its neighbour nodes are, the more influential the node itself is	$e_i = \alpha\sum_{\{i,\ j\}\in N} e_j$ i = the index for the node of interest e_i = the eigenvector centrality of i n = the total number of nodes N = the set of all nodes j = the index for the neighbour nodes (connected to i) α^{-1} = the largest eigenvalue of A (satisfies $Ax = \alpha^{-1}x$) A = the adjacency matrix for the network x = the corresponding eigenvector

Note. Equations modified from Bonacich 1972; Katz 1953; Kolaczyk and Csárdi 2014; and Sabidussi 1966. The centrality values are normalised to lie in the interval [0, 1].

analysis method. To characterise RAO, we observed multiteam interaction networks in real-time at a simulated training environment of incident action planning and then analysed the component CMTs' relative importance using node centrality measures. This section describes our research settings (2.1), participants (2.2), protocols to collect (2.3) and analyse (2.4) data for the characterisation of RAI and RAO, and then protocols to compare those characterisations (2.5).

2.1. Research settings

Our study took place in a high-fidelity testbed named the Emergency Operations Training Center (EOTC) at the Texas A&M Engineering Extension Service. The EOTC is a training facility sponsored by the Federal Emergency Management Agency for the educational delivery of the NIMS guidelines and skills necessary to respond to and recover from various kinds of large-scale incidents. The EOTC creates a realistic representation of an IMT due to its functional and physical resemblance to the actual incident action planning circumstances.

The EOTC functionally replicates an IMT by providing highly sophisticated scenario-based training simulations. The EOTC provides up to two training courses per month, each of which accommodates 40–45 trainees with years of multidisciplinary backgrounds—e.g. firefighting, law enforcement, and emergency medical service—to form a realistic IMT. Each training course takes about 3.5 days, including four (three half-day and one full-day) scenario-based simulation exercises and two half-day lectures at the beginning and end of the course. Typically, the EOTC provides a different combination of those four scenarios per training course, ranging from an earthquake, tornado, city disturbance, or university shooting, to football stadium terrorist attack. Each scenario-based simulation exercise has more than 200 computer-based injects (e.g. requesting resources, feeding unvetted informational input regarding situational changes or predictions) that can unexpectedly stimulate trainees' interactions for adaptive coordination.

The EOTC physically replicates the layout configuration of a common IMT facility established at an incident command post or an emergency operations centre. As shown in Figures 2 and 3, the EOTC has nine compartmental areas with the associated real-world tools in place: five station areas, two meeting room areas, one classroom area, and an overlooking area. The (five) station areas are designated for the IMT's (five) component sections, reflecting the nested organisational structure of an IMT. In each station area, 10–12 trainees take their designated sitting area per assigned roles, equipped with laptops, desktop computers, paper forms, radios, landline phones, microphones, personal cellphones, printers, fax/copy machines, and whiteboards. Those five station areas are located together in a large open area so that trainees from the five sections can move around easily when needed. Two meeting room areas are designed to conduct meetings between the cyclic phases of incident action planning and hold conference calls with jurisdictional authorities. One classroom area is used for holding incident briefings at the beginning and the end of a simulation exercise. Three large displays are used to provide real-time information necessary for the entire IMT, such as geographical maps, event logs, weather, and media reports. Lastly, the overlooking area is designed for instructors playing roles outside the IMT (e.g. mayor, field observer, group supervisor) to provide computer-injected information to downstairs in real-time using the computer simulation software specifically developed for the EOTC—called Emergency Management*Exercise System.

To reiterate, as shown in Figure 4, an IMT has a nested organisational structure that can be mapped into ten operationalizable system components, the first five of which belong to a plans section which was the focus of this research: info/intel unit (C1, labelled in yellow), situation unit (C2, labelled in red), section chief unit (C3, labelled in blue), instructor unit (C4), others unit (C5), command section (C6), operations section (C7), logistics section (C8), finance/admin section (C9), and non-IMT (C10).

2.2. Participants

To characterise RAI, semi-structured interviews were conducted with instructors at the EOTC. In each monthly training course at the EOTC, two out of 18–21 instructors are designated to guide the individuals in plans sections throughout four different incident

Figure 2. Birds-eye view of the EOTC during a scenario-based training simulation.

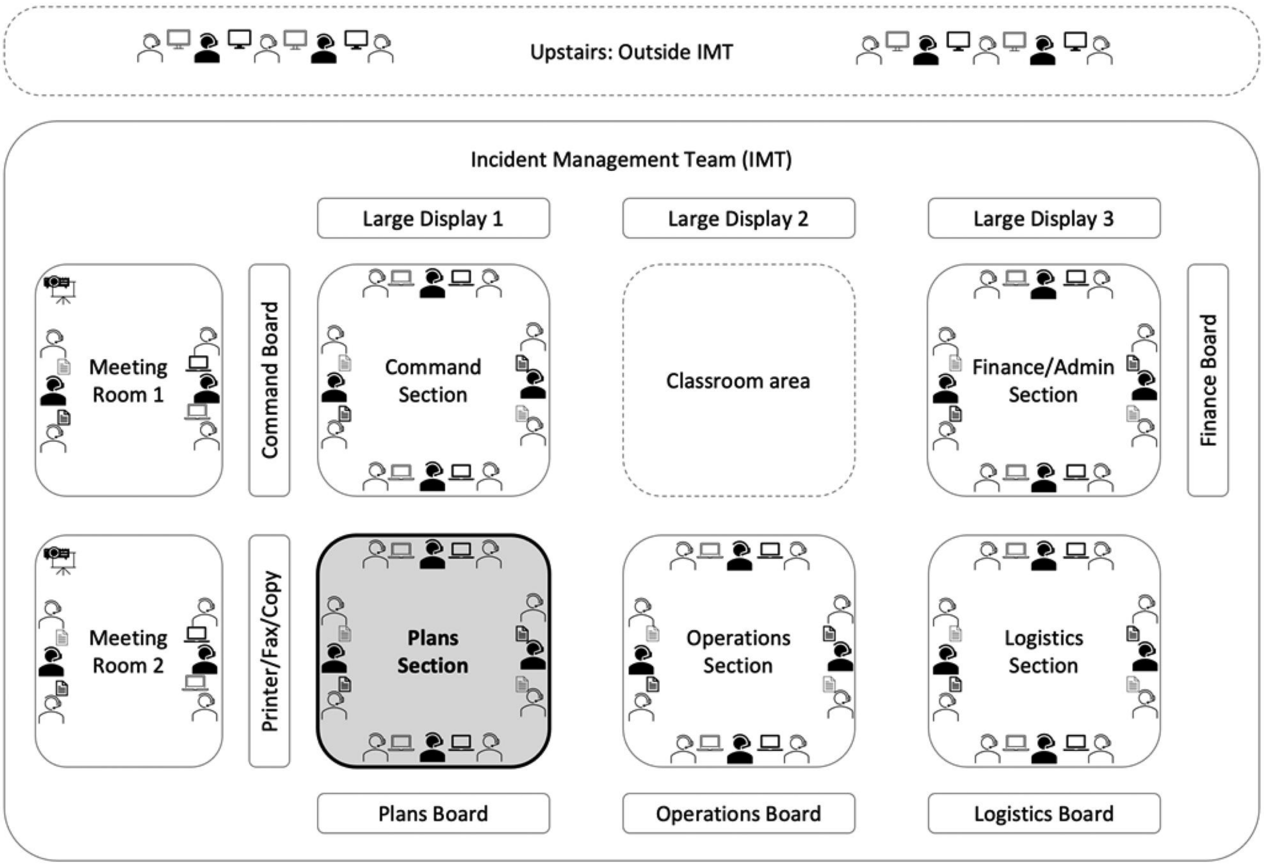


Figure 3. Physical layout of the EOTC during a scenario-based training simulation.

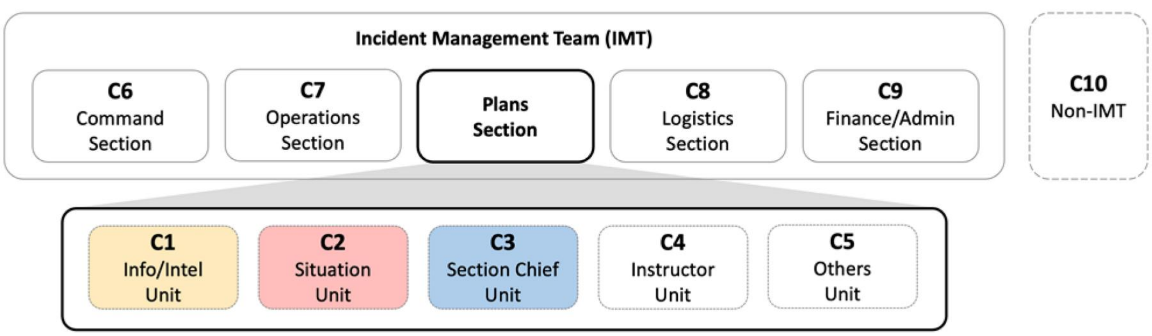


Figure 4. Nested organisational structure of an IMT's plans section in the EOTC environment: info/intel unit (C1, yellow), situation unit (C2, red), section chief unit (C3, blue), instructor unit (C4), and others unit (C5).

scenario-based exercises. Those instructors qualify as subject matter experts of the responsibilities and functions of an IMT's plans section due to their years of practical experience in the complex process of incident action planning as well as teaching experience specifically in the EOTC environment. Thus, we specifically targeted four instructors responsible for training the trainees in plans sections during two monthly training courses at the EOTC. As a result of such targeted recruiting, we recruited three out of those four instructors. The average age of the subject matter experts (all male) was 65 (SD = 0.8, MIN = 64, MAX = 66). The average overall length of their career in emergency service was 35.3 years (SD = 2.9, MIN = 32, MAX = 39) and the average overall length of their career in emergency training was 19.3 years (SD = 14.8, MIN = 6, MAX = 40). All three subject matter experts consented to participate in the current study, as approved by the authors' institutional review board [IRB No. 2016-0489D].

To characterise RAO, we recruited participants on the first day of two separate training courses in June and August 2017. In total, 39 out of 44 (the first course) and 32 out of 46 (the second course) trainees consented to participate in the current study, as approved by the authors' institutional review board [IRB No. 2016-0489D]. The recruited participants had multidisciplinary experience, knowledge, and cultural backgrounds. For instance, the 46 participants in the second training course came from the following disciplines: fire service (15), law enforcement (14), emergency management (7), public works (3), public health (2), public safety communications (2), transportation security (2), and emergency medical services (1). Although we observed all four scenarios offered by each course, only the third scenario is included in this study to minimise potential training effects since the same group of participants was trained throughout the four consecutive scenarios. Also, the third scenario for both courses was regarding the same incident, i.e. a tornado hitting a city named 'Needland'. Henceforward, we will refer to the observation of the third scenario in those two courses as the first and second observations.

2.3. Protocols to collect data for the characterisation of RAI and RAO

To characterise RAI, we interviewed three targeted subject matter experts (i.e. three recruited out of the four instructors responsible for training the trainees in plans sections during two monthly training courses at the EOTC). Two separate interviews took place at the EOTC in May 2019, i.e. one interview with a group of two instructors altogether and another interview with an individual instructor. Each interview took about 60–80 minutes, and we placed it on the last day of the monthly training, immediately after all the training duties, so that the instructors could share their training experience while their memories were reliable. Two graduate students (JM and CS) prepared, facilitated, and audio-recorded those interviews. To be specific, they designed a semi-structured interview protocol to cover the subject matter experts' understanding of a plans section's role. Before the interviews, those graduate students were able to discuss the interview questions and relevant themes through multiple rounds of preparation meetings under the advisement of two faculty members. The preparation meetings were held every week for a semester with both graduate students and their two faculty advisors. Table 2 shows an example question (the one related to this specific study) and its relevant themes. Additional questions were asked only when further clarification was needed. Note that Appendix Table A1 lists example questions and themes for an additional topic out of our scope in this study (i.e. the current practice of evaluating a plans section's performance as a whole); yet we elicited the subject matter experts' understanding of the topic to provide insights on future research agenda.

To characterise RAO, each individual of a plans section was shadowed by a trained observer for the ease of real-time coding of interactions with time-tracking. Interactions were documented using the 3-Cs taxonomy (Sasangohar 2015): who initiated interaction with whom using which technology (*contexts*), when and for how long (*characteristics*), and for what actions or conversations (*contents*). Table 3 shows the finalised codebook for the first two Cs (contexts and characteristics). Note that the third C (contents) remains out of our scope in this study, yet we audio- and video-recorded the interactions (while shadowing and coding them in real-time) for the retrospective and qualitative coding of their transcribed contents in the future. To collect data on the 2-Cs of interaction, we developed a codebook based on our pilot observations and subject matter experts' feedback. During the pilot observations, two graduate students (JM and CS) made a list of potential initiators, receivers, and mediating technologies of interaction at the EOTC. The first column of Table 3 lists potential initiators and receivers such as the members of the five sections and field observers. Additionally, the first column lists other options such as observer breaks, working alone, and meetings. The research team decided to add those options so that the shadowing observers can take a break (the 'observer break' option) and make a note when their target participant is participating in a meeting (the 'meeting' option) or not interacting (the 'working alone' option). The second column of Table 3 lists potential mediating technologies such as paper form, computer, and whiteboard. Additionally, the second column lists non-technology options such as face-to-face and working alone. The research team decided to add those options so that the shadowing observers could make a note when their target

Table 2. Example questions and relevant themes covered in the semi-structured interviews with subject matter experts.

Topic	Example question	Relevant themes
Role of a plans section	Can you tell us about the role of a plans section and its three component units: info/intel, situation, and section chief units?	Role of info/intel unit (C1) Role of situation unit (C2) Role of section chief unit (C3)

Table 3. Codebook for the real-time coding of interactions' contexts and characteristics.

Contexts		Characteristics
(a) Who initiated (b) with whom	(c) Using which technology	(d) When and for how long
Observer break	Face-to-face (No tech)	Start time
Working alone	Working alone (No tech)	End time
Meeting	Paper form	
Group supervisor	Whiteboard	
Field observer	Large display (Screen)	
Mayor	Mic (Announcement)	
EOC manager	Personal cellphone	
Staging	Computer	
Planning section members	Telephone	
Command section members	Radio	
Operations section members	Printer	
Logistics section members	Copy machine	
Finance/Admin section members	Fax	
	Others	

Note. Referred to as (a) initiator; (b) receiver; (c) technology; (d) timestamps in Figure 5.

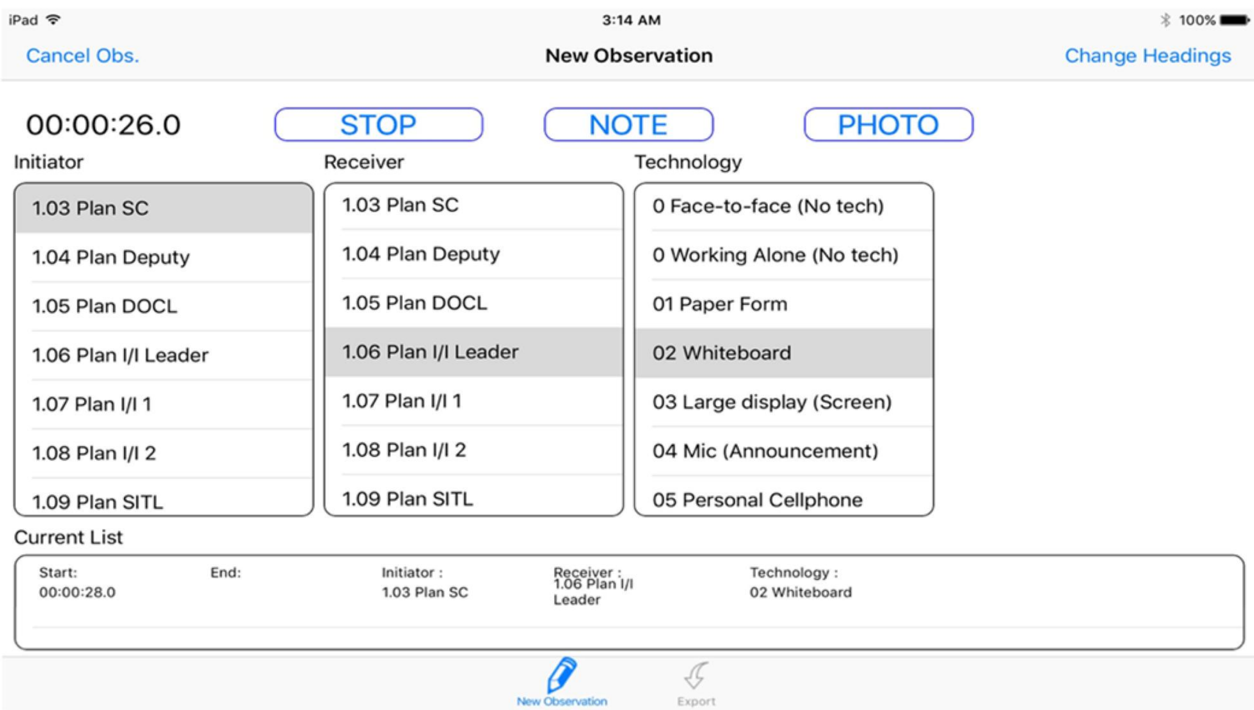


Figure 5. Example screenshot of the DELTA iPad-based tool used for real-time coding of interactions.

participant was not using any technology while interacting with others (the 'face-to-face' option) or working alone (the 'working alone' option). To finalise this codebook, the research team asked for the feedback of subject matter experts, i.e. two instructors assigned to the plans section during the pilot observations. The experts were asked to check if the options are collectively exhaustive so that shadowing observers can cover all potential interactions of the plans section members.

This codebook was reflected in the dynamic event logging and time analysis (DELTA) iPad-based tool. The DELTA app allows creation of codes for multiple categories and enables selecting and creating time-stamped and parallel events in real-time (Sasangohar 2015). Figure 5 illustrates an example screenshot of the DELTA app with three columns to code the contexts of interactions (i.e. cognitive system components, (a) initiator, (b) receiver, and (c) technology) and an automatically created list of timestamps to code the characteristics of interactions (i.e. (d) starting and ending timestamps which will be later used to calculate the frequency and duration of interactions).

For the ease of real-time coding of interactions using the DELTA app, we trained the observers, i.e. two graduate and five undergraduate students under the advisement of two faculty members. Those seven observers participated in two inter-coder reliability training

Table 4. Functional roles in an IMT's plans section and their shadowing assignment.

Units	ID	Functional roles	Shadowing observer assigned	
			1st obs.	2nd obs.
C1: Info/intel unit	P1	Info/Intel Unit Leader	✓	✓
	P2	Info/Intel Agent 1	✓	
	P3	Info/Intel Agent 2		✓
C2: Situation unit	P4	Situation Unit Leader	✓	✓
	P5	Situation Log		✓
	P6	Situation Map		
C3: Section chief unit	P7	Plans Section Chief		✓
	P8	Deputy Plans Section Chief	✓	✓
	P9	Documentation Leader		
C4: Instructor unit	P10	Plans Section Instructor 1	✓	✓
	P11	Plans Section Instructor 2		
C5: Others unit	P12	Resource Leader		
	P13	Resource Status Check-in		
	P14	Incident Command System (ICS) 209		
	P15	Demobilisation		

Note. An empty cell in P1–P9 indicates that the person did not consent for participation.

sessions, each taking about two hours, where each observer coded a training episode independently using pilot data. Inter-coder agreement ratios were 72% and 74% for the first and second training sessions, respectively. Then the group of observers compared the codes and reached a consensus through discussion.

Table 4 shows which functional roles were shadowed for the first and second observations. In this study, we are particularly interested in the role of three major component units for the plans section's overall information processing capability in the EOTC environment: the info/intel unit's leader and two other agents (P1, P2, and P3), the situation unit's lead, log, and map (P4, P5, and P6), and the section chief unit's chief, deputy chief, and documentation lead (P7, P8, and P9). With a given priority to the info/intel (C1), situation (C2), and section chief (C3) units of a plans section, the specific roles shadowed were ultimately determined based on whether the participants in those three units had consented to participate in the study (i.e. P1–P9 in Table 4). The instructors (P10 and P11) guide other individual members' learning throughout the complex process of incident action planning. The others unit's resource lead and status check-in (P12 and P13) track the location, status, and organisation of resources including personnel. The others unit's ICS 209 (P14) makes an incident status summary while demobilisation (P15) develops a plan for demobilising resources. The total number of shadowing observers was five in the first observation and seven in the second observation.

2.4. Protocols to analyse data for the characterisation of RAI and RAO

To characterise RAI, we processed and (qualitatively) analysed the audio-recorded interview data. The audio recordings were first transcribed using artificial intelligence-based speech recognition and transcription service (Temi 2018). Then, one of the graduate students (JM) conducted an open coding of the transcripts as a single coder and made a qualitative synthesis around the themes (Braun and Clarke 2006). For our major question 'can you tell us about the role of a plans section and its three component units: info/intel, situation, and section chief units?,' we made a qualitative synthesis about RAI around three deductive themes: the role of info/intel unit (C1), the role of situation unit (C2), the role of section chief unit (C3).

To characterise RAO, we processed and (quantitatively) analysed the observed interaction data. The DELTA-recorded interactions were first extracted in .csv file formats. Each observer resulted in one output file for each scenario. Then, one of the graduate students (JM) integrated the output files for all observers and for all four scenarios (per observation) to gain aggregated insights. JM also processed the integrated output files to be translated into the form of network nodes and edges. Two original networks were created from the DELTA-recorded interactions of the first and second observations (Sasangohar 2015; Son, Sasangohar, Neville, et al. 2020). Those original networks represent an IMT operating in the EOTC environment, with nodes representing individual IMT members (their roles as listed in Table 4) and edges representing real-time interactions among the individual members. Before calculating network centrality measures, we mapped those two original networks that represent interactions among 54 individual IMT members into two coarsened networks that represent interactions among ten operationalizable system components (labelled as C1-C10 in Figure 4). In a *coarsened* network of an IMT, nodes represent those ten system components and edges represent interactions within and across them.

Five different R packages (i.e. *sand, igraph, network, sna,* and *tnet*) were used to build and visualise those two coarsened networks (Kolaczyk and Csárdi 2014; Newman 2010). Then, four different types of node centrality measures (explained in Table 1) were calculated and compared among the nodes—particularly among info/intel unit (C1, yellow), situation unit (C2, red), and section chief unit (C3, blue)—to characterise their relative importance. For ease of comparison among the nodes, we visualised their four different node centrality values in four radial layouts, for each observation (i.e. for each coarsened network). In a radial layout, the proximity to the centre means higher centrality.

2.5. Protocols to compare the characterisation of RAI and RAO

We used different sources of information to characterise RAI and RAO. Using documents and interviews as sources of information, RAI was characterised in the form of verbal descriptions. Using real-time interactions as sources of information, RAO was characterised in the form of network centrality measures. Thus, it is not straightforward to compare them.

To facilitate the comparison of RAI and RAO, we put an additional step of reformulating the verbally described RAI in terms of node centrality measures (using their definitions and interpretations; see Table 1).

- Info/intel unit (C1) is expected to serve as *an information collector (or 'worker bee' that validates the contextual appropriateness of information)*, and this would be evidenced by C1 having a higher degree and closeness centrality than other units.
- Situation unit (C2) is expected to serve as *an information controller (or 'bridging broker' that pushes out the validated and projected information to the rest of the IMT)*, and this would be evidenced by C2 having higher betweenness centrality than other units.
- Section chief unit (C3) is expected to serve as *an information integrator (or 'in-between negotiator' that facilitates cross-sectional meetings to finalise incident objectives and courses of actions to be taken)*, and this would be evidenced by C3 having higher eigenvector centrality than other units.

The reformulated RAI characterisations served as *the expectations about RAO*, under our assumption that 'RAO would adhere to RAI (i.e. the observed roles would align with the prescribed roles)'. Since the expectations about RAO were in the form of network centrality measures, they can be directly compared with the characterisation results of RAO from the network analysis of real-time interactions. If the expectations about RAO turned out to be supported by the characterisation results of RAO, then we could conclude that our assumption was supported (i.e. RAI and RAO were indeed consistent). Otherwise, we could confirm the existence of inconsistencies between RAI and RAO. With this additional step, comparing RAI and RAO became more straightforward.

3. Results

To facilitate the comparison of RAI and RAO, we put an additional step of interpreting the verbal characterisation results of RAI (shown in Section 3.1) into a comparable format. Section 2.5 presents this additional step of formulating expectations about RAO regarding node centrality measures, assuming that RAO would adhere to RAI. Section 3.2 examines this assumption by checking if the expectations about RAO align with the characterisation results of RAO from the network analysis of real-time interactions. Their alignment would mean that our assumption was supported, i.e. RAI and RAO were indeed consistent. Overall, the findings demonstrated their misalignment and confirmed the existence of inconsistencies between RAI and RAO.

3.1. Characterisation of RAI

To characterise RAI, two sources were evaluated: (1) the written descriptions from the NIMS guidelines (Federal Emergency Management Agency 2017, 91–99) and (2) the verbal excerpts from the subject matter experts' interviews. Overall, the subject matter experts' understanding of the roles of three major component units (i.e. C1: info/intel, C2: situation, and C3: section chief units) at the EOTC environment was mostly aligned with the NIMS guidelines (Table 5 for selected excerpts and quotes).

Info/intel unit (C1) was described as the 'eyes and ears' of a plans section and was responsible for collecting and validating information mostly from outside of the plans section and eventually delivering the validated information (i.e. intelligence) back to the plans section, especially to a situation unit so that it can be pushed out to the entire IMT if needed. This way, the info/intel unit contributes to the entire IMT by

Table 5. Characterisation of RAI as prescribed in written or verbal forms.

Units	RAI from the NIMS guidelines	RAI from the interviews
C1: Info/intel unit	'… Enhances the [Plans] section's normal information collection and analysis capabilities. It [Info/Intel unit] helps ensure that investigative information and intelligence is integrated into the context of the overall incident management mission' (p.99)	• 'Main responsibility is collecting information and validating it and making sure it's good information.' • 'The eyes and ears for a plans section. Their job is to gather as much information around the room and bring that back to situation unit leader.' • 'Their primary purpose is to get their hands on all that information, vet it and investigate it and transition only the appropriate ones to true intelligence. And that's what gets pushed out to the rest of the team.'
C2: Situation unit	'… Collect, process, and organise situation information, prepare situation summaries, and develop projections and forecasts related to the incident. They [Situation unit members] gather and disseminate information for the incident action planning. This unit produces Situation Reports (SITREP) as scheduled or at the request of the Planning Section Chief or Incident Commander' (p.92)	• 'A situation unit would oversee everybody in the plans section, monitor them, and help them what they can do. Tries to manage those people.' • 'Makes sure that something valid to be put on the map, so that when people come in, they can look at the event log and bring themselves up to speed.' • 'Goes into meetings with the plans section chief and the other section chiefs to update them on what's going on and to give them the most recent information in hand.'
C3: Section chief unit	'… Oversees incident-related data gathering and analysis regarding incident operations and assigned resources, facilitates incident action planning meetings, and prepares the IAP for each operational period. … [The section chief] normally comes from the jurisdiction or organisation with primary incident responsibility and may have one or more deputies who may come from other participating jurisdictions or organizations' (p.91)	• '[Section chief is] the orchestra leader and the orchestra are the members. Primary function is to get that team through the planning process in the time allotted for the operational period.' • 'Responsible for running the meetings, an objectives meeting, a tactics meeting, and then a plans meeting. Primary function is to make sure that all meetings are on time and that people are there when needed to be there.' • 'While the team works at managing the incident, the planning section chief works at managing, getting the team through the planning process with the ultimate outcome being an incident action plan by the beginning of the next operational period.'

Note. NIMS guidelines extracted from (Federal Emergency Management Agency 2017, 91–99).

delivering the current common operating picture and updating how such a picture may have changed over time. The info/intel unit also evaluates the discrepancy or potential inconsistencies in the information posted on the five sections' whiteboards.

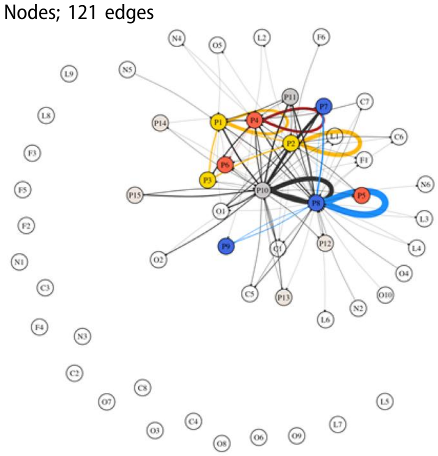
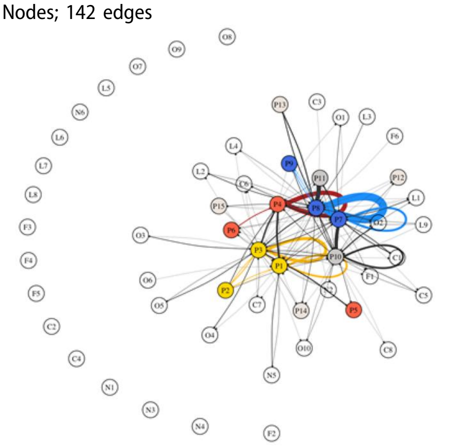
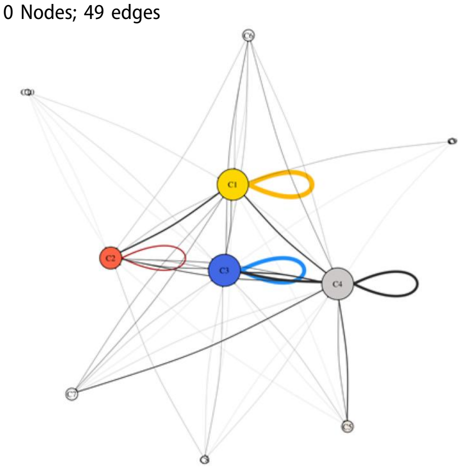
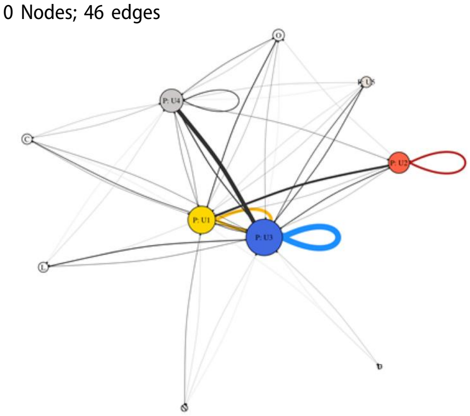
Situation unit (C2) was described as the entity *'overseeing'* the information flow into, and out of the plans section. The situation unit also shares the validated and the most updated information with the plans section members and the entire IMT to manage and help them get up to speed. To do so, the situation unit selects important information to be shared (among the information validated and conveyed by info/intel unit) and then posts the selected ones on the shared area visible to the rest of the IMT, e.g. event log, map, and whiteboard. A situation unit leader attends several meetings (i.e. objectives, tactics, and planning meetings) to share the most recent information-at-hand with the (five) section chiefs, expecting the shared information to serve as the basis upon which coordinated decisions can be made during the meetings.

The section chief unit (C3) was described as the 'leader (director) of an orchestra'—i.e. the leader of not only a plans section but of the entire IMT—with its chief responsibility being to lead the team through the complex process of incident action planning to secure the ultimate outcome (an incident action plan) by the beginning of the next operational period. While the IMT works at managing an incident, the section chief unit works at managing the IMT itself. To do so, the section chief unit ensures that all meetings (i.e. objectives, tactics, and planning meetings) run smoothly on time and that all the people needed to be in the meetings are present. At the EOTC, a plans section chief is often located in one of the meeting rooms to prepare and facilitate the meetings; in the meantime, a deputy plans section chief stays outside the meeting room and controls any issues coming up on the floor, particularly what's happening in the plans section.

3.2. Characterisation of RAO

To characterise RAO using the node centrality measures, two multiteam interaction networks were created from the first and second observations. From the DELTA-recorded real-time interactions among 54 individuals, two original networks were built with 121 and 142 edges for the first and second observations,

Table 6. The original and coarsened networks of real-time coded interactions based on degree centrality.

	First observation	Second observation
(a) Original network	54 Nodes; 121 edges 	54 Nodes; 142 edges 
(b) Coarsened network	10 Nodes; 49 edges 	10 Nodes; 46 edges 
Colour legend	C1: Info/intel unit C2: Situation unit C3: Section chief unit C4: Instructor unit C5: Others unit	C6: Command section C7: Operations section C8: Logistics section C9: Finance/admin section C10: Non-IMT

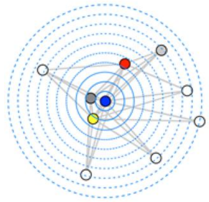
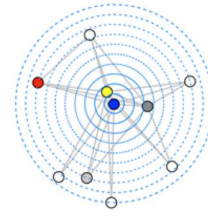
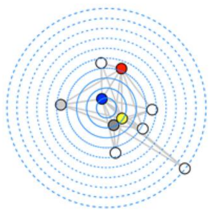
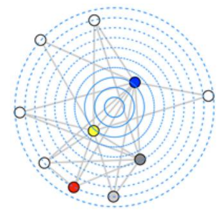
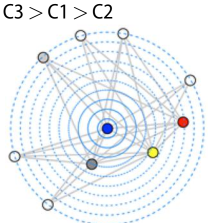
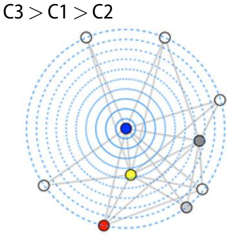
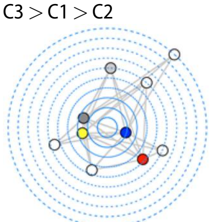
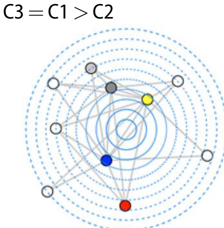
Note. The size of a node represents the node's degree centrality.
Note. The thickness of an edge between two nodes represents the frequency of interactions connecting the same nodes.

respectively. Those original networks were then mapped into two coarsened networks among the ten system components (labelled as C1–C10 in Figure 4) with 49 and 46 edges for the first and second observations, respectively. Coarsened networks effectively illustrated what subject matter experts referred to as the 'rainbow effect'—i.e. how the plans section members (whom the observers shadowed) interacted within as well as across their own units and sections. Table 6 visualises both original and coarsened networks for the first and second observations.

For both types of networks in Table 6, the size of a node represents the node's degree centrality, and the thickness of an edge between two nodes represents the frequency of interactions connecting the same nodes. That is, multiple interactions among the same nodes will increase the thickness (weight) of the connecting edge. For instance, the section chief unit (C3; labelled in blue) is depicted with the largest node size (which refers to the highest degree centrality) in the second observation's coarsened network.

Next, we checked the expectations about RAO using four different node centrality measures of two coarsened networks. Table 7 shows the radial layouts of the coarsened network's ten nodes based on their node centrality measures calculated for the first and second observations. As explained earlier in Table 1, the centrality measures were calculated based on the number of edges, and the values were normalised to lie in the interval [0, 1]. In radial layouts in Table 7, a node's proximity to the centre represents its centrality compared to other nodes.

Table 7. Node centrality values of the 10 cognitive system components and their radial layouts.

First observation			Second observation		
Nodes	Degree	Radial layout	Nodes	Degree	Radial layout
C3	**0.944**	C3 > C1 > C2 	**C3**	**1.000**	C3 > C1 > C2 
C4	0.833		**C1**	**0.889**	
C1	**0.778**		C4	0.722	
C2	**0.611**		C7	0.389	
C6	0.389		**C2**	**0.333**	
C5	0.333		C5	0.333	
C7	0.333		C6	0.333	
C8	0.333		C8	0.278	
C10	0.278		C10	0.222	
C9	0.167		C9	0.167	
Nodes	Closeness	Radial layout	Nodes	Closeness	Radial layout
C3	**1.000**	C3 > C1 > C2 	**C3**	**1.000**	C3 = C1 > C2 
C1	**0.900**		**C1**	**1.000**	
C4	0.900		C4	0.818	
C2	**0.643**		**C2**	**0.600**	
C6	0.643		C5	0.600	
C5	0.600		C6	0.600	
C7	0.600		C7	0.600	
C8	0.600		C8	0.563	
C10	0.600		C10	0.563	
C9	0.000		C9	0.529	
Nodes	Betweenness	Radial layout	Nodes	Betweenness	Radial layout
C3	**0.435**	C3 > C1 > C2 	**C3**	**0.745**	C3 > C1 > C2 
C4	0.259		**C1**	**0.398**	
C1	**0.208**		C4	0.181	
C2	**0.097**		C7	0.009	
C5	0.000		**C2**	**0.000**	
C6	0.000		C5	0.000	
C7	0.000		C6	0.000	
C8	0.000		C8	0.000	
C9	0.000		C9	0.000	
C10	0.000		C10	0.000	
Nodes	Eigenvector	Radial layout	Nodes	Eigen value	Radial layout
C3	**0.467**	C3 > C1 > C2 	**C3**	**0.478**	C3 = C1 > C2 
C1	**0.429**		**C1**	**0.478**	
C4	0.429		C4	0.431	
C6	0.314		C5	0.273	
C2	**0.300**		C6	0.273	
C7	0.256		C7	0.273	
C5	0.231		**C2**	**0.241**	
C8	0.231		C10	0.188	
C10	0.231		C8	0.179	
C9	0.000		C9	0.094	
Colour legend		C1: Info/intel unit C2: Situation unit C3: Section chief unit C4: Instructor unit C5: Others unit			C6: Command section C7: Operations section C8: Logistics section C9: Finance/admin section C10: Non-IMT

Note. Centrality measures' definitions and associated equations for normalised calculation is explained in Table 1.
Note. Proximity to the centre in a radial layout means higher centrality.

From the radial layout's proximity to the centre (and more specifically based on the node centrality values), we ranked the first three components. Across both observations and four centrality measures, there was a common pattern of ranking: *section chief unit (C3)* $\geq$ *info/intel unit (C1)* $>$ *situation unit (C2)*. Using this pattern of ranking, we examined if RAO would indeed meet the aforementioned expectations (2.5) and adhere to RAI prescribed by the NIMS guidelines and subject matter experts.

The info/intel unit (C1) was expected to serve as *an information collector*, evidenced by it having higher degree and closeness centrality than others. In other words, C1 was expected to be the most involved node having the greatest number of communications with others and the quickest one to access information operationalised as having shortest distances to others. As shown in Table 7, this expectation was partially supported by the info/intel unit (C1) having its degree and closeness centrality higher than the situation unit (C2) but lower than the section chief unit (C3). Overall, the info/intel unit (C1) ranked the second highest across both observations and four centrality measures, except for the second observation's closeness and eigenvector centrality rankings where the info/intel unit (C1) was ranked the highest along with the section chief unit (C3).

The situation unit (C2) was expected to serve as *an information controller*, evidenced by it having higher betweenness centrality than others. In other words, C2 was expected to be the most controlling node over the plans section's communication flow by it having the greatest number of times sitting on the shortest paths among others. However, as shown in Table 7, this expectation was not supported. On the contrary, the situation unit (C2) ranked the lowest (among the three main components) across both observations and four centrality measures.

The section chief unit (C3) was expected to serve as *an information integrator*, evidenced by it having higher eigenvector centrality than other units. By the definition, it was expected to be the most well-connected one by it having the greatest number of communications with other well-connected ones. As shown in Table 7, this expectation was fully supported by it having higher eigenvector centrality than other units. Overall, the section chief unit (C3) ranked the highest across both observations and four centrality measures, except for the second observation's closeness and eigenvector centrality rankings where it was ranked the same as the info/intel unit (C1).

4. Discussion

In this study, we aimed to extend our understanding of naturalistic human behaviours in crisis management to the team- and multiteam-levels—how multiple CMTs work together as an integrated cognitive system when they need to make rapid decisions in adapting to the complexity of managing informational needs. This study was motivated to understand the cognitive roles of multiple CMTs in incident action planning. We had a particular interest in characterising and comparing the component CMTs' RAI and RAO for the MTS's overall cognitive functioning.

4.1. Comparison of RAI and RAO, and its implications

Although the necessity of the RAI descriptions has been acknowledged, their sufficiency has not been demonstrated through the lens of interaction. In this study, we addressed this practical gap by investigating both RAI and RAO (and their deviation). While RAI was characterised by interviewing subject matter experts and reviewing the NIMS guidelines, RAO was characterised by observing actual interactions in real-time at the EOTC environment and analysing node centrality measures in multiteam interaction networks. As mentioned earlier, the relationship between RAI and RAO can be analogous to the relationship between WAI and WAD. Inspired by the safety-II approach which argues that WAD's deviation from WAI may provide information necessary to improve the work (Hollnagel, Robert, and Jefferey 2015; Hollnagel 2017), understanding RAO in addition to RAI (and their deviation) can be viewed as a source of information necessary to improve the role descriptions in the NIMS guidelines and the subsequent design and training of CMTs working in the complex context of incident action planning.

Findings demonstrated that the cognitive roles' *behavioural* characterisation (RAO) identified from self-organising interaction patterns was not fully aligned with the *functional* characterisation (RAI) prescribed by the NIMS guidelines and elicited from subject matter experts' mental models. A plausible explanation for this discrepancy is that the component units contributed to the plans section's overall cognitive functioning by making adjustments to (instead of complying with) their prescribed roles in adaptation to the complexity of incident action planning. The info/intel unit (C1), while (partially) serving as an information collector as expected, also (partially) served as an information controller and integrator. The situation unit (C2) did not serve as an information controller as expected. The section chief unit (C3), while serving as an information integrator as expected, also (partially) served as an information collector and controller.

Practically, this study highlighted the inconsistencies between the RAI and RAO in the context of multiple and multidisciplinary CMTs working on their adaptive coordination. Those findings imply that the current design and training practices of IMTs should incorporate their self-organising interaction patterns and adaptive roles, rather than solely depending on their prescribed role descriptions. The NIMS guidelines assume that the provision of specific role descriptions would be sufficient (Federal Emergency Management Agency 2015). Such an emphasis on the national-level policy on *individuals' compliance with the prescribed roles* influenced how incident management personnel are currently being trained and evaluated. However, our findings suggest a change of paradigm in the national-level policy design, i.e. a change of focus from individual-level role compliance to *system-level role adaptation*. This implies that an evaluation of their training process and effectiveness may need to be adjusted towards assessing their interactive behaviours and their contribution to the overall team and multi-team. Despite the intuitive temptation to individually train potential crisis management personnel, the true meaning of training comes from understanding and experiencing their unique contributing roles for the cognitive functioning of larger units embedded in sections.

Theoretically, this study expanded ITC's scalability to the MTS level in the context of crisis management. This study was motivated to understand cognition in multiple CMTs using within-team and between-team interaction as a lens or a proxy to observe their system-level cognitive functioning. Although interaction has been recognised as an essential lens to understand how cognition is formed in a complex adaptive team such as a CMT (Cooke et al. 2013; Cooke and Gorman 2009), a general gap exists in assessing how multiple CMTs adaptively reorganise themselves in the real-world or naturalistic settings. While a behavioural observation methodology has been prevalently used by ITC researchers to assess adaptive coordination in a single CMT (e.g. Gorman et al. 2020; Pfaff 2012; Stachowski, Kaplan, and Waller 2009; Uitdewilligen and Waller 2018), there is a gap in empirical approaches to explore the unfulfilled potential of ITC's scalability to multiple CMTs or even a system of CMTs (Moon 2019; Moon et al. 2019). In this study, we addressed this theoretical gap by observing naturalistic interactions within and across CMTs, thanks to the EOTC's functional and physical resemblance to the actual incident action planning circumstances.

Methodologically, this study utilised node centrality measures to characterise and compare RAI and RAO. This study was motivated to understand the cognitive roles of multiple CMTs in their interaction networks. Team researchers have clearly distinguished between those two types of team roles (i.e. functional and behavioural roles) and emphasised the sparsity of empirical evidence on behavioural roles due to the methodological limitations in observing and analysing team members' communication (Belbin 2012; Lehmann-Willenbrock, Beck, and Kauffeld 2016). It is indeed challenging to investigate the RAO of an IMT's plans section because the component units in their naturalistic settings interact not only within but also outside a plans section (e.g. with the other four sections of an IMT) for their adaptive coordination. In this study, we addressed this methodological gap by creating a coarsened network where its nodes represent multidisciplinary units/sections and edges represent interactions among them. Also, we utilised four distinct types of node centrality measures to capture the relative importance of each unit in a coarsened network and characterise its contributing role (RAO) for the plans section's overall cognitive functioning.

4.2. Limitations and future research agenda

CMTs are highly complex systems, and the naturalistic investigation of such systems is resource intensive. While this study addressed a clear gap in theoretical, practical, and methodological understanding of cognition in CMTs, this effort is considered exploratory, and several limitations need to be addressed in potential future research.

First, the observational settings and participants at the EOTC involved potential variabilities in the IMTs' formation and functioning, which could affect the generalisability of the findings to other real-world IMTs or similar complex team settings. However, the EOTC creates a realistic representation of an IMT (with good generalisability to other IMT settings) due to its functional and physical resemblance to the actual incident action planning circumstances. The EOTC is indeed a mecca of incident management training as one of the two national facilities sponsored by FEMA for the educational deliveries of the NIMS guidelines and skills. Our previous investigation of the IMTs specifically formed during Hurricane Harvey showed a great degree of similarity between how IMTs function in the real-world and how they are being trained at the EOTC (Son, Sasangohar, Neville, et al. 2020). Future work may include further investigating the extent to which this study's findings can be generalised to and across other similar complex team settings (e.g. IMTs in healthcare).

Second, we lacked control over the observational sampling at the EOTC—team compositions, sizes, and demographics. Since the EOTC has its own training program which rotates the assigned roles of the IMT members, we could not control who will be assigned to the plans section; otherwise, only the consented person could have been assigned to the plans section for consistency and convenience of coding. Therefore, selection bias may need to be considered as a potential confound because we had more information about some roles. One may need to be careful in inferring because the specific roles shadowed (Table 4) were ultimately determined based on whether the participants in the plans section's info/intel, situation, and section chief units had consented to participate. Also, this study inevitably included the training contents and the instructor influences. Although this study views the EOTC as a simulated environment for naturalistic observation, the interactions of those three units inevitably involved interactions with instructors. Future work may include further investigating the extent to which this study's findings can be validated with relatively more controlled settings and samples without any training contents or instructor influences.

Third, we lacked consideration regarding alternative approaches to model multiteam interaction networks and compare the component units' RAI and RAO. Our approach (i.e. the descriptive analysis of a MTS's network data using node centrality measures) was selected because node centrality measures (Table 1) enable us to quantify each unit's influence over other units and sections. Yet, we acknowledge that other network modelling approaches could have been used for characterising RAI and RAO. The epistemic network analysis (ENA, e.g. Shaffer, Collier, and Ruis 2016), in particular, could have been used for modelling and visualising the structure of within- and between-team interactions. Although it was originally developed in the education psychology field, human factors and ergonomics researchers have used ENA to address methodological challenges in analysing interactions among work system components, especially in complex health care systems.

Notably, ENA would have enabled us to compare the visual models of RAI and RAO qualitatively and quantitatively and would have allowed us to say if RAI and RAO are different with statistical significance. Recently, Weiler et al. (2022) used a case study on dementia caregiving to illustrate the utility of ENA as an analytical method to represent work system interactions as network graphs, facilitate both qualitative and quantitative interpretations of the network graphs, and compare the network graphs through summary statistics. Also, Wooldridge et al. (2022), in their investigation of team cognition in care transitions from operating room to intensive care unit, utilised ENA to understand how work system factors in inter- versus intra-professional handoffs influence team cognition functions and outcomes. ENA enabled the comparison of the network graphs of inter- and intra-professional handoffs through summary statistics. However, applying ENA to the current study would have challenged us to compare across two different network styles. Although ENA can be used for any qualitative sources of information such as the documents and interviews that characterised RAI, ENA cannot be used for the RAO observations data coded in real-time using the 3-Cs taxonomy of interactions and the DELTA iPad-based tool. Accordingly, applying ENA to the current study would have resulted in two different network styles (i.e. one from the application of ENA to represent RAI and another one depicted in this paper to represent RAO) that cannot be directly compared to each other.

In the current study, we could not directly compare RAI and RAO because they were characterised in incompatible forms. While RAI was characterised in the form of verbal descriptions, RAO was characterised in the form of node centrality measures. The sources of information for characterising RAI were documents and interviews that do not quantify structural relationships among component teams. This is the reason why we acknowledge that RAO is inherently richer, and more accurate than RAI because RAO is less reductionist and therefore inherently closer to the complexity of real-world problems and real-world systems. Therefore, we had to go through an additional step of reformulating the verbally described RAI in terms of node centrality measures (compatible form) in order to use the reformulated RAI characterisations as 'the expectations about RAO' which can be directly compared with the characterisation results of RAO. Our assumption in this additional step was that RAO would adhere to RAI (i.e. the observed roles would align with the prescribed roles). Although we could successfully examine the assumption, we could not provide the statistical significance of the differences between RAI and RAO. Therefore, future work may include further investigating the extent to which this study's findings can be statistically validated with the quantifiable sources of information for characterising RAI and RAO that can feed into the various network modelling approaches such as ENA.

Fourth, we made another assumption that central nodes would inherently provide more control over other nodes and be beneficial for performance, ignoring the fact that node centrality can also accelerate the failure propagation (Adriaensen et al. 2022;

Falegnami et al. 2020). Additionally, distinct command modes may induce inconsistent centrality patterns, as Hollnagel referred to this by discriminating between scrambled, opportunistic, tactical, and strategic modes (Hollnagel 1998) and then applied to similar emergency response exercises (Palmqvist, Bergström, and Henriqson 2012). Thus, another future work may include further examining such an assumption by investigating how the static description of RAI will differ from RAO in distinct command modes.

Fifth, the RAO characterised in Table 7 may not fully reflect its involvement in the more-than-two-person interactions during the meetings. Notably, we acknowledge that our observational data collection was limited to '*two-person (dyadic) interactions*' occurring on the '*floor*' (within the EOTC's classroom area and five station areas—outside the meeting rooms). The observers in this study had a consistent policy to ignore more-than-two-person interactions or individual working time. Particularly, interactions occurring in the meeting rooms (mostly more-than-two-person interactions) could not be fully coded due to the limited physical space for observers and the absence of cameras in the rooms. Such exclusion of meeting room interactions may affect the validity and generalisability of this study's findings. Future work may include updating the data collection methods to enable the '*multiple-initiator and multiple-receiver interactions*' coding.

Lastly, the absence of the *contents* in the DELTA-recorded real-time coded interactions limits the findings. Among the 3-Cs taxonomy of interaction (i.e. contexts, characteristics, and contents), the third C (contents) remains out of our scope in this study. In a recent review paper, cognition in a system of CMTs was generally defined as interaction within and across *cognitive system components* to achieve *cognitive system capabilities* (Moon et al. 2020). Without the contents of observed interactions, we cannot examine which *cognitive system capabilities* (i.e. perceiving, diagnosing, or adapting) the component units contributed to. This is why we audio- and video-recorded the interactions while shadowing and coding them in real time. Thus, future work may include the retrospective and qualitative coding of their transcribed contents to shed more light on the true nature of interactive team cognition in IMTs.

4.3. Broader industrial applications

CMTs are unique in their formation and functioning, yet this study conveys a common message to future researchers interested in studying complex adaptive teams in other application domains. The message is that we need to focus on interactions not only within but also between the teams, especially in naturalistic settings, to understand the roles of each team for the system-level functioning and then provide them with appropriate design, training, and evaluation.

The importance of investigating naturalistic interaction networks is also highlighted in our interviews with the subject matter experts around an additional topic out of our scope, i.e. the current practice of evaluating a plans section's performance (see Appendix Table A1 for the list of example questions and relevant themes). The subject matter experts emphasised evaluating a plans section around its process (in addition to its input and output)–specifically, how well interactions occur across units and sections. The increase in such interactions would be observable as the different vest colours (labelled according to the units and/or sections) move around the EOTC. In this study, we demonstrated this colour mixture, referred to as a '*rainbow effect,*' which has been used as a proxy measure of the good flow of information during the incident action planning process. Such a rainbow effect may be a core interest for future researchers interested in studying complex adaptive teams in other application domains through the lens of interaction.

Also, our conceptualisation of both RAO and RAI is in line with a prevalent trend to reconcile WAD and WAI (Hollnagel 2017; Hollnagel, Robert, and Jefferey 2015) for the promotion of adaptive coordination in CMTs, which has been commonly operationalised through narratives and resilience models (Aguilera et al. 2016; Gomes et al. 2014; Lundberg and Rankin 2014; Mendonça 2007; Rankin, Dahlbäck, and Lundberg 2013; Son, Sasangohar, Neville, et al. 2020). The original principles of WAI and WAD have been applied to different settings including the maritime domain (de Vries 2017), autonomous driving (Grabbe et al. 2020), healthcare (Clay-Williams, Hounsgaard, and Hollnagel 2015), aviation (Adriaensen et al. 2019), cyber-socio-technical systems (Patriarca et al. 2021) and even emergency response planning (Steen, Patriarca, and Di Gravio 2021). Then, those concepts have been further extended and refined to more than what's originally conceptualised, e.g. the concepts of 'work-as-prescribed' and 'work-as-disclosed' (Moppett and Shorrock 2018; Patriarca et al. 2021) ultimately being extendable and fractal in nature in the generic 'work-as-x' (WAX) concept (Patriarca et al. 2021). Our original conceptualisation of RAI and RAO delivers a research contribution in highlighting roles as a property of adaptive capacity from previous literature, originating from Rasmussen

(1997) and extended by others (e.g. Naikar 2017; Naikar and Elix 2021).

5. Conclusion

We found that the RAO identified from self-organising interaction patterns was inconsistent with the RAI prescribed through written or verbal forms. When a disaster occurs, multidisciplinary CMTs are expected to serve their roles as described in written or verbal guidelines. However, according to our naturalistic observations of multiteam interaction networks, such descriptions may be (necessary but) insufficient for designing, training, and evaluating CMTs in the complexity of managing informational needs together. The resulting inconsistencies between RAI and RAO imply the need to investigate cognition in multiple CMTs through the lens of interaction.

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Appendix

Table A1. An additional topic covered during the semi-structured interviews (yet remains out of our scope in this paper).

Topic	Example questions	Relevant themes
Evaluation of a plans section performance	• Can you tell us how you evaluate a plans section as a whole? • Are there any metrics or tools you use?	• Input ○ Formation of common ground • Process ○ Learning of planning process ○ Effectiveness of interaction under pressure ○ Increase in interaction across units and sections • Output ○ Validity of information ○ Appropriateness of documentation