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Using a digital data analytic tool to capture dynamic change in coordination patterns: An exploratory study of the Apollo 13 mission

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ABSTRACT

The operational environment of complex sociotechnical systems is inherently uncertain, demanding constant coordination restructuring to adapt to dynamic situational demands. However, coordination changes in the Human Factors and Ergonomics Field have primarily been studied using static methods, overlooking moment-by-moment adjustments. In the current study, we address coordination restructuring by using THEME, a digital analytical tool capable of visualising and exploring coordination restructuring from a multi-layered perspective. We examine restructuring in coordination patterns during NASA's Apollo 13 Mission, revealing significant shifts from stable, long-duration 'coordination hubs' in routine operations to shorter-duration patterns during a crisis situation. Additionally, the results highlight the importance of flexible switching between reciprocal and one-directed coordination, along with enhanced role distribution. This study underscores how exploring temporality-sensitive phenomena like coordination through digital technologies such as THEME, advances our understanding of incident analysis and resilient performance within complex systems.

1. Introduction

Complex sociotechnical systems operating in high-risk environments, such as aerospace or emergency response management, often face the challenge of adapting their coordination processes to align with dynamically changing task demands (Righi et al., 2015; Son et al., 2020). The process of coordination undergoing alterations within these closely intertwined systems, hereinafter termed "*coordination restructuring*" constitutes a pivotal element of resilient performance, defined as the capacity of systems to prevent breakdown in the face of disturbances (Hollnagel, 2017). Coordination restructuring is necessary for the timely transfer of work information, joint diagnosis of defects or identification of opportunities for action, and collective execution of operating procedures (Lin et al., 2011; Wang et al., 2020), thereby maintaining high levels of functioning and prevention of system collapse (Woods, 2018). Dynamic shifts in coordination in response to environmental challenges can enhance resilient performance, as evidenced by successful adaption to disturbances (Grimm et al., 2023), while poorly displayed dynamic shifts in behaviours have been associated with system failures (David and Schraagen, 2018). Hence, a robust relationship exists between coordination restructuring, involving the dynamic adjustment of coordination processes, and the facilitation (or hindrance) of resilient performance.

Dynamic changes in coordination processes are inherently bound to time, making coordination restructuring an intrinsically temporal phenomenon. to investigate this temporality, it is essential to employ a time-sensitive, data-rich methodology, proficient in capturing the time-related aspect of coordination restructuring (David et al., 2021; Klonek et al., 2019). The development and application of digital technologies and data analytic tools enable researchers to embrace this temporality as they offer time-intensive data analytics for mapping, visualising, and better capturing coordination restructuring (David et al., 2022). However, research in the field of Human Factors and Ergonomics (HFE) predominantly focuses on static approaches for investigating and mapping coordination interactions (Kozlowski and Chao, 2018; Leenders et al., 2016), often overlooking the potential of temporality-sensitive analysis techniques. Embracing a temporal perspective, we argue that to advance our understanding of how resilient performance manifests in closely intertwined systems, such as teams and multi-team systems, it is crucial to explore the *continuous nature* by

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which teams dynamically restructure their coordination processes as they interact.

This paper aims to demonstrate how we can effectively capture and utilise the dynamic nature of coordination restructuring to enhance our understanding of resilience performance facilitation. In doing so, we contribute to resilience engineering theory, emphasising the importance of both the structure (what changes) and timing (when it changes) of coordination patterns, as they directly impact the team's abilities to meet the task demands (Chuang et al., 2022; Gorman and Wiltshire, 2024; Grimm et al., 2023).

Despite previous contributions in resilience engineering (e.g. David and Schraagen, 2018; Gorman et al., 2019; van den Oever and Schraagen, 2021; Wiltshire et al., 2019), a recent review reveals a largely untapped potential of digital analytic tools, which can help to comprehend the dynamic changes (i.e., the when) and structural make-up (e.g. the what) of coordination patterns through detailed micro-behavioural analysis (David et al., 2021). To address this gap, we not only apply digital tools such as THEME (Magnusson, 2000, 2018) but also propose and employ a multi-layered framework to shed new light on the dynamics underlying resilient performance. Moreover, our study elucidates the temporal mechanisms and unfolding dynamics behind successful anomaly handling in a high-risk environment, as we analyse the renowned case of NASA's Apollo 13 Mission. In doing so, we enrich the theoretical understanding of resilience performance in complex operational contexts.

2. Literature review

2.1. Coordination restructuring and resilient performance

Coordination, defined as managing task-related interdependences to achieve common goals (Marks et al., 2001; Okhuysen and Bechky, 2009), has long been associated with the concept of team adaptability (Grote et al., 2018; Rico et al., 2008). When operating under familiar, expected conditions, the sequence of coordination between agents in a team forms a set of primarily stable or predictable interactions associated with standard operation procedures (Howard-Grenville, 2005). However, during disruptive, challenging situations, teams naturally strive to align their interaction with the demands of the task by restructuring their coordination behaviours (Gorman and Cooke, 2010; Grote et al., 2018). It is thus discernible that coordination restructuring, which pertains to the changes in coordination throughout team interaction, can be captured through coordination patterns: micro-behaviours forming recurrent structures and sequences that dynamically restructure throughout a team's lifecycle of interaction (David et al., 2021; Hoogeboom and Wilderom, 2020; Kolbe et al., 2014; Lehmann-Willenbrock and Allen, 2017).

It is important to note that not only the mere presence of coordination restructuring but also the manner in which this is manifested in the emergence of different behavioural patterns affect a team's ability to outmanoeuvre complexity displaying resilient performance. After all, Hollnagel (2022) has advocated that resilient performance entails an ongoing process, where unfolding challenges are addressed through respective change. For example, teams that have effectively coped with disruptions, thus displaying resilient performance, show more reciprocal behavioural patterns (e.g. a question followed by an instant provision of feedback; Zhang et al., 2023). On the other hand, teams that have failed to adapt exhibit patterns involving only one agent (Zijlstra et al., 2012), or exhibit a preferential attachment towards only one team agent (i.e. repeatedly directing communication to only one team member; David and Schraagen, 2018). Further, rapid coordination restructuring, referring to changes that immediately follow a disruptive event, has also been associated with more effective and efficient management of disruptive events (Gorman et al., 2019; Grimm et al., 2023). If, on the other hand, interaction remains rigid for longer, the ability to swiftly adapt to unforeseen circumstances is hindered (Burke et al., 2006). These findings further suggest that investigations of coordination restructuring aimed at understanding how resilient performance is facilitated should focus on capturing both the *structure* (e.g., what patterns are made of and how they are manifested) and *timing* of these changes (e.g., at which moments throughout an event new patterns emerge) in coordination patterns.

2.2. A multi-layered framework for capturing coordination restructuring

Coordination restructuring, as expressed in team communication behaviours that emerge and evolve in different patterns, is multifaceted in nature, occurring at different layers of interaction. Most studies focus on capturing patterns between agents of a team engaged in coordination (*actor layer*), patterns on the kind of message being coordinated (*message layer*), or patterns in which coordination is conveyed (*mode layer*). All layers exhibit restructuring during team interaction. However, the existing body of research has predominantly taken a reductionist approach, focusing on each layer in isolation. Such an approach, while informative, overlooks the fundamental nature of dynamic system interactions. It treats each coordination layer as a self-contained entity rather than acknowledging the intricate interactions across layers (Cooke et al., 2013; Underwood and Waterson, 2014).

To enhance the understanding of the value of each layer, Table 1 presents an overview of the layers including the corresponding units of analysis. Additionally, we include examples from study findings that illustrate how coordination patterns at each layer can influence resilient performance in rapidly changing environments. The examples are meant to be illustrative rather than exhaustive.

Based on the illustrative findings listed in Table 1, it becomes apparent that each layer contributes significantly to performance, is dynamic in nature, and is intricately linked to the others. Thus, rather than focusing solely on isolated behaviours or agent relationships, a comprehensive analysis including all layers is warranted. A framework that incorporates two layers of coordination -message and mode-is the Co-Act framework (Kolbe et al., 2013, 2015). Co-Act presents a set of validated behaviours observed and used in Acute Healthcare Teams that encompass the two layers of message (i.e., action vs. information-oriented message) and mode (i.e., explicit vs implicit modes of coordination). For example, the behaviour labelled as "information request" corresponds to an information-oriented message of explicit coordination, while "instructing" represents an action-oriented message of explicit coordination. Instances of implicit-information coordination messages include providing "information without request," while implicit-action coordination involves "providing assistance" on action-related tasks. However, this framework neglects the specific actors as senders of coordinative behaviours.

To adopt a systems ergonomics perspective, an exhaustive multi-layered analysis is necessary to determine the interrelatedness and independencies of the system components (Adriaensen et al., 2019). A comprehensive model of Actor-Message-Mode coordination effectively captures the emergence of development of different patterns; patterns that derive from the bottom-up interaction across layers, and that would remain hidden if examining individual layers in isolation (Kozlowski and Chao, 2018). We therefore propose the AMM Framework; an all-encompassing framework that enables us to holistically capture coordination restructuring, as patterns between actor, message, and mode of coordination emergence and change (see Fig. 1 for visual representation of the AMM framework).

Below we discuss how the digital software THEME (Temporal Hierarchical Event Matching), developed by Magnusson (2000, 2018) can be used to detect coordination restructuring across all layers.

2.3. Coordination restructuring using the THEME software

THEME is a software tool that allows for the detection of T-patterns or T-system structures. T-Pattern analysis (TPA) is a robust method for discovering complex patterns in temporal datasets. Implemented in the

Table 1
Coordination restructuring layer and exemplary findings.

Layer	Unit of analysis	Exemplary study	Findings
Actor	Actor (i.e. team member) displaying coordination behaviours	van den Oever and Schraagen (2021)	During a crisis, teams displaying resilient performance show patterns that decentralise and become more evenly distributed across actors.
		Rico et al. (2021)	the behavioural patterns of specific agents in a team, such as team leaders, have been found to affect performance in challenging situations
		David and Schraagen (2018)	In cases of system failure during crisis, there is increasing reliance on immediately preceding team agents as opposed to deliberate, pre-meditated decisions regarding communication distribution
Message	Nature of the coordination messages exchanged: a Behaviours conveying action-oriented messages b Behaviours conveying information-oriented messages (Kolbe et al., 2013)	Sohrab et al. (2021)	Teams performing well in challenging training conditions typically adhere to a structured sequence of messages. They begin with information-oriented messages, followed by planning for action, and ultimately directing the team's efforts toward executing the necessary actions Lower-performing teams often exhibit less organised coordination between information and action-type messages
		Burtscher et al. (2010)	High-performing anaesthesia teams displayed more action-oriented coordination behaviours (in their research referred to as task-oriented behaviours) than did lower-performing teams.
Mode	Manner in which coordination is executed either explicitly or implicitly a Implicit coordination: accurately transferring messages to other agents in the team without being asked to and without the need for overt action plans (Kleinman and Serfaty, 1998) e.g. a communicative act of providing information without being requested to do so shows anticipation of the team's needs and acting ahead (Kolbe et al., 2013) b. Explicit coordination: overt request for information or command for action (Rico et al., 2008)	Stout et al. (2011)	Implicit coordination has been associated with increased team situation awareness, particularly in cases where the task environment imposes constraints on the team's ability to openly strategise.
		Rico et al. (2008)	Implicit coordination can lead to higher performance levels under particular situations, depending on task routineness and task interdependence.
		Mansikka et al. (2023)	In air combat training missions, there are fewer instances of explicit communication in successful events, as opposed to those resulting in system failure.

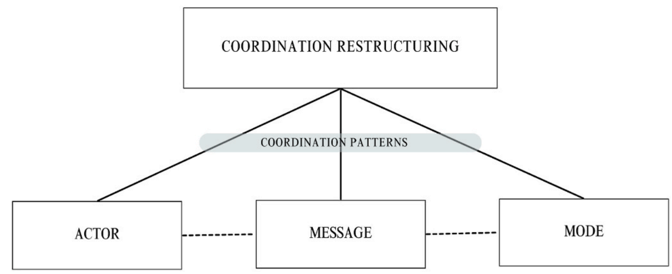


Fig. 1. The AMM multi-layered framework of coordination restructuring.

THEME software, it employs statistical tests like Chi-Square and permutation tests to uncover hidden behavioural patterns called "T-Patterns" (Magnusson, 2000). In TPA, the first step involves identifying the units of analysis, such as coordination behaviours and their initiating actors. The combined units of analysis (behaviour and actor displaying the behaviour) comprise one "event-type" accompanied by its temporal stamp.

A T-pattern comprises an ordered sequence of event-types, each separated by approximate temporal distances called "critical intervals". Critical intervals are considered significant if they deviate from a null hypothesis of random distances between event-types over *n* occurrences of the pattern within the time series.

THEME uses a bottom-up search algorithm on time-series data, starting with simple patterns and progressively detecting more complex ones. It identifies pairs of event-types with the same critical interval, then combines them with a third event-type to search for higher-level patterns. This method efficiently uncovers patterns in an organised manner. Detected patterns are identified by the number of sequential event-types in each pattern (length) and their hierarchical structure (level). T-patterns may occur multiple times in a time-series, indicating cyclical organization. Fig. 2 provides a simplified example illustrating a detected T-Pattern of three event-types, with two levels, recurring twice in the time series. For detailed algorithms and model description, see Magnusson (2000, 2018, 2020).

The TPA output provides quantitative and qualitative characteristics of the detected T-Patterns. Quantitative characteristics include pattern

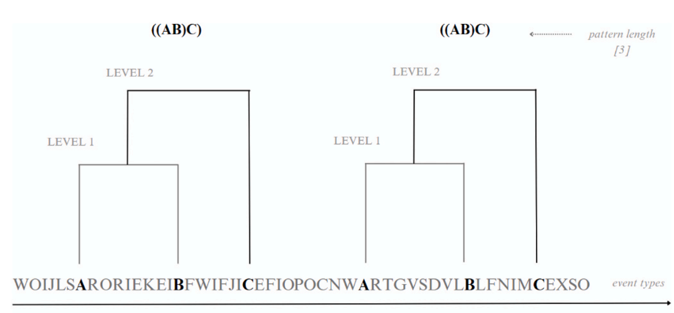


Fig. 2. A T-Pattern in a time-series; Event-types are represented by letters of the alphabet; The pattern recurs twice in the data Pattern levels: 2, Pattern Length: 3, T-Pattern string: ((AB)C).

occurrence, pattern heterogeneity, mono-actor patterns, pattern length and pattern level. Qualitative output provides information about pattern strings.

Pattern occurrence is the total number of detected patterns. A higher pattern occurrence would be associated with higher structure in coordination, reflecting periods of 'equilibrium' (Gorman et al., 2012). *Pattern heterogeneity* indicates how many different patterns are detected. For example, a pattern of "instruction-information request-instruction", is different from a pattern of "information request-instruction-instruction", and each can recur multiple times in the data.

Mono-actor patterns refer to patterns which include only one actor in the data, thus indicating lack of reciprocal behaviour as the pattern only involves one agent showing different behaviours and does not entail behaviours from other team members (Zijlstra et al., 2012). *Pattern length* represents the number of event-types comprising a pattern's sequential composition, and *pattern level* denotes hierarchical complexity, according to the number of levels in its hierarchical structure.; i.e. a pattern can be comprised of simpler patterns, which may, in turn, be comprised of even simpler patterns, and so on. More levels indicate a higher degree of complexity and intricacy in coordination. Even simple patterns of only two event-types are not isolated; they are organised and connected hierarchically, forming the basis for more complex ones, indicating a higher internal structure (Casarrubea et al., 2015). Thus, each behaviour does not serve only to provide an on-the-spot solution, but is part of a larger set of behaviours. Overall, patterns have been found to be less reciprocal, shorter, and less hierarchically complex in non-routine training situations (Lei et al., 2016; Stachowski et al., 2009).

Pattern strings represent the content-based, qualitative composition of patterns, indicating the event-types included in each pattern, in order of occurrence. It can thus be used to identify possible qualitative structural elements present in resilient teams. The most representative pattern string, which needs to be interpreted (Casarrubea et al., 2015; Magnusson, 2000, 2020), is depicted in the *Pattern Diagram*; a visualisation of the pattern of the longest length and level that has recurred the most times in the data. The diagram shows how many times this pattern, as well as the patterns it entails (its 'building blocks'), are detected in the data. This enables grasping the exact moments at which the preeminent pattern and all its lower-level patterns first appeared, as well as when they recurred throughout the time-series.

From the above, it is evident that THEME enables capturing the fine-grained temporal changes that reflect coordination restructuring, including both quantitative and qualitative insights, enhancing our understanding of how coordination restructuring is manifested across all layers.

Despite previous use of TPA to compare teams during disruptions (Hoogeboom and Wilderom, 2020; Lei et al., 2016; Stachowski et al., 2009; Zijlstra et al., 2012), research has primarily focused on short observation periods. There are no studies available yet that explored how coordination restructuring manifests in prolonged real-life crisis situations, which are common in socio-technical systems. Continuous coordination is crucial during such disruptions, requiring exchanges of information, diagnosis of defects, and collective action. Thus, coordination patterns may emerge and restructure differently over longer time scales and vary throughout the event.

2.4. Aim of the study

We have explored how previous research underscores the importance of coordination restructuring as a critical factor influencing a team's resilient performance. However, the potential insights from temporally-intensive datasets regarding these changes have been underexamined, possibly due to the complexity and intricate nature of restructuring. Our study addresses this gap by leveraging the digital analytic tool THEME, which can detect subtle pattern changes in real-time, thereby capturing the dynamic nature of coordination restructuring throughout team interaction.

We use the case of NASA's Apollo 13 Mission as this is one of the most well-known examples of resilient performance in the realm of coordination (cf. Woods and Hollnagel, 2006, p.77). Despite facing a life-threatening crisis, the Apollo 13 team successfully returned to Earth. During the mission, effective and efficient coordination amidst adversity were deemed as pivotal factors in overcoming time-sensitive and resource-constrained challenges (e.g. Sohrab et al., 2021; Uitdewilligen and Waller, 2018). We explore a 12-h-long excerpt of the Mission and capture coordination restructuring based on the multi-layered AMM framework, to investigate how characteristics of restructuring, including pattern cyclicity, duration, connectivity, reciprocal fashion and content-based composition evolve during routine team operations and as the crisis unfolds.

3. Methods

3.1. Dataset and transcript

Apollo 13 (April 1970) was scheduled to be the third lunar landing, but due to an explosion in an oxygen tank on the second day of the mission, the mission had to be aborted, and the NASA team had to figure out a way to safely return to Earth. The mission lasted a total of 5 days, with the 'crisis' lasting 6 h (02:07:55:20–02:13:44:26). The unexpected nature of the event, the limited MOs available at hand, and the severe consequences that would follow if the team did not manage to work around it, make this a leading example of a resilient team whose coordination was a key means through which the team extended its boundaries of operation.

NASA's Apollo 13 mission was managed and controlled by a distributed system of flight controllers on the ground, and the astronauts on the Saturn-V rocket. Three agents were the Astronauts in the rocket: the Mission Commander (CDR), the Command Module Pilot (CMP), and the Lunar Module Pilot (LMP), and the NASA Mission Control Centre on the ground was made up of a total of sixteen control rooms, each of which had a different expertise. Decisions from Mission Control were passed on to the astronauts via the Capsule Communicator (CAPCOM), who was in turn authorised to communicate with the Astronauts and pass information from the spacecraft back to Mission Control and vice versa.

The transcripts of the Apollo 13 Air-to-Ground voice loop were extracted from https://apolloinrealtime.org/13/(Feist, 2020), consisting of communication between five agents (CAPMCOM, CDR, CMP, LMP). The Air-to-Ground loop was chosen for the analysis as it consists of structured data communication between the astronauts and the Mission Control Room on the ground. A total of 12 h of communication were analysed, consisting of 6 h of normal operations and 6 h of the team operating under a crisis situation following the unexpected explosion of the oxygen tank.

The dataset was divided into two sections, one for the normal phase and one for the crisis. The normal phase started at hour 49:46:16 of the dataset, thus incorporating exactly 6 h of normal operation communication. This was done because, for optimal use of THEME, the data must include datasets of equal time duration. The crisis phase started at hour 55:55:20:16, when the team realised there was a disruption in their environment. It was marked by the famous line "Houston, we've had a problem here". The crisis phase ended at hour 62:02:04, recorded as the moment where "after 6 h of continual crisis, Apollo 13 is now safely back on a trajectory towards Earth, with a stable configuration and no immediate dangers" (Tseng, n.d.).

3.2. Codebook and coding

To code the dataset, the first round of coding used a deductive approach in the first 10% of the data (519 rows) by using the validated Co-Act codebook of Kolbe et al. (2013, 2015). The original codebook consisted of 10 codes, reflecting either action-related or information-related behaviours and further classified into explicit and implicit communication behaviours. The codebook was adjusted in code definition and examples (see Table 2), and two extra codes were added, "call out" and "acknowledgement". The codes were necessary to capture the frequently used closed-loop communication occurring in NASA's Air-to-Ground Loop. All utterances were coded by one of the authors. To ensure interrater reliability in the codes applied to each utterance, an extra coder (an MSc student at the University of Twente) applied the same codebook to code the data. A good interrater agreement (Cohen's $\kappa = 0.80$) was obtained.

To apply the codebook, two Excel documents were created, one for the normal and one for the crisis phase. The normal phase included 353 event-types (datapoints), and the crisis phase included 1180. Each file consisted of four columns: the time at which each event occurred (the original format of hh:mm:ss was transformed into integer timescale measured in seconds, as requested by THEME), the actor speaking (CAPCOM, CDR, CMP, LMP), the utterance spoken, and the code of each respective utterance.

3.3. Data analysis

3.3.1. Pattern analysis (TPA)

To perform TPA analysis, two .txt documents were created for the normal and crisis phase. The crisis phase was further divided into six subsets of 1 h each and connected under a multi-samples file, so that patterns occurring significantly more in some samples than in others could be compared, to provide a more fine-grained analysis, adding to the temporal resolution of our exploratory comparisons. Each .txt file contained a list of all datapoints, including the time (integer value) at which each event-type occurred, and the event-type itself (e.g. "CAPCOM,b,Instruction"). Note that 'b' was added for each event to mark the beginning of the event-type, as requested in the software manual for best results; it is however redundant for the output and interpretation of the results.

To run TPA analysis in THEME, certain parameters had to be specified: Critical Interval Type = free; Univariate Patterns = Include, *minimum occurrences* (minimum number of times a t-pattern must occur to be detected) = 3; *significance level* (maximum accepted probability of any critical interval relationship to occur by chance) = 0.001. The analysis was also set to Exclude event-types occurring more frequently than the mean + 2.5 standard deviations. That was to ensure that certain event-types that were occurring much more frequently than others would not clutter up all diagrams or cause overloading of the software.

To ensure the validity of the detected t-patterns, the software was also set to perform simulation (Monte-Carlo) randomisations, running five Shuffling and Rotation rounds on the data, in each run maintaining the same number and frequency of event types as the original data, only arranged in a different randomised temporal order. We compared the average number of patterns found in the randomised data to the number of patterns identified in the actual data.

3.3.2. Further analysis

Descriptive statistics were computed for the results of the TPA, including the means and standard deviations of pattern length, level and actor switches. Due to the violation of the normality assumption in the dataset, a non-parametric test was used to compare the Normal and Crisis phases. Specifically a Wilcoxon Signed-Rank Test was run to test for significant differences between median ranks of pattern length, level, and actor switches. For sub-phase comparisons of the crisis phase, one-way repeated measures Friedman's tests followed by Bonferroni post-hoc comparisons were used to test for significant differences in length, level, and actor switches for each of the crisis sub-phases.

4. Results

4.1. Normal-crisis phase comparisons

4.1.1. T-pattern validity

Monte Carlo rotation and shuffling runs indicated high validity of the detected patterns, as the detection of patterns in the real data significantly surpassed the occurrence of patterns in the randomised data (see Fig. 3). These results support the notion that the T-Patterns in the real data were not detected merely due to chance, but rather reveal underlying meaningful temporally structured characteristics of coordination behaviours.

Table 2
Updated codebook (Kolbe et al., 2013, 2015) with adjusted definitions and examples.

Coordination Category	Code	Definition	Example
Explicit action coordination	Instruction	Includes directives, commands, or assignment of subtasks	"Give me minimum fuel usage configuration that'll keep me attitude."
	Planning	Includes verbalisations of non-immediate considerations regarding what should be done and when, also in the form of questions	"We'll get a word on that"
	Speaking-up	Questions and direct remarks concerning procedure and further courses of action, also disagreements, also opinion	"I'd like to bring on jet A-4.", "Standby"
Implicit action coordination	Action-related talking to the room	Includes comments on the performance of own current behaviour	"Okay. The lights are down, and BMAG 2's going from STANDBY to OFF."
	Monitoring	Observes the actions of colleagues and anticipates what they are looking for	"Your attitude is just straight pitch down, Jim."
	Provide assistance	Task-relevant action completed without being asked to do so, backing team members up	"I have some circuit breakers that you can open up in order to power down displays."
Explicit information coordination	Information request	Coded if one directly asks another for (task-relevant) information	"How far are we out of attitude right now?"
	Information evaluation	Statements expressing doubt or assurance regarding the accuracy or source of information	"Okay, but if we got any problems in system I want to make sure that we Can we review our status here"
	Information on request	Coded if one answers a (task-relevant) question asked by another	"No, they were just thinking about P52"
	Call out	Initiating communication with a specific member of the crew	"Houston, 13"
	Acknowledgement	Response indicating that a message has been received	"Okay", "Copy that"
Implicit information coordination	Gather information	Coded if one actively gathers information from the environment (but not from others → monitoring)	"Looks like I'm cross-coupling here."
	Information related talking to the room	If one appeared to address a communication not directed to a specific other	"That concludes the power down of displays"
	Information without request	Providing information to a team member without being asked to do so	"He's turned off all jets now."

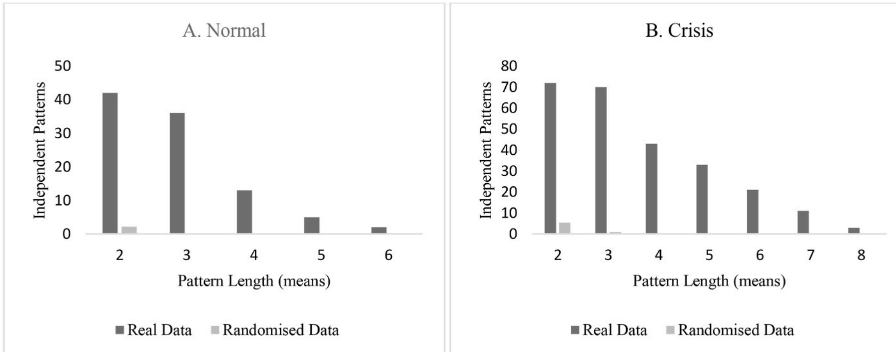


Fig. 3. Real vs. Randomised Data for Normal (A) and Crisis (B) phase. Detected T-Patterns in Real Data compared to Monte Carlo Randomisation and Shuffling Means (5 runs). Little-to-no patterns are detected when randomising the data in both phases.

4.1.2. T-pattern quantitative output

Table 3 presents the total number of event-types in each phase (irrespective of them belonging to a pattern or not). The table also includes the number of pattern occurrences, pattern heterogeneity and mono-actor patterns, and descriptive statistics for pattern length and level for the normal and crisis phase. The total number of T-Patterns occurring in the normal phase was 537 (of these, 24% were heterogenous patterns), and 1790 (of these, 21% were heterogenous patterns). The increased number of patterns can be attributed to the higher number of total event-types present in the data during the normal and crisis phases ($n_{normal} = 353$, *crisis* $n_{crisis} = 1180$). What is interesting, however, is the manner in which restructuring of patterns was manifested during these two phases. In the normal phase, *mono-actor patterns* made up 42% of the total pattern occurrence. In contrast, mono-actor patterns in the crisis phase made up only 26% of the total pattern occurrence. This is an indication of less reciprocal behaviours in the actor-layer during the normal phase as compared to the crisis.

Regarding *pattern length*, the related-samples Wilcoxon Signed-Rank Test on the relative frequencies of each phase indicated significant differences in median pattern length ranks. Specifically, in the crisis phase, $Mdn = 3.00$, were significantly higher than in the median pattern length ranks of the normal phase, $Mdn = 2.00$, $Z = 6.138$, $p < 0.001$. This indicates, that coordination patterns during the crisis phase tended to form hubs between a greater number of event-types as compared to the normal phase, revealing the involvement of more coordination behaviours. Significant differences were also found for pattern level, with the median pattern level ranks in the crisis phase, $Mdn = 2.00$, being significantly different from the median pattern level ranks in the normal phase, $Mdn = 1.00$, $Z = 5.745$, $p < 0.001$. This indicates higher hierarchical complexity and more organised order in the crisis phase. Both in terms of length and level, the findings suggest an overall increased sequential and hierarchical complexity in coordination behaviours. The increased complexity may reflect an overall restructuring towards more elaborative coordination, to account for the increased perplexity of the situation.

4.1.3. T-pattern diagram

For qualitative interpretation, we used THEME's Pattern Diagram of the normal phase (Fig. 4) and crisis phase (Fig. 5). The diagram maps the preeminent pattern detected in each phase, on the phase's time-series. As mentioned in section 1.3., the preeminent pattern is the one of longest length and level that has occurred most often in the data. Since the preeminent pattern is the most hierarchically complex one (highest number of levels), it is made up of simpler patterns, lower in the hierarchy, which are also mapped in the pattern diagram. The Detection Tree on the left-side of the Figure shows all event-types included in the preeminent pattern and their hierarchical connections to lower-level patterns. For example, in Fig. 4, the simplest pattern (level = 1) includes the event-types "LMP information request" followed by "CAPCOM information on request" (length = 2), which is also followed by the event-type "LMP action talking to the room" significantly more often than chance. Therefore, it is also comprised in a higher-level pattern (level = 2, length = 3). The full pattern string and characteristics are presented in the bottom box of the Figure. The occurrence tree on top of the Figure, shows the number of times the preeminent pattern has occurred in the time-series. Finally, the lines in the connection chart (in the middle of the Figure) show at exactly which moment each pattern (preeminent pattern as well as all lower-level patterns it entails) is observed.

When comparing Figs. 4 and 5, it is evident that even though the preeminent patterns of each phase reoccur three times respectively, their duration, i.e. how much of the time-series they cover, differs. The preeminent pattern in the normal phase covers a total of 30% of the time-series, which denotes reduced coordination flexibility compared to the crisis. Most coordination in the normal phase includes a stable use of this preeminent pattern, which dominates the largest portion of the data. However, during the crisis phase, despite its increased length, the preeminent pattern lasts for a shorter period of the total duration time, while its lower-level patterns of shorter length occur interchangeably throughout the time-series. This indicates higher flexibility in coordination restructuring, further resonating the increased need for adaptation to the demands of the situation.

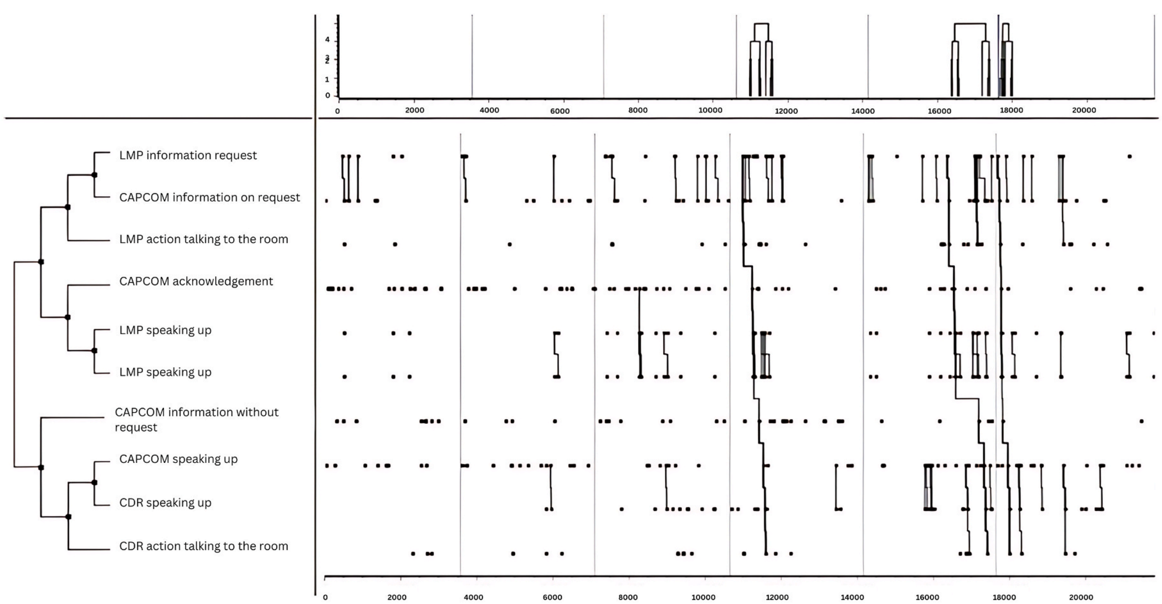
Another interesting observation points to the timing of how coordination restructuring unfolds in each phase. the preeminent pattern, which includes the highest internal organisation (level) and sequential composition of behaviours (level), is present from the very beginning of the phase, and is distributed normally across the time-series. This indicates a high-level of coordination order without the need for changes in how patterns are structured. However, the preeminent pattern of the crisis phase only appears at hour four, revealing constant restructuring between shorter and less hierarchically complex patterns, before developing a means of coordination of higher internal ordering.

Table 3
Pattern occurrences and descriptive statistics for the Normal and Crisis phase.

	Total event-type occurrence	Total Pattern occurrence	Pattern heterogeneity	Mono-actor occurrence	Pattern length mean	Pattern length sd	Pattern level mean	Pattern level sd
Normal	353	537	130	227	2.83	0.97	1.71	0.74
Crisis	1180	1790	381	476	3.99	1.80	2.41	1.11

(CAPCOM callout ((CDR acknowledgement , CAPCOM information request)(CAPCOM call out (CAPCOM planning , CAPCOM instruction))))
Occurrence= 3 | Length= 6 | Level=3 | %Duration= 30

Fig. 4. Pattern Diagram of preeminent pattern in Normal phase (optimised for readability). *Detection Tree* (left): all event-types comprising the preeminent pattern and their connections; *Occurrence Tree* (top): number of the preeminent pattern's recurrence over the observation period plotted on the x-axis; *Connection chart of all patterns* (middle): dots represent all raw event-types and the lines represent those that are connected and form recurring patterns over the observation period. Pattern string and characteristics of the preeminent pattern (bottom box).



((((LMP information request CAPCOM information on request) LMP action talking to the room)(CAPCOM acknowledgement (LMP speaking up , LMP speaking up)))(CAPCOM information without request ((CAPCOM speaking up , CDR speaking up) CDR action talking to the room)))
Occurrence= 3 | Length= 10| Level=4 | %Duration= 9

Fig. 5. Pattern Diagram of preeminent pattern in Crisis phase (optimised for readability). *Detection Tree* (left): all event-types comprising the preeminent pattern and their connections; *Occurrence Tree* (top): number of the preeminent pattern's recurrence over the observation period plotted on the x-axis; *Connection chart of all patterns* (middle): dots represent all raw event-types and the lines represent those that are connected and form recurring patterns over the observation period. Pattern string and characteristics of the preeminent pattern (bottom box).

4.1.4. Qualitative characteristics of pattern composition

Here, we briefly showcase how the qualitative output of the patterns offers valuable insights into the ongoing coordination processes occurring at different moments throughout the interaction. In Fig. 4, the preeminent pattern in the normal phase mostly includes closed-loop communication behaviours (e.g. call out followed by acknowledgement), and directive behaviours (e.g. CAPCOM in mission control giving instructions). However, during the crisis (see Fig. 5), closed-loop communication processes such as 'call out' seem to be abandoned. Instead, there is an increased occurrence of patterns involving speaking-up processes from all the astronauts (a quality absent in the normal phase), and final decision-making behaviours from the mission Commander (e.g., implicit action coordination behaviours after repetitive speaking-up behaviours from the rest of the team). Moreover, the diagram illustrates that while initially, patterns are simpler and information-driven (e.g., information request – information on request), as the crisis unfolds, patterns become more complex and action-oriented (e.g. speaking up – action talking to the room), in line with the task environment's demands at the time.

We therefore see that this temporal analysis enables us to not only spot the structurally quantitative aspects of the patterns but also associate task-specific qualities with the respective team coordination that was in place at the time of occurrence, as well as how it evolves with changing task demands.

To illustrate how THEME's qualitative output can be utilised to capture and understand coordination restructuring, Fig. 6 shows the frequencies of patterns according to the content of the event-types (Actor-Message-Mode) they encompass. The changes shown here correspond to the previously identified patterns in Figs. 4 and 5. In the normal phase, the predominant patterns exhibit more behaviours associated with explicit action and information (e.g., planning, instruction and information request), while fewer patterns involve implicit coordination behaviours. During the crisis phase, however, it is noteworthy that while explicit coordination behaviours remain relatively stable, there is an increase in patterns involving implicit action coordination (e.g., providing assistance, action-related talking to the room). Implicit action coordination almost surpasses the prevalence of implicit information coordination behaviours (e.g., sharing information without a request, engaging in information-related conversations), which actually decrease in prevalence during the crisis phase. This is an example of how, in the case of Apollo 13, by examining the pattern frequencies, we can infer the importance of switching to more action-oriented patterns of coordination when immediate action processes are required.

The qualitative results of the pattern diagram, as well as the results presented in Fig. 6 demonstrate the added value of the multi-layered approach in researching coordination restructuring. The results enable us not only to spot the exact timing of restructuring, i.e. the moment at which a pattern emerges, but also help in understanding the complexity and multi-layered fashion of the patterns. For example, by breaking down each behavioural layer (Actor-Message-Mode) as specified in Fig. 6, it is evident that each layer changes in a different manner. Therefore, capturing the interconnected, emergent changes necessitates considering how all layers shift.

4.2. Crisis sub-phase comparisons

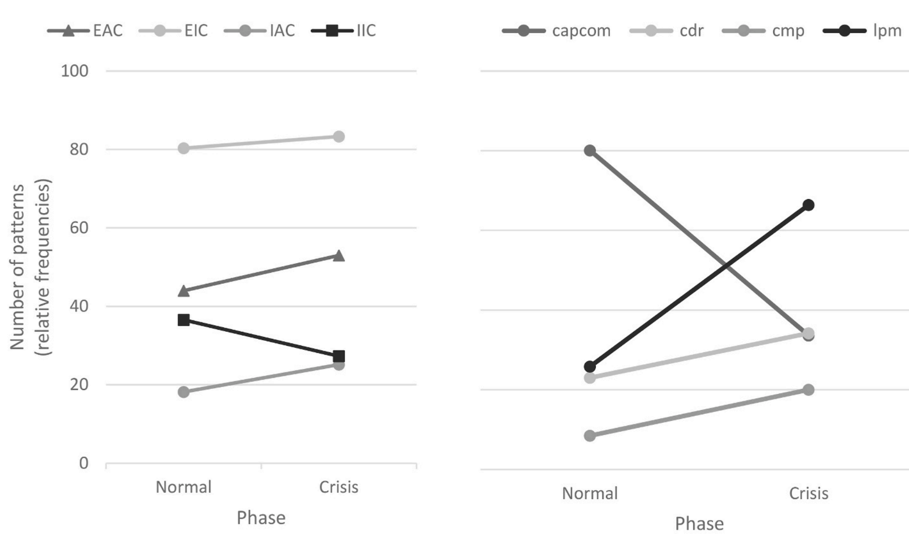
To get a more in-depth understanding of how restructuring in coordination patterns unfolds, we also broke down the crisis phase into six sub-phases of equal duration (1 h each). We explore how pattern occurrence, pattern heterogeneity, mono-actor patterns, pattern length, and pattern level change throughout these sub-phases.

4.2.1. T-pattern quantitative output

Table 4 includes the quantitative characteristics of the patterns in the six sub-phases.

Interestingly, while the total event-types present in each sub-phase are relatively stable ($M = 196, SD = 6$), both pattern occurrence and pattern heterogeneity fluctuate drastically throughout the crisis sub-phases. From the beginning of the crisis (C1), pattern occurrence shows an increase of 33% in C2, and a further increase of 51% in C3. In other words, the total number of coordination patterns drastically increased during the first 3 h of the crisis. In contrast, the increase drops to a negative 25% from C4 to C5, and to a further negative 45% from C5 to C6; thus indicating a gradual drop in pattern occurrence during the last 2 h of the crisis. A similar finding is reflected in pattern heterogeneity (see Fig. 7).

Exploring further how restructuring was manifested in these patterns, *mono-actor patterns* in the crisis phase also mark big fluctuations. The use of mono-actor patterns decreases from C1 to C2, before increasing in C3. They then remain stable throughout C3 to C5, before



A. Message-Mode B. Actor

Fig. 6. Relative frequencies of patterns including [A] Explicit-Action Coordination (EAC), Explicit Information Coordination (EIC), Implicit-Action Coordination (IAC), and Implicit information Coordination (IIC); [B] Different actors initiating a pattern in Norman and Crisis phase.

Table 4
Pattern occurrences and descriptive statistics for Crisis sub-phases.

	Total event-type occurrence	Total Pattern occurrence	Pattern heterogeneity	Mono-actor occurrence	Pattern length mean	Pattern length sd	Pattern level mean	Pattern level sd
C1	190	171	112	116	*3.0*	*1.4*	*1.8*	*0.9*
C2	196	228	147	119	*2.7*	*1.3*	*1.7*	*0.8*
C3	205	344	215	241	*3.2*	*1.4*	*1.9*	*0.9*
C4	194	479	274	335	*3.4*	*1.4*	*2.0*	*0.9*
C5	205	361	194	263	*3.3*	*1.5*	*1.7*	*0.9*
C6	190	207	142	112	*3.4*	*1.4*	*1.7*	*0.9*
mean	*197*	*298*	-	-	-	-	-	-
sd	*7*	*117*	-	-	-	-	-	-

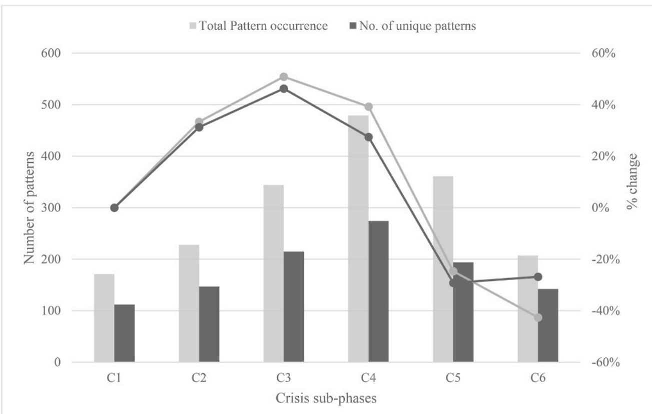


Fig. 7. Number of pattern occurrences (grey bars) and pattern heterogeneity (black bars) and the respective % changes throughout the crisis sub-phases (grey line and black line respectively).

decreasing again in C6 (see Fig. 8). This indicates a fluctuation in the use of reciprocal coordination throughout the crisis, which reflects the changes in situational task demands. For example, during the first hour of the flight, Air-to-Ground communication necessitated an exchange of information from the Astronauts to the Ground to identify possible defects in the Main Valves and Batteries condition. This changed in C2, where malfunctions in the command module necessitated the need to gather information on the on-board displays, and follow instructions to prepare the Lunar Module. This type of coordination is often one-agent coordination of behaviours. From the third to the firth hour within the crisis the team had to coordinate behaviours to move from the command module to the Lunar Module and manoeuvre the Lunar Module to achieve a new course trajectory. During the sixth hour, the situation becomes less demanding providing an opportunity to share flight plan updates mostly from Mission Control.

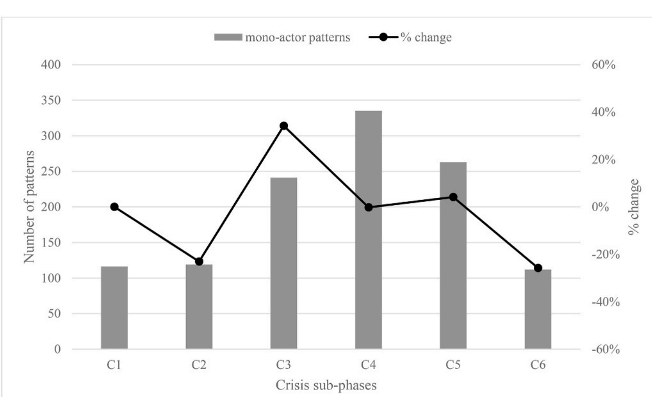


Fig. 8. Total number of event-types (black line) and total number of pattern occurrence (grey line) per sub-phase.

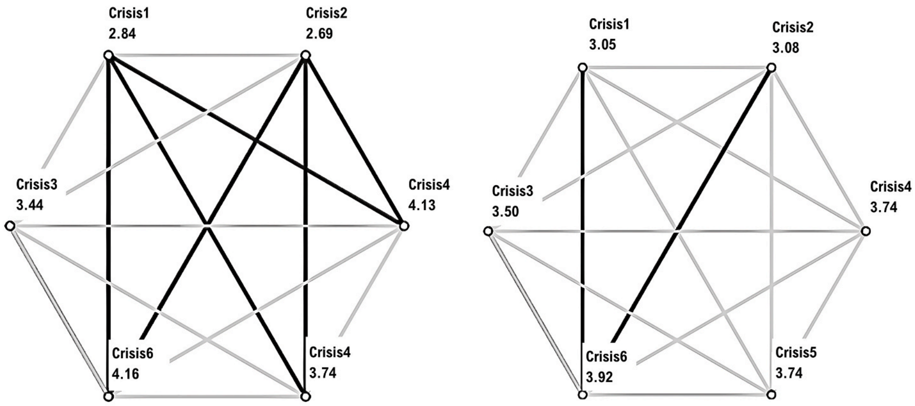
For pattern length comparisons over the six crisis sub-phases, the Friedman's test analysis produced a statistically significant result ($\chi^2(5) = 162.206$, $p < 0.001$) with a large effect size, as assessed using Kendall's W (W = 0.324). This indicates that there were significant differences in the patterns' duration across the phases. Bonferroni post-hoc comparisons indicated significant differences between some of the phases, as these are marked by the black lines in Fig. 9A. To account for Type-I error, significance was assessed via the adjusted Cohen's α. It is interesting to note that Crisis1 (*Mdn* = 2.8) showed no significant differences from Crisis2 (*Mdn* = 4.1) nor Crisis3 (Mdn = 3.44), but marked a significant increase in pattern length when compared to the three phases that followed later on (Crisis4, *Mdn* = *4.13*; Crisis 5, *Mdn* = *3.74*, Crisis 6, *Mdn* = 4.16). This shows that even though there is some fluctuation in the number of patterns increasing in length during the crisis (see Fig. 9), this is only significantly important after the first 2 h into the crisis, showing the team's attempt to stick to existing patterns of coordination.

For pattern level, results also indicated significant differences in the related samples ($\chi^2(5) = 162.206$, $p < 0.001$), with a large effect size (W = 0.324). Fig. 9B depicts the phases that were significantly different in pattern level from one another. The significant differences in mean ranks were only noted between Crisis1 (*Mdn* = 2.84) and Crisis6 (*Mdn* = 4.16), as well as Crisis2 (*Mdn* = 2.69) and Crisis6.

5. Discussion

This exploratory study aimed to demonstrate how the real-time evolution of coordination restructuring within a closely intertwined multi-team system occurs. We used the THEME digital analytic tool (Magnusson, 2000, 2020) to capture and map this temporally-sensitive phenomenon as it unfolded in the real-life case of the Apollo 13 Mission. The findings show that the patterns detected manifested differently across the normal phase of operations and the crisis phase. During the crisis, coordination patterns exhibited were comprised of more behaviours with a heightened level of complexity, revealing an increased internal structure in the team's coordination. In contrast, the structural elements in the normal phase indicate shorter and less complex patterns, signifying concise and direct command-control coordination of standard operating procedures (Howard-Grenville, 2005), based on existing 'coordination hubs', with less need for restructuring. These findings align with the premises of Ashby's law of requisite variety, which posits that for appropriate regulation of a disturbance, the variety of the regulatory process (in this case coordination behaviours) must be equal to or larger than the variety in the system being regulated (Ashby, 1956; Guastello, 2017).

The high internal structure in the crisis phase was accompanied by increased flexibility in how patterns were used. During the crisis, shorter and simpler patterns were more frequently and interchanged with longer and more complex patterns. Furthermore, there was notable variability in the actors performing behaviours, which changed dynamically throughout the event and crisis. For example, in the normal phase, directive and information-giving behaviours were primarily



[A] Pattern Length rank means [A] Pattern Level rank means

Fig. 9. Bonferroni post-hoc comparisons, [A] Pattern Length rank means and [B] Pattern Level rank means. Nodes (dots) represent each phase, and connections (black lines) represent significant differences between phases as indicated by adjusted alpha.

exhibited by the Capsule Communicator in Mission Control and were coupled with closed-loop communication processes, reflecting procedural interaction. However, during the crisis, we observed the active involvement of all astronauts in speaking-up and information-sharing without request. Additionally, the mission's Commander, James Lovell, engaged in more implicit action behaviours following these information-provision and opinion-sharing initiatives from the team. This highlights how systematic restructuring of coordination can facilitate resilient performance by introducing variability in coordination behaviours without creating complete disarray. Furthermore, it underscores the importance of studying variety in coordination alongside the variety exhibited in the system's environment, as suggested by Ashby's law of requisite variety, by examining it as an event unfolding moment-by-moment, through the use of digital analytics and visualisation such as THEME's output and pattern diagram.

In our AMM multi-layer approach, we have observed coordination restructuring across all three layers. Actor participation in these coordination patterns highlights an increase in reciprocal patterns throughout the crisis, suggesting a flexible interchange between one-directed and reciprocal patterns. This observation emphasises the significance of reciprocity (Ostrom, 2003; Stachowski et al., 2009; Woods, 2019; Zijlstra et al., 2012), and its flexible use in facilitating effective coordination under challenging situations. In the normal phase, we observe more explicit, shorter and less complex action-related coordination initiated by the Capsule Communicator (CAPCOM), whose primary responsibility involved transferring information and decisions from Mission Control to the Astronauts. However, during the emergency, we see more implicit, information-related behaviours exchanged from the Lunar Module Pilot (LMP), responsible for navigation and guidance as well as operating the Lunar Module, and from the Commander (CDR) responsible for leading the crew. This reflects restructuring based on role distribution, and further provides support to the importance of initiative, a characteristic behaviour of resilient teams (Woods, 2019). Initiative in the Apollo 13 team emerged throughout the crisis and was allocated effectively in alignment with robust transactive memory systems (i.e. knowing who knows what in the team, Decuyper et al., 2010).

It is noteworthy that our study's findings differ from previous studies in the field, which have shown that better performance in challenging events was associated with smaller pattern lengths and levels (Stachowski et al., 2009) or that non-routine situations had interaction patterns of shorter lengths and levels as compared to routine ones (Lei et al., 2016). It is essential to recognise that these differing conclusions may be attributed to significant contextual differences, particularly evident in the normal vs. crisis phase of the Apollo 13 case study. While previous studies have focused on non-routine events by introducing short-lasting perturbations during normal operations, for Apollo 13, the whole 6 h of the crisis phase was unprecedented and required a different set of responses and actions. This extended timescale of the total observation period in our study, enabled us to capture a wide spectrum of coordination restructuring, rather than solely focusing on isolated segments or aggregated data. This approach also brings us closer to the reality and complexity of real-life crisis situations that complex socio-technical systems face (Waterson et al., 2015).

5.1. Theoretical and practical contributions

Hollnagel (2022) emphasises that resilient performance entails a continuous process, wherein a team constantly re-evaluates actions, collects information, and executes procedures. He further notes the unfeasibility for a team to analyse and identify risks and opportunities "all at once" (Weick, 1987); they rather have to constantly adapt to the situation. Our findings depict the dynamic nature of coordination processes, and how coordination restructuring, captured in real-time data of fine-grained coordination patterns, can enrich our comprehension of the temporal dynamics facilitating resilient performance. We expand upon existing resilience engineering literature by showing that a resilient team demonstrates flexibility in their hubs of coordination by employing reciprocal vs. one-directed coordination, initiative vs. compliance, and role distribution, according to the task at hand.

We summarise these findings under umbrella themes of coordination restructuring for resilient performance:

i. *Adaptive variability in coordination hubs*: Woods and Hollnagel (2006, p. 77 previously discussed Mission Control's successful anomaly handling by emphasising the avoidance of fixation. However, they did not delve into the specific details of what this successful handling entails. With our findings, we were able to elucidate the underlying mechanisms of the adaptive variability necessary to effectively respond to rapidly changing situations. Specifically, during the crisis, we observed a greater complexity in patterns' internal structure, contrasting with the simpler and more rigid coordination hubs of straightforward closed-loop communication behaviours observed during the phase of normal operations. This suggests that teams exhibit a higher level of variability in their coordination behaviours during crises, expanding and adapting their otherwise rigid coordination hubs to effectively manage each unique task demand. By introducing variability in coordination without causing disarray, teams are better equipped to respond to unexpected events and maintain operational effectiveness under challenging circumstances.

ii. *Adaptive reciprocity and initiative*: During uncertainty, team interdependencies become reciprocal (Davison et al., 2012; Sherman and Keller, 2011). The temporal and structural changes observed in the increased occurrence of reciprocal patterns during crises underscore the pivotal role of reciprocity in facilitating work under challenging circumstances. What is more, it highlights the importance of flexible transitions between one-directed and reciprocal patterns throughout crises, enabling efficient adaptive coordination in dynamic environments. Similarly, when facing heightened potential for unforeseen circumstances, interactions bolster initiative, a phenomenon evident in military operations and emergency management (Shattuck and Woods, 2000). Our findings show that the emphasis on taking initiative extends beyond mere action; it involves the careful acquisition of information and decision-making based on robust transactive memory systems. This is a novel result that can only be obtained by carrying out a detailed analysis of coordination patterns using tools such as THEME.
iii. *Adaptive role distribution*: The observed restructuring of roles during the crisis highlights that the importance of allocating responsibilities based on expertise and role clarity to enhance coordination and decision-making processes during crises. Jonassen and Hollnagel (2019) have also emphasised the significance of clear role and task distribution in reducing confusion and errors and improving operational efficiency and resilient performance. The results from our study further enhance these insights by elucidating the specific contributions needed from each actor at various moments to effectively manage the situation, as well as the required flexibility and role changes therein. These novel insights contribute to our understanding of adaptive role distribution, which can only be attained through detailed analysis of coordination patterns using tools such as THEME.

The proposed AMM framework introduces a new way of capturing coordination restructuring through a multi-layer systems perspective, as illustrated by the aforementioned themes. The framework's added value is apparent in its ability to identify emergent patterns that display distinct characteristics that would not be discernible in any of the individual layers when analysed in isolation, This perspective and method of analysis aligns with the intricate nature of resilient performance processes and emergent resilience skills (Wachs et al., 2016).

Finally, this study underscores the value of digital analytics in gaining a deeper understanding of real-time temporal coordination processes. We demonstrate the utility of digital tools in enhancing research on resilience performance and incident analysis by leveraging intrinsically connected, dense data that may otherwise be too complex to decipher. Tools such as THEME offer a method to extract meaning from apparent chaos, adding to the scrutiny and often overlooked aspects of incident analyses. Digital tools such as THEME can act as a means for advancing the principles of resilience engineering, which couple system safety with "a condition where as much as possible goes well … due to the ability of people, alone or together, to adjust their performance to meet the challenges – and opportunities – of the situations they encounter" (Hollnagel et al., 2021, p.2).

TPA enables researchers to capture the often overlooked multi-layered aspect of coordination restructuring above and beyond other temporal analyses such as, for example, Relational Event Modelling (Butts, 2008; Butts and Marcum, 2017), which focuses only on the interactions of the involved actors. THEME stands out as an exemplary digital tool that can be utilised for such an analysis due to its robustness and validation checks. TPA is robust when dealing with noisy or complex datasets, making it applicable to a wide range of research domains from behavioural sciences, biology, physiology and many more (Anguera et al., 2023). The integration of Monte Carlo randomisations in THEME ensures that all detected patterns are significant indicators of behaviours and are not simply present due to chance. Furthermore, the bottom-up binary-tree approach of TPA is another major advantage that adds to the granularity and richness of the analysis, contributing to a more comprehensive understanding of coordination dynamics.

5.2. Limitations and future research directions

A main limitation of this research is its exploratory nature in using only one case for exploring patterns. This makes the generalisation of our results difficult. We do, however, hope that through the detailing of our findings, and the demonstration of the possibilities offered through a temporal analysis facilitated by digital analytics, more researchers will be prompted to utilise digital analysis tools such as THEME to research temporality and emergence in interaction, this being an integral process of resilient performance.

We should also note that, throughout our paper, we encourage a multi-layered approach to researching coordination. However, it is important to acknowledge that our framework neglects different "forms" of coordination, including non-verbal behaviours such as physical proximity, movements (Onnela et al., 2014), or even positioning in the room (Ciolek and Kendon, 1980). Such forms of coordination may provide further insights into the coordination restructuring through an interplay of different layers (Kelso, 2021; Wiltshire et al., 2022). Future research could incorporate other coordination forms into a multi-level coordination approach, that can be further enhanced with physiological features (David et al., 2022; Endedijk et al., 2018; Hoogeboom and Wilderom, 2020).

It is important to note that the layers of the AMM framework discussed in this paper (Actor-Message-Mode) are based on interactions at the team-level. However, we acknowledge that coordination restructuring can also occur at inter-team scales, i.e. at a multi-team level or even at the level of polycentric governance systems (Woods and Branlat, 2011). Even though outside the scope of the current study, we encourage future research to apply the AMM framework at these higher levels of interactions. In such cases, while the framework would remain multi-layered (i.e., including layers of actor, message and mode), the units of analysis would change. For example, in a higher-level analysis of a large-scale polycentric governance system (i.e. a system with multiple centres of authority), the unit of analysis at the 'actor' layer can shift from a single actor within a team, to that of a team or a authority centre within the polycentric governance system.

Future research could also incorporate such fined-grained analyses into higher-level models of how interactions unfold in real-time, to gain deeper insights into the dynamics at play within complex sociotechnical systems. Salmon and Read (2019) emphasised the importance of addressing the functioning of complex socio-technical systems by integrating both high-level methodologies and those that delve into the intricacies of moment-by-moment interaction processes in many model thinking approaches. Such an approach could capture the needs and potential for effective and holistic interventions, such as designing for resilient performance.

6. Conclusion

This study has shed light on the critical role of coordination restructuring in dynamic interactions, and its significance in resilient performance. Through the utilization of the THEME digital analytic tool, we have demonstrated how real-time changes in coordination patterns can be effectively captured and mapped, underscoring the structural and temporal sensitivity of this phenomenon. Coordination restructuring is inherently linked to the operational task environment, with resilient teams demonstrating a greater ability to adjust the complexity of their coordination, exhibit flexibility in certain coordination processes, and adhere to protocols based on environmental demands. These findings emphasise the potential of the THEME digital tool in enhancing our understanding of coordination behaviours in complex sociotechnical systems during challenging events.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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