MASTER THESIS

AN EXPLORATION OF COORDINATION BEHAVIOUR PATTERNS DURING THE APOLLO 13 MISSION

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Every journey must come to an end, and here I am, procrastinating on the final touches and words to complete my project. I believe I am consciously prolonging it because finishing this project means I will not be a student anymore, which is very exciting but, at the same time, fearful.

I would like to express my gratitude to my first supervisor, Lida David, who provided me with the freedom and support to explore my ideas while also challenging me to stay on the right track. I also want to extend my thanks to my second supervisor, Marcella Hoogeboom, whose nuanced and valuable feedback helped shape this paper into what it is today.

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I was fortunate to attend a university with a phenomenal learning atmosphere, and I will carry the knowledge I gained during this time with me as I move forward. Thank you to everyone who made this possible.

Elena Ryzhova,
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Abstract

Background: This study investigates coordination behaviour patterns during the Apollo 13 mission to understand how action teams adapt their coordination strategies in response to crises. The mission's transformation from routine space exploration to critical crisis management provided a unique context for examining shifts between explicit and implicit coordination behaviours and their effectiveness in emergent situations.

Methods: Using a quantitative case study approach, this study analysed air-to-ground voice loop transcripts during the Apollo 13 mission. Coordination behaviours were systematically coded using a pre-set codebook. T-pattern analysis through THEME software was employed to identify recurrent coordination patterns, which were further visualised using the PlantUML tool.

Results: The analysis revealed distinct shifts in coordination patterns from pre-crisis to during-crisis phases. Before the accident, coordination patterns were relatively simple (i.e., consisting of relatively few layers and behaviours) and procedural. In contrast, during the crisis, there was a significant increase in the complexity and frequency of explicit coordination behaviours, indicative of the team's adaptive strategies to manage the unfolding emergency. These patterns underscored a critical reliance on robust, explicit communication to ensure team alignment under rapidly changing conditions.

Conclusion: The findings demonstrate that effective crisis management hinges on flexible and complex coordination behaviours capable of adapting to new, uncertain, or rapidly evolving situations. This study contributes to theoretical models of team dynamics, offering insights into the design of training protocols and communication frameworks for action teams in high-stakes environments.

Introduction

In high-stress environments, the swift adaptability of teams, particularly those known as action teams, is crucial to their success. These teams are composed of individuals who bring specialised skills to operate under high-stakes conditions where time-constrained performance is essential and the outcomes irreversible (Sundstrom et al., 1990, as cited in Edmondson, 2003; Ishak & Ballard, 2012). Action teams, such as emergency room staff, firefighting units, and space mission controls, face challenges that can significantly disrupt their operations, such as unforeseen events, changing circumstances, or external pressures. Therefore, it is crucial for teams to be able to adjust and respond proactively to such disruptions to ensure their success.

This ability of the team to extend the capacity for adaptation is known as graceful extensibility or resilience, as defined by Woods (2018). This concept is not merely a desirable quality; it is foundational to ensuring the teams' efficiency and dependability. It enables them to navigate unpredictable obstacles and evolving circumstances, maintaining stability and performance in adversity (Woods, 2006, 2018). Rather than being a quality to be owned, resilience is more about the potential actions a team can perform (Woods, 2018). The value of resilience can be observed in the ability of resilient teams to recover quickly from setbacks, adapt to new circumstances, and maintain stable performance despite unexpected challenges (Chapman et al., 2020). Thus, resilience is the foundation of an action team's adaptive capacity, making it an essential asset in challenging situations (Woods, 2006).

Real-life examples illustrate how resilient teams navigate life-threatening situations and develop solutions to unfolding events, shedding light on the crucial role of adaptive coordination. One such example is the Apollo 13 mission in 1970, where an onboard explosion occurred. Despite limited knowledge of what had occurred, the Mission Control team demonstrated exceptional information coordination (van den Oever & Schraagen, 2021). They meticulously analysed available data, ensured precise and timely communication among different technical teams, and strategically developed solutions that enabled the astronauts' safe return to Earth. This transformation of a potential catastrophe into a "successful failure" highlights the remarkable resilience displayed by teams and underscores the importance of effective information exchange and decision-making in high-stress environments (Kirkman & Stoverink, 2021; McDivitt, 1970; Orloff, 2000).

In contrast, the lack of adaptability can lead to severe consequences - as seen in the Chernobyl nuclear disaster (Jackson, 2007). Investigations into the disaster pinpointed a critical failure: ineffective communication among workers and inadequate coordination of crucial safety information. Specifically, the inability to share urgent, critical updates about the reactor's condition between shifts and among different levels of staff led to misinformed decision-making. This breakdown in communication and coordination resulted in a systematic failure to act on and disseminate essential details of the plant's safety protocols effectively (INSAG, 1992). In retrospect, had there been a more adaptive approach, it could have involved the establishment of robust, real-time communication channels that could update all stakeholders of the nuclear plant on the reactor's status and emerging risks.

The ability of teams to adapt can be examined by analysing the shifts in their coordination (Arrow et al., 2000; Grote et al., 2010; Wittenbaum et al., 2002; Zhang et al., 2023). By focusing on these shifts, the aim is to elucidate how coordination can enhance the resilience and effectiveness of action teams. The adaptive coordination defined by Riethmüller et al. (2012) as a "change between explicit and implicit coordination behaviours that triggered by situational changes" (p.58). Action teams employ this combination of behaviours to effectively manage their environments' dynamic demands (Riethmüller et al., 2012). Explicit coordination involves clear, direct communication among team members, while implicit coordination relies on the tacit processing of information, using non-verbal cues and subtle behavioural adjustments to maintain team synergy (Kolbe et al., 2013; Riethmüller et al., 2012). This combination of coordination behaviours is crucial in reacting to immediate changes and daily operations, ensuring teams can respond seamlessly and efficiently to both anticipated and unforeseen challenges, which is a hallmark of resilience (Son et al., 2020).

While the importance of coordination behaviours in cultivating resilience is well-established, current methods may not fully capture the temporal evolution of these behaviours (David et al., 2022; Endedijk et al., 2018). Methods, such as post-event surveys, offer retrospective insights that may not fully reflect the dynamic changes in coordination behaviours as they happen in real-time (Schraagen & David, 2021; van den Oever & Schraagen, 2021; Wiltshire et al., 2022). In other words, these methods might miss the fluid and dynamic nature of how team members interact and coordinate with each other as situations unfold. To fully comprehend the dynamic nature of coordination behaviours, it is necessary to explore how coordination evolves and manifests over time (David et al., 2023; Lei et al., 2016). This means observing and analysing coordination within the team as an ongoing process rather than a series of separate, static events. By adopting this lens, we can view the coordination behaviour dynamics within the action team not just as isolated acts but as a continuous, evolving process of changes between explicit and implicit behaviours(David et al., 2022; David et al., 2023). This approach could allow us to understand how coordination behaviour emerges, adapts, and potentially changes in response to unexpected events.

Against this backdrop, this research explores the dynamic nature of coordination behaviours by investigating the moment-by-moment interaction of the Apollo-13 mission, capturing the team's coordination behaviour as they responded to an unfolding crisis. By analysing coordination behaviours before and during the accident as it developed in a sequential manner, this study adopts a longitudinal lens, revealing the moment-by-moment adjustments and adaptations the team made in real-time. This approach moves beyond the limitations of retrospective analysis, documenting the unfolding coordination continuously and holistically as the high-pressure situation escalates. This promises a more specific understanding of how resilience evolves, providing deeper insights into the dynamic essence of team coordination and the emergence of resilience in action (Lei et al., 2016). Examining coordination in such a way, as a temporally situated process rather than isolated acts, can enhance our understanding of how teams sustain their adaptability when facing unexpected challenges.

Theoretical Framework

This section discusses the action teams' definition, outlining their defining characteristics and the high-stakes environments in which they operate. It further investigates team coordination, focusing on the types of coordination behaviours—explicit and implicit—and their impact on team functionality under pressure. This exploration sets the foundation for analysing how these coordination behaviours play out in real-time situations, particularly during the Apollo 13 mission. At the end of this section, an overview of the Apollo 13 mission is provided to set the scene and contextualise these theoretical findings within a practical example.

Action Teams

Action teams are defined as groups of individuals with specialised skills (Sundstrom et al., 1990, as cited in Edmondson, 2003) operating under high-stakes conditions, where time-constrained performance is critical and the outcomes are irreversible (Ishak & Ballard, 2012). This specialised skill set is not solely technical but also encompasses the ability to coordinate effectively under duress (Edmondson, 2003). This definition captures what distinguishes action teams from conventional teams - their ability to perform under pressure and in complex scenarios. The nature of their work is such that it requires immediate and decisive action, underscoring the irreducibility and urgency of their tasks (Edmondson, 2003; Ishak & Ballard, 2012).

A defining characteristic of action teams is their temporary nature. They are often formed to tackle specific, time-sensitive challenges and navigate through phases of preparation, simulation, production, and adaptation (Ishak & Ballard, 2012). The crux of this research lies within the adaptation phase, focusing on how team members recalibrate their actions in response to the dynamic nature of unfolding events (Ishak & Ballard, 2012).

Even though action teams, by definition, operate in high-risk and technologically complex environments (Edmondson, 2003), soft skills, such as the ability to coordinate effectively, play a significant role in an action team's success (Krenz & Burtscher, 2021; Lingard, 2004; McKinney et al., 2004). Research shows that the performance of action teams is directly affected by the dynamics of coordination behaviours among team members, which can manifest as concise, direct communication (Edmondson, 2003) or through strategic realignment led by a team leader (Ishak & Ballard, 2012). Likewise, the dynamics of coordination behaviours have been directly linked to the occurrence of critical errors. Research indicates that failures in effectively transmitting and receiving crucial information—such as misinterpretations of medical data in hospitals (Lingard, 2004) or miscommunications during equipment checks in nuclear facilities (Stachowski et al., 2009)—have led to significant operational failures. These coordination breakdowns, often under conditions of high pressure and urgency, result in errors that could have been prevented by clearer and more precise exchanges of information.

The ability to adapt coordination behaviours within the team to new or evolving circumstances is a key aspect of effective action team performance (Ishak & Ballard, 2012). This adaptability is not just a reactive measure but a proactive strategy that enables action teams to maintain efficacy under pressure (Burke et al., 2006). Therefore, a detailed examination of changes in coordination behaviour is essential to understanding how action teams achieve their objectives under demanding conditions.

Coordination in Action Teams

Coordination within action teams represents an essential facet of team processes, especially in high-stress situations where rapid, decisive action is paramount (Edmondson, 2003; Marks et al., 2001). The concept of coordination is central to understanding how teams effectively navigate complex tasks and environments, ensuring that individual efforts converge towards a common goal harmoniously and efficiently (Salas et al., 1993, 2000). Team coordination is the emergent process that occurs when individuals work interdependently towards a common goal within a specific time frame (Cannon-Bowers et al., 1995). It involves strategic integration and alignment of team members' actions, knowledge, and goals to perform effectively (Gorman, 2014; Malone & Crowston, 1994; Salas et al., 1993).

Information and Action-related Coordination

One of the most common distinctions in team coordination is between information-related and action-related coordination (Boos et al., 2011; Riethmüller et al., 2012; Wittenbaum et al., 2002). Information-related coordination refers to active information management within the team, for example, requesting task-relevant information or providing information to a team member without being asked (Arrow et al., 2000; Kolbe et al., 2013; Wittenbaum et al., 2002). Action-related coordination refers to facilitating action coordination, for example, by giving instructions or backing the team members up by completing task-relevant action without being asked to do so (Arrow et al., 2000; Kolbe et al., 2013, 2014). These two types of coordination are not isolated; they dynamically interact and are interdependent (Kolbe et al., 2013). For instance, a team member's ability to effectively back up a colleague in completing a task (action-related coordination) is significantly enhanced by timely and relevant information received about the task's status or requirements (information-related coordination) (Kolbe et al., 2011, 2014). Thus, the seamless interplay between these two types of coordination is important for the adaptability, efficiency, and success of teams, particularly in high-stakes environments (Arrow et al., 2000; Boos et al., 2011; Kozlowski & Ilgen, 2006; Malone & Crowston, 1994).

Implicit and Explicit Coordination

Another way to characterise coordination is by mode (Kolbe et al., 2013), which can be either implicit or explicit. Explicit coordination involves direct verbal communication strategies which synchronise actions and decisions across team members (Kolbe et al., 2011; Wittenbaum et al., 2002). This form of coordination is crucial for clarifying roles, responsibilities and procedures, especially in unfamiliar or complex tasks (Kozlowski & Bell, 2003). Explicit coordination can be exemplified by overt actions such as providing direct instructions, requesting information directly, or initiating communication with a specific team member (Kolbe et al., 2013). Such coordination is essential in action teams, where the precise sequence and timing of interdependent actions are critical (Konradt et al., 2021), as observed in healthcare settings (Kolbe et al., 2011), aviation (Grote et al., 2010) or control crews in nuclear power plants (Zhang et al., 2023). For instance, in an emergency room, a lead surgeon might explicitly call out specific tasks to team members to ensure a surgical procedure is performed seamlessly, or an air traffic controller might use explicit commands to manage the safe landing of multiple aircraft. Additionally, specific behaviours crucial within these settings include the use of standardised communication protocols, which ensure that all members understand and follow the same procedures and terminologies, thereby reducing ambiguity and enhancing response times (Grote et al., 2010; Kolbe et al., 2011). In high-stakes environments in which action teams operate, command-and-control communication often dictates the operational flow. Commanders provide clear, concise, and direct orders to facilitate quick reactions and compliance (Konradt et al., 2021). However, excessive use of this type of coordination may lead to information overload among team members, resulting in a loss of efficiency (Kolbe et al., 2013, 2014). When too much communication occurs, it can disrupt individual focus and the natural rhythm of task execution, ultimately decreasing the overall effectiveness of team performance (Wittenbaum et al., 2002).

In contrast, implicit coordination is characterised by its tacit nature within a team, occurring naturally and sometimes unconsciously, without being directed towards any specific team member (Rico et al., 2008). This form of coordination enables team members to align their actions seamlessly and anticipate the needs of the task and their colleagues, often without the need for explicit verbal communication (Rico et al., 2008). Implicit coordination may manifest through subtle behaviours such as unconsciously commenting on one's own behaviour, providing information to a team member without being asked, observing colleagues and anticipating what they need or non-verbally signalling a strategy shift (Kolbe et al., 2013). For instance, in high-pressure work environments such as police teams, implicit coordination includes behaviours such as adjusting their position in response to the movements of their peers without explicit directions or picking up and preparing tools that another team member will soon need based on the unfolding situation (Marques-Quinteiro et al., 2013). Studies have highlighted that implicit coordination positively impacts team performance by enhancing operational efficiency and safety (Konradt et al., 2021; Marques-Quinteiro et al., 2013). In other words, their overall performance tends to improve when team members can work together smoothly and effectively without explicit communication. However, a potential challenge with implicit coordination is the risk of misalignment, especially in novel situations or when team members' mental models are not completely congruent (Marques-Quinteiro et al., 2013). Overreliance on tacit understanding can lead to coordination breakdowns if the non-verbal cues are misinterpreted or assumptions about shared knowledge are incorrect (Marques-Quinteiro et al., 2013; Rico et al., 2008, 2011). In the context of action team operations, this could mean misjudging a colleague's readiness to perform a task or misunderstanding a non-spoken signal, which can result in operational errors or safety hazards.

Temporal understanding of Team Coordination in Action Teams

The importance of coordination is illustrated by scenarios such as the Apollo 13 mission, where aligning actions, knowledge, and objectives among team members can significantly impact outcomes. However, there remains a gap in understanding coordination behaviour as a continuous process which evolves in response to unexpected events (David et al., 2022).

Bridging this gap, coordination dynamics emerges as a concept that encapsulates the fluid and continuous interplay between explicit and implicit coordination within a team (David et al., 2022). For action teams, whose functionality and success depend on adaptability and resilience, the seamless integration of these coordination forms is integral (Edmondson, 2003; Ishak & Ballard, 2012). The ability to toggle between explicit, clear verbal directives and the more subtle, non-verbal cues of implicit coordination reflects a team's capacity to navigate high-pressure environments effectively (David et al., 2024; Rico et al., 2008; van den Oever & Schraagen, 2021). Historically, the study of team coordination began with a focus on explicit coordination; however, the recognition of implicit coordination importance has shifted the research paradigm towards understanding the complex dynamics that contribute to a team's agile response to real-time challenges (Rico et al., 2008; Salas et al., 2000). This paradigm shift has led to an acknowledgement of the complex interplay between both forms of coordination and has spurred a deeper inquiry into how these dynamics evolve. Therefore, analysing the transitions between implicit and explicit coordination becomes essential to understanding the full spectrum of coordination behaviours contributing to team success.

The unpredictable nature of the Apollo 13 mission, with its extensive demands on crew resilience, presents an instructive opportunity to explore how coordination behaviours manifest in action teams under stress. The study explores how and why resilient team might favour explicit coordination or opt for the subtleties of implicit and what role this coordination plays in enhancing team resilience.

Case Study

The Apollo 13 mission, officially known as Apollo 13 Lunar Module 7, was the seventh manned mission in NASA's Apollo space program. Launched on April 11, 1970, from the Kennedy Space Center, Florida, the mission's primary objective was to land on the Moon. The crew members included Commander James A. Lovell Jr., Command Module Pilot John L. Swigert Jr., and Lunar Module Pilot Fred W. Haise Jr.

However, the mission had to be aborted after approximately 56 hours of flight due to an oxygen tank explosion in the service module. This critical failure led to a severe reduction in the spacecraft's life-support capability. In what is now considered a remarkable feat of human ingenuity, resilient and teamwork, the crew and ground control worked together to safely return the astronauts to Earth on April 17, 1970, using the Lunar Module as a "lifeboat."

The Apollo 13 mission is often remembered for the phrase "Houston, we've had a problem," signifying the calm and composed communication between the crew and ground control in the face of life-threatening adversity. Despite not achieving its original objective of landing on the Moon, the mission was deemed a "successful failure." This term encapsulates how, despite the mission's setbacks, the successful, safe return of the crew and the invaluable lessons learned in crisis management and emergency ingenuity were significant achievements (McDivitt, 1970; Orloff, 2000). These experiences not only enhanced NASA's procedural guidelines but also demonstrated the importance of adaptive coordination under extreme conditions.

The Apollo 13 scenario provides a distinct example of how action teams can dynamically adjust their strategies in real-time to effectively manage unforeseen challenges. It makes a rich case for exploring the coordination behaviours that lead to performance under pressure.

Aim of the Study

This study aims to investigate the shifts in coordination behaviours employed by action teams in response to crisis situations, with a focus on the Apollo 13 mission as a case study. It seeks to understand how a team known for its resilience (Kirkman & Stoverink, 2021) adapts its coordination methods in the face of unforeseen challenges. This is crucial for clarifying the mechanisms underpinning successful team coordination under pressure, offering insights into the real-time strategic adjustments teams make in critical scenarios. Specifically, the research will examine the patterns of explicit and implicit coordination behaviours within the team, integrating the actors of communication, as it allows for granular analysis of role-specific responses to accident (Stachowski et al., 2009, Zhang et al., 2023). This approach facilitates a detailed examination of how individual and collective actions evolve in response to a developing crisis situation. The research question for this exploratory study is: *How do the coordination dynamics within a resilient action team shift before and during an unfolding accident?* This inquiry will contribute to a deeper understanding of the adaptive processes that ensure team effectiveness in high-stakes environments.

Research Design and Methods

Research Design

This exploratory study uses a mixed methods study approach on a secondary dataset in the form of a transcript from a real-life situation to investigate whether there are shifts in coordination behaviours as the event unfolds. The data consists of a moment-by-moment air-to-ground voice loop transcript during the Apollo-13 mission. The voice loop was divided into two equal sets of six hours each, one before the accident and one during. The dataset was systematically coded using a qualitative coding approach, which was used to identify types of coordination behaviour based on an adjusted codebook from Kolbe et al. (2013). Software THEME was used to identify hidden repetitive patterns in behaviour and interactions in the coded data through t-pattern analysis.

Dataset

The dataset comes from the audio transcript of the Apollo 13 mission in 1970, available at https://apolloinrealtime.org/13/ (Feist, 2020). The transcript contains a loop of air-to-ground voice communication involving four distinct speakers. These include the CAPCOM (Spacecraft Communicator) responsible for communicating with the crew from the Mission Control room (Kennedy, 2016); CMP (Command Module Pilot) - John L. Swigert Jr., LPM (Lunar Module Pilot) - Fred W. Haise Jr.; CDR (Commander) - James A. Lovell. The data analysis covers a six-hour period before the accident, starting from 49:08:17 and ending at 55:53:12 (hh:mm:ss) and includes 419 speech acts. The second part of the analysis covers a six-hour duration during the accident, starting from 55:55:20 and ending at 62:05:27. This period includes 1205 speech acts and begins with the famous line "Houston, we've had a problem here" after the explosion and rupture of an oxygen tank in the service module.

Coding Scheme and Codebook

The dataset was coded with an adjusted version of the Kolbe et al. (2013) codebook. The codebook is based on the Co-ACT framework, "Framework for Observing Coordination Behaviour in Acute Care Teams", a model developed for the systematic observation and analysis of coordination behaviour in acute care teams (Kolbe et al., 2013). The framework categorises coordination behaviours along two dimensions: explicit versus implicit coordination and action versus information coordination (**Figure 1**). This structure results in four quadrants, each containing three specific behavioural categories, as seen in **Figure 1**. These quadrants provide a view of the diverse coordination strategies employed by teams (Kolbe et al., 2013).

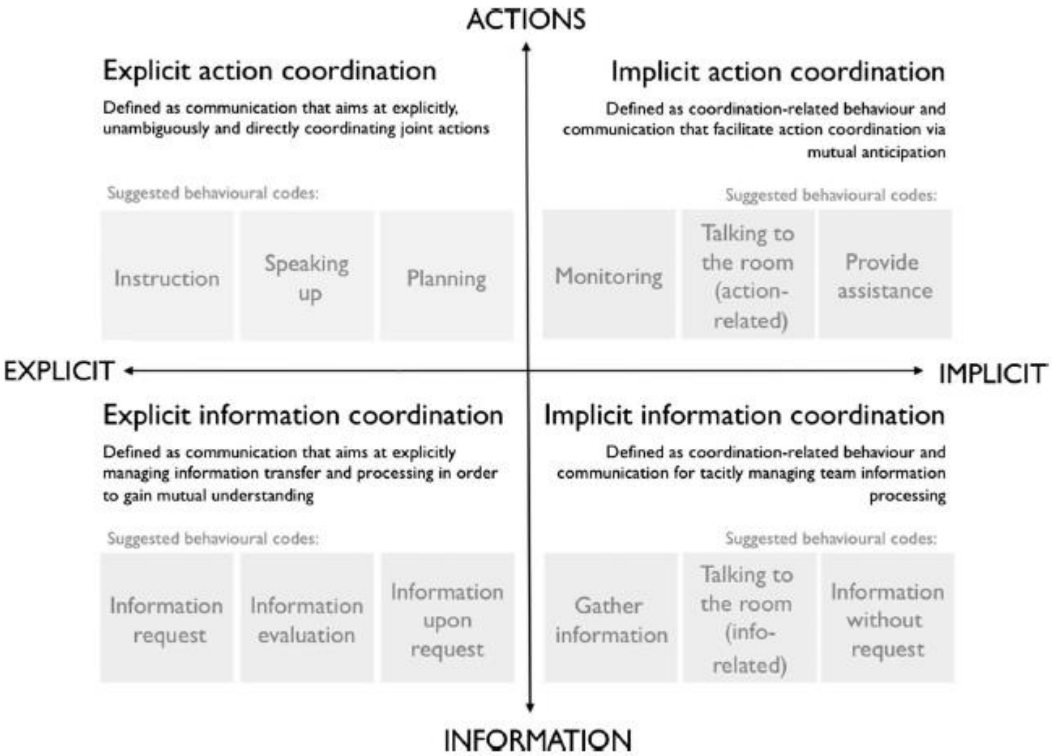

Figure 1. *Co-ACT. Framework For Observing Coordination Behaviour In Acute Care Teams.*

Additionally, Muller (2021) introduced and added two new codes, "acknowledgement" and "call out" to the initial codebook. These additions were prompted by their consistent emergence across the dataset, highlighting their significance in the coordination of action teams. Including these codes is instrumental for dissecting the nuances of closed-loop communication, a critical component in environments requiring high levels of precision and accountability (Sexton & Helmreich, 2000). Closed-loop communication is characterised by the initiation of a message (call out “Huston, 13”), followed by a confirmation or acknowledgement (“Go ahead”, “Okay”, “Roger”) that the message has been understood and, if necessary, acted upon. This cycle ensures that information is transmitted, received, and comprehended as intended, reducing the likelihood of errors (Peyre, 2014). By incorporating these codes into the analysis, the study aimed to provide a more comprehensive examination of team coordination strategies. **Table 1** presents the adjusted codebook. The codes are designed to be mutually exclusive, ensuring that no two codes can be applied simultaneously to a single event. This is essential for the reliable analysis of coordination patterns among team members (Saldana, 2013).

Table 1

Adjusted Codebook

Coordination Category	Code	Definition	Example
Explicit action coordination (EAC)	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 (IAC)	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 (EIC)	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 the system I want to make sure that we Can we review our status here”
	call out	initiating communication with a specific team member	“Huston, 13.”
	acknowledgement	response indicating that a message has been received	“Go ahead”, “okay”, “roger”
	information on request	coded if one answers a (task-relevant) question asked by another	the defibrillator is in the operating room next door
Implicit information coordination (IIC)	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.”

For the coding scheme, five columns were created in an Excel document: “Time”, “Actor”, “Utterance”, “Code”, and “Comment”. The “Time” column shows the exact time each event occurred in hh:mm:ss format, as mentioned in the transcript. The “Actor” column shows who speaks, while “Utterance” displays what they say. The column labelled “Code” contains the given code, and the “Comment” column includes any comments made by the coder. **Table 2** presents an example of the coded transcript.

Table 2

Example Of Coded Transcript

Time	Actor	Utterance	Code	Comment
049:08:16	CMP	Hey, Houston, are we clear to torque? Are you reading the torquing angles?	inforequest	-
049:08:28	CAPCOM	13, Houston. Go ahead and torque.	acknowledgement	-
049:08:35	CMP	Okay. Time of torquing will be 49 hours, 8 minutes, 35 seconds.	infowithoutrequest	-
049:08:41	CAPCOM	Roger that.	acknowledgement	Comm break.

The coding process was conducted by an MSc student from the Faculty of Behavioural, Management, and Social Sciences (BMS), employing a deductive approach to coding, which involved assigning codes to each speech event. Notably, the coding was performed not solely on the text version of the transcripts, but also, the coder was listening to the audio as it happened. This dual-method approach enabled a more precise and nuanced understanding of the data, facilitating the identification of subtleties and nuances that may not have been evident in the text alone.

Another independent researcher coded the dataset to ensure inter-rater reliability and consistency of results. Once approximately 10% of the data was coded (Bakeman et al., 2005), the coders reconvened to discuss the outcomes and ultimately decided to readjust certain speech acts, assign alternative codes, and refine certain codes and definitions. The final codebook was applied to the entire dataset, resulting in a good inter-rater agreement (Cohen’s κ =.80).

Data Analysis

T-Pattern analysis was employed using the THEME software (see https://patternvision.com) to identify differences in coordination behaviour before and during an unfolding accident. THEME software is a tool designed to identify intricate t-patterns within behavioural data. Its algorithm simplifies complex patterns into discernible sequences by retaining only the most comprehensive detections (Magnusson, 2000, 2017). A T-pattern is a repetitive sequence of actions or behaviours that occur consistently and in a specific order over a period of time (Magnusson, 2000). T-pattern analysis detects and analyzes patterns of events occurring in temporal or spatial sequences (Magnusson, 2000). The significance of this type of analysis lies in its ability to uncover hidden structures in complex behavioural data, providing a more nuanced understanding of the temporal relationships between events compared to traditional analysis techniques (Magnusson, 2017).

To analyse the datasets, data need to be organised into a format compatible with THEME software. This involves creating a category table (a reference table) and data files in a specific structure. The category table, identified by a reserved name vvt.vvt (variable-value table), is needed to define the dataset's variables and elements. Data files are formatted in a tab-delimited text-file format, containing only two columns: time and event, where each line represents a time-stamped event.

First, the category table is made. The created vvt.vvt file contains three Class names (or variables): the actors, the begin/end variable (for identifying for software whether some behaviour begins and ends), the verbal act variable and Items (or values) for each variable which presents codes from codebook. An example of a created category table is shown below. The full vvt.vvt table has been added in **Appendix A**.

actors
cmp
CAPCOM
…

b_e
b
e

verbalacts
instruction
planning
speakingup
…

The next step involves preparing the data files for importation into the software. To achieve this, the original Excel file with five columns is transformed into a text file with only two columns – “time” and “event”. Initially, the transcript was in hh:mm:ss format, but it was converted to a general format to comply with THEME standards. The “time” column contains the timestamp in a general format, while the “event” column merges items in this order: actor, the beginning of behaviour, and assigned code. The two separate text files with coded data were made to the before and during accident datasets. Each data file contains a timestamp, indicated by a “:” at the beginning of the file and “&” at the end. This is done so that the THEME can recognise the beginning and end of the file. An example of a data file for analysis is listed below.

time	event
0	:
2	cmp,b,inforequest
13	CAPCOM,b,acknowledgement
20	cmp,b,infowithoutrequest
…	…
25000	&

After the data files are prepared, they are imported into the THEME software. To start t-pattern analysis, it is necessary to set the parameters. These parameters include defining critical intervals, the minimum occurrences of patterns, and significance levels, among others (as shown in **Figure 2**). The search parameters are chosen based on suggestions from the THEME manual (Magnusson, 2017a). For example, the chosen significance level is 0.05, which indicates a 95% probability requirement. In other words, any identified patterns are unlikely to occur by chance in 95% of cases.

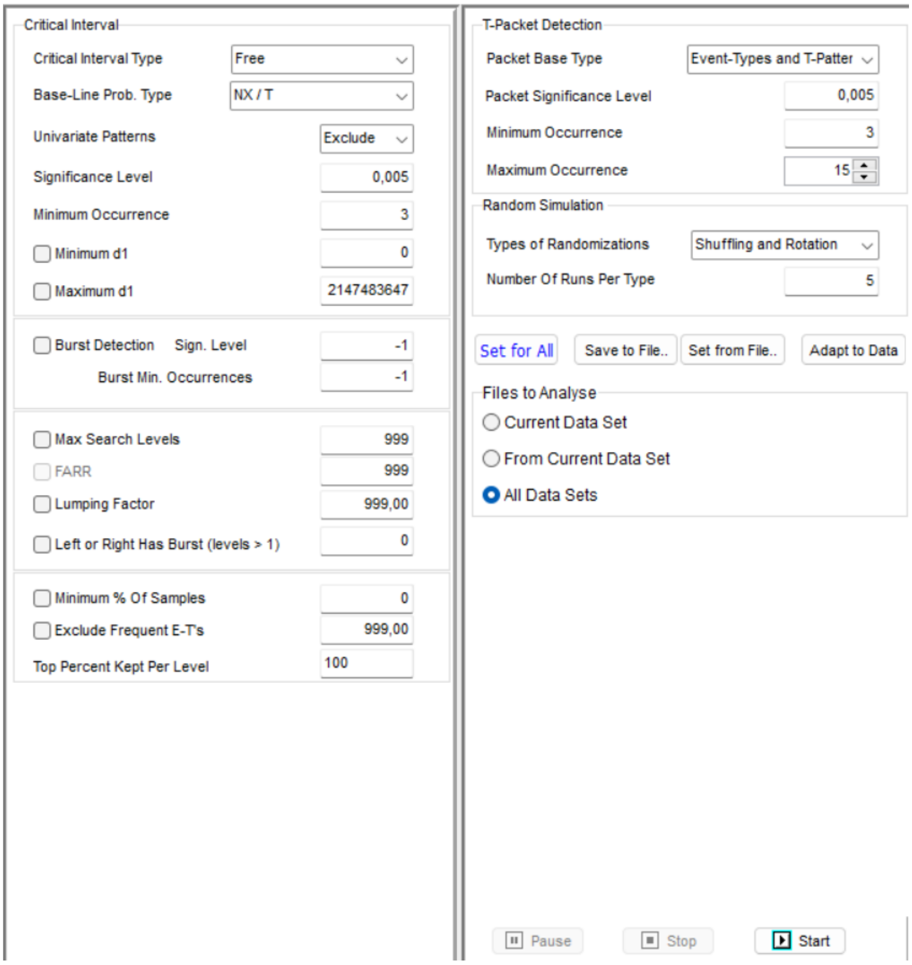

Figure 2. *Search Parameters Example.*

Data Attributes

After parameters are set, the program can run the search for T-patterns. In order to compare the coordination patterns before and during an accident, several data attributes are analysed. Each attribute chosen reflects a specific aspect of coordination behaviour and is instrumental in interpreting the team's ability to adapt and collaborate under stress. Below, we elucidate the importance of these parameters, shedding light on their significance for our study.

First is the **number of different patterns** (labelled Pattdiff), which refers to the unique patterns identified within the dataset. A greater number of patterns during a crisis may indicate that they are displaying a wider range of behaviours. This could be an indication of their adaptability and using innovative approaches in the face of unforeseen challenges. Alternatively, Kanki et al. (1991) found evidence that team effectiveness decreases with more heterogeneous team interaction. However, a more recent study by Hoogeboom & Wilderom (2020) found no connection between team interaction heterogeneity and team effectiveness. Therefore, further exploration is needed to reconcile these contrasting results. In addition to this attribute, the **mean number of different patterns** (labelled n_mean) is used, which refers to the average number of times a particular pattern is observed within a dataset.

Next is the **number of pattern occurrences** (labelled Pattocc), which refers to the total number of patterns that occur in the datasets. A greater number of pattern recurrences can be an indication of certain stability or "equilibrium" in coordination (Gorman et al., 2010, 2012). This can provide insight into which period had greater stability or how stable team members remained during the unfolding crisis. In addition, research has shown that a higher frequency of recurring team interaction patterns can decrease information sharing among team members, ultimately reducing overall team effectiveness (Hoogeboom & Wilderom, 2020). However, it is worth noting that an increase in pattern frequency is also an indication of an increase in communication (the more speech acts in the dataset, the more recurring patterns can be found).

A **number of loops** (labelled Hasloop) means that the pattern contains a loop where one or more event types recur as pattern terminals within the detected T-pattern. This indicates that certain events repeat within the structure of a pattern, forming a loop-like structure. The presence of loops in a pattern can be significant for understanding the dynamics of the behaviours being analysed, as it represents the iterative nature of communication and action within a team. Loops emphasise the significant role of recurring sequences, for example, in closed-loop communication, which is a crucial component of effective team coordination (Marzuki et al., 2020). Closed-loop communication ensures that messages are not only transmitted but also acknowledged and acted upon, preventing misunderstandings and ensuring task alignment (Peyre, 2014). Examining the behaviours that manifest within these loops and taking a closer look at possible closed-loop structures, both before and during the accident, could potentially reveal insights about the nuances of team communication.

A **number of single-actor patterns** (labelled Monodiff) refers to the number of patterns involving behaviours attributed to a single actor. Research by Zijlstra et al. (2012) found that less effective teams exhibit more mono-actor patterns, which indicate a lack of reciprocal behaviour, an important aspect of teamwork. Alternatively, a **number of multi-actor patterns** (labelled Interdiff) shows the number of patterns with two or more actors involved. An escalation to multi-actor patterns during the accident could signify enhanced team collaboration, reflecting a shift towards more integrated and collective problem-solving approaches. In addition to these attributes, a **mean number of actors** (labelled Nactors_mean) is used, which indicates the average of how many different actors are typically involved in the detected patterns. A higher mean could suggest a more inclusive and diverse set of inputs and interactions, possibly indicative of the team's utilisation of its collective resources to tackle the challenges posed by the accident. Furthermore, a **mean number of actor switches** (labelled Nswithces_mean) is utilised to indicate the average number of switches between actors within the indicated pattern. This frequency in actor switches was found to be significantly related to team effectiveness, as demonstrated by Hoogeboom & Wilderom (2020). Taking a closer look at these attributes provides a picture of the coordination complexity and degree of collaboration that underpinned the mission team's effectiveness.

Next is the **pattern length** (labelled EtsinPats) attribute, which shows the number of event-types in a pattern. This can indicate the complexity or simplicity of a pattern, with more extended patterns involving more sequential actions. According to Zijlstra et al. (2012), the more effective teams show a more stable, less variable pattern length in their coordination behaviour, as the crew establishes coordination patterns earlier, and the new environment does not significantly affect their coordination behaviour. Thus, by comparing the length of the patterns before and during the accident, it is possible to understand what the team is experiencing in terms of coordination complexity, whether it is adapting or remaining unchanged in response to crises.

Another helpful average is the **mean number of pattern levels** (labelled Level_mean), representing the average number of hierarchical levels within the detected pattern. Research by Zijlstra et al. (2012) shows that effective teams maintain stable complexity in their coordination patterns, indicative of a well-established internal structure that enhances collective performance. A stable level of complexity in patterns during the crisis, as compared to pre-crisis levels, may imply that a team was not merely reacting spontaneously to the situation. Instead, it would suggest that actions were part of a systematic (maybe pre-trained) approach, integrating behaviours into a comprehensive and coherent response plan.

Table 3 summarises the quantitative data attributes used for the analysis.

Table 3

Quantitative Data Attributes For T-Pattern Analysis

Data attribute	Label
Number of different patterns	Pattdiff
Mean number of different pattern	n_mean
Number of pattern occurrences	Pattocc
Number of loops	Hasloop
Number of single-actor patterns	MonoDiff
Number of multi-actor patterns	InterDiff
Mean number of actors	Nactors_mean
Mean number of actor switches	Nswithces_mean
Pattern length	EtsinPats
Mean number of pattern levels	Level_mean

The pattern diagram, analysed as a qualitative data attribute both before and during the accident, visually represents the most prominent patterns within the dataset. This prominence is defined by the pattern's length, hierarchical complexity, frequency of occurrence, and cumulative duration within the dataset (Magnusson, 2017a). The patterns depicted in the pattern diagram are comprised of pattern strings, which are sequences of event types from the pattern interconnected in a specific manner to form the observed pattern. By studying the pattern diagram, the connections between event types within the most prominent patterns can be visually inspected. This can help to provide a detailed breakdown of how specific behaviours are linked, potentially providing insights into the underlying structure and dynamics of team coordination. By assessing these connections, patterns of behaviour can be identified, such as the prevalence of certain behaviours. This qualitative investigation complements the quantitative findings, potentially providing a more nuanced understanding of team coordination and processes.

Pattern Visualisation

To overcome the THEME software's limitations in visualising intricate pattern strings and enhance the depiction of how event types and actors interconnect, the use of Unified Modelling Language (UML) diagrams was adopted. UML diagrams are commonly used by software engineers to conceptualise the structure, design, and implementation strategies of complex software systems coherently and comprehensively (Booch, 1998). To aid in creating these diagrams, PlantUML (see https://plantuml.com/), an open-source tool, was employed. PlantUML enables the generation of UML diagrams, providing a more user-friendly and descriptive approach to visualising the interactions within the pattern strings observed in the study.

Results

This chapter presents an analysis of the coordination behaviours within the Apollo 13 mission team, balancing quantitative metrics with qualitative insights that explore these patterns' substantive content and contextual nuances. This approach enables a dual perspective that reveals the structural dynamics of team coordination and the adaptive strategies employed before and during the crisis, providing a multifaceted understanding of team processes.

Quantitative Results

Data Attributes

T-pattern analysis was conducted for both datasets using the same search parameters. The analysis performed on the coordination behaviour before and during the Apollo-13 accident revealed substantial quantitative differences. Table 4 presents the absolute frequency (*N*), mean (*M*) and standard deviation (*SD*) of the data attributes measures separately for the before and during accident datasets.

The number of distinct coordination patterns (Pattdiff) increased from N_{before}=358 (*M*=4.19, *SD*=2.5) in the pre-accident phase to N_{crisis}=6276 (*M*=3.24, *SD*=0.9) during the accident. Correspondingly, the frequency of these patterns (Pattocc) escalated from N_{before}=1503 instances before the accident to N_{crisis}=20314 instances during the accident (after the oxygen tank explosion).

In assessing specific pattern types, the number of loops (Hasloop) rose from N_{before}=123 to N_{crisis}=4714, indicating a heightened recurrence of certain communication behaviours during the crisis. Single-actor patterns (MonoDiff) were less frequent, from N_{before}=75 before to N_{crisis}=183 observed during the accident. In contrast, multi-actor patterns (InterDiff) increased from N_{before}=283 to N_{crisis}=6093.

Patterns observed became more complex during the accident, with the pattern length (EtsinPats) extending from N_{before}=36 (*M*=3.82, *SD*=1.41) to N_{crisis}=43 (*M*=9.01, *SD*=3.53), which reflects the team's engagement in more elaborate sequences of actions.

The mean number of pattern levels (Level_mean) increased considerably from *M*=2.42 (*SD*=1.08) to *M*=4.83 (*SD*=1.58), illustrating an increase in the hierarchical complexity of coordination behaviour, pointing towards more layered communication structures in response to the crisis. The mean number of actors (Nactors_mean) increased from *M*=1.86 (*SD*=0.51) to *M*=2.71 (*SD*=0.57), indicating a broader involvement across team members. Lastly, the average number of actor switches within patterns (Nswithces_mean) increased from *M*=1.22 (*SD*=0.87) before the accident to *M*=3.49 (*SD*=1.81) during the accident, suggesting a more dynamic and versatile interaction among team members.

Table 4

Change in Coordination Behaviour Before Vs. During Accident

Attributes	Label	Frequency					
		Before accident			During accident		
		N	*M*	*SD*	*N*	*M*	*SD*
Number of different patterns	Pattdiff	358	4.19	2.5	6276	3.24	0.9
Number of pattern occurrences	Pattocc	1503	-	-	20314	-	-
Number of loops	Hasloop	123	-	-	4714	-	-
Number of single-actor patterns	MonoDiff	75	-	-	183	-	-
Number of multi-actor patterns	InterDiff	283	-	-	6093	-	-
Pattern length	EtsinPats	36	3.82	1.41	43	9.01	3.53
Mean number of pattern levels	Level_mean	-	2.42	1.08	-	4.83	1.58
Mean number of actors	Nactors_mean	-	1.86	0.51	-	2.71	0.57
Mean number of actor switches	Nswithces_mean	-	1.22	0.87	-	3.49	1.81

To examine whether significant differences existed in various attributes before and during the accident, a series of two-sample t-tests were conducted. These attributes included the mean number of different patterns (Pattdiff), the mean of pattern length (EtsinPats), the mean number of pattern levels (Level_mean), the mean number of actors (Nactors_mean), and the mean number of actor switches (Nswithces_mean).

The t-test for the mean number of different patterns (Pattdiff) before and during the accident revealed a statistically significant difference between the two periods, $t(6632) = 17.981$, $p < .001$. The 95% confidence interval for the difference in means ranged from 0.9 to 1.12, suggesting a significant variation during the accident. In terms of the mean of pattern length (EtsinPats), the results indicated a significant difference between the means of the two samples, $t(77) = -8.70$, $p < .001$, with a 95% confidence interval extending from -6.25 to -3.92. This finding confirms the substantial change in pattern length associated with the accident. Similarly, the mean number of pattern levels (Level_mean) showed a significant difference, $t(6632) = -28.29$, $p < .001$, with the 95% confidence interval ranging from -2.55 to -2.22. The analysis of the mean number of actors (Nactors_mean) also indicated a significant change, $t(6632) = -27.321$, $p < .001$, with a 95% confidence interval ranging from -0.89 to -0.77. Lastly, the mean number of actor switches (Nswithces_mean) also revealed a significant difference with $t(6632) = -23.446$, $p < .001$, with a 95% confidence interval ranging from -2.44 to -2.06.

Comparative Analysis of the Coordination Patterns

The comparative analysis of the coordination patterns before and during the accident, as shown in the figures below, reveals a significant change in the complexity of coordination within the team. In particular, **Figure 3** illustrates a marked increase in pattern length during the accident, with pattern #8501 having a length of 23 compared to the pre-accident maximum of 8 (pattern #483), indicating more complex coordination required to manage the crisis.

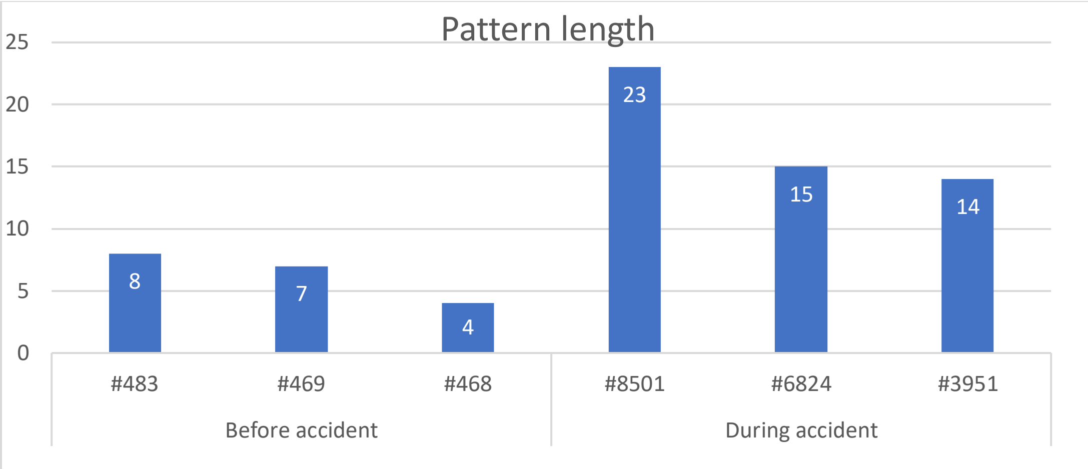

Figure 3. *Pattern length comparison diagram*

Concurrently**, Figure 4** highlights the dominance of Pattern #8501 during the accident, which accounted for 57% of the total pattern duration, a significant increase from the 6% observed for Pattern #483 before the accident.

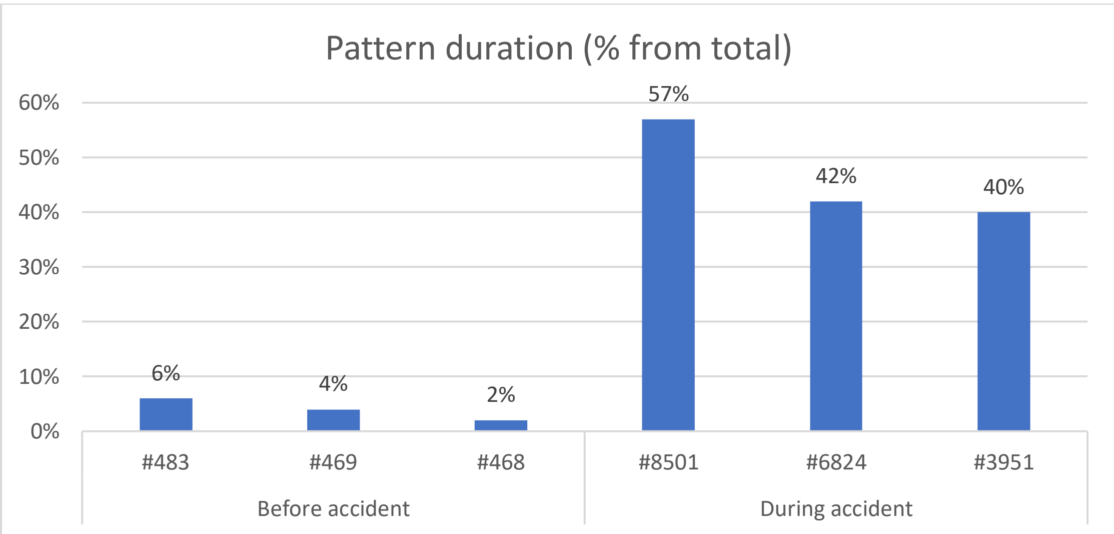

Figure 4. *Pattern duration (% from total) comparison diagram*

Qualitative Results

The qualitative dimension of this research focuses on the substantive content within the coordination behaviour patterns identified during the Apollo 13 mission. While quantitative results have offered insights into the composition and frequency of these patterns, the qualitative examination delves into the nature and implications of the communication and actions that constitute these patterns. To visually investigate the most prominent patterns for the datasets, the patterns were visualised with the PlantUML tool. This approach clarifies the sequence and flow of team interactions and highlights the foundational coordination strategies that underpin mission operations.

The Most Recurrent Patterns Before the Accident

The t-pattern diagram for the dataset before the Apollo 13 accident (**Figure 5**) visually represents the coordination dynamics within the mission team under normal operating conditions. The vertical axis categorises the coded behaviours, while the horizontal axis maps them over time. Branching structures within the diagram represent common sequences of interactions, with accompanying numbers indicating the frequency of these patterns. The diagram allows to investigate visually the most prominent patterns within the dataset (the patterns that are the highest in the hierarchy).

In the pre-crisis dataset, three patterns stand out (#483, 469 and 468)[1]. Pattern #483, the most complex, involves eight interrelated event types and constitutes 6% of the observed communication. Following this, pattern #469, with seven event types, covers 4% of communications, while the simpler pattern #468 involves four event types, accounting for 2%. Taken together, these patterns provide a comprehensive view of the structured communication sequences that prevailed during the pre-crisis phase of the mission. The pattern strings (sequences of event types which form the pattern) are presented in **Appendix B**.

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[1] The THEME software randomly assigns names to patterns (#). We will continue to use these names for consistency in analysis.

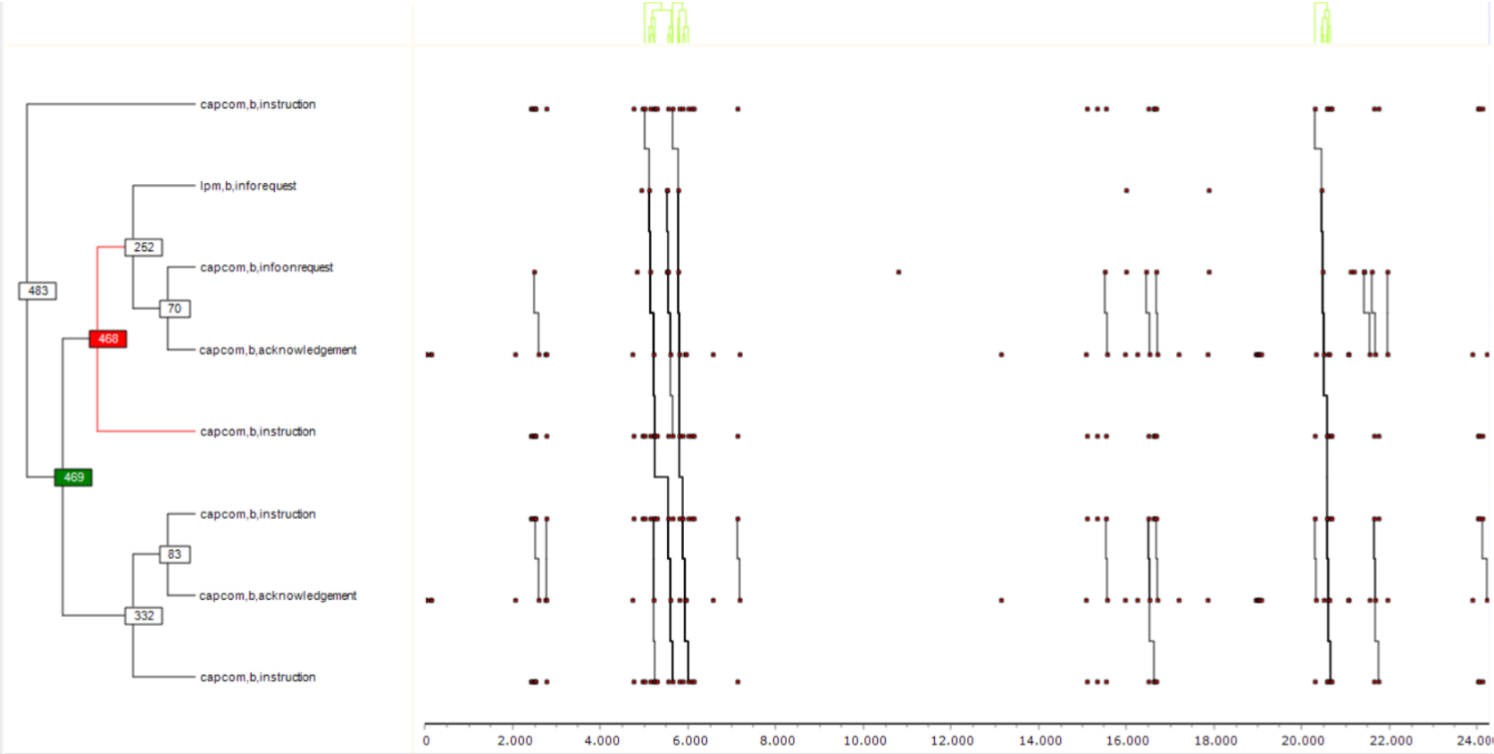

Figure 5. *T-Pattern Diagram For Dataset Before Accident.*

The most recurrent pattern for the pre-crisis dataset (#483) unveils a multifaceted interaction between two actors, CAPCOM (spacecraft communicator) and LPM (Fred W. Haise Jr.), marked by a series of instructions, information requests, and acknowledgements. **Figure 6** presents the pattern visualisation. The sequence begins with CAPCOM issuing instructions

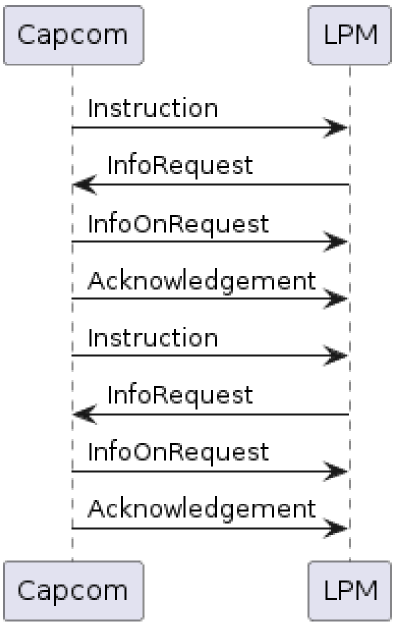

Figure 6. Pattern #483

to LPM, establishing the directive nature of their communication. LPM, seeking additional details or clarification, counters with an information request directed back to CAPCOM. CAPCOM responds, fulfilling the information request and simultaneously providing an acknowledgement, confirming receipt and understanding of LPM's request. This cycle repeats throughout their communication, ensuring that each task is completed correctly and that both parties clearly understand the ongoing operations.

Such a pattern suggests a procedural dialogue in which each completed task or received a piece of information cues the next instruction. The iterative nature of this communication is further evidenced by a recurring acknowledgement from CAPCOM, indicating a consistent acknowledgement of ongoing tasks and signalling a continuous, collaborative effort to refine and progress through the operational steps. This pattern represents a responsive dialogue between CAPCOM and LPM, characterised by a rhythm of directive and reactive exchanges that emphasise procedural adherence and iterative refinement. In contrast, during the crisis phase, the dialogue shifts toward more frequent and complex exchanges. These are necessitated by the urgent need to manage the unfolding emergency, where rapid, accurate problem-solving and decision-making take precedence over routine procedural adherence.

The next pattern (#469) demonstrates a layered interaction between CAPCOM and LPM. **Figure 7** presents pattern visualisation. The sequence begins with LPM seeking information and taking a proactive approach to clarify or gather necessary data for task execution.

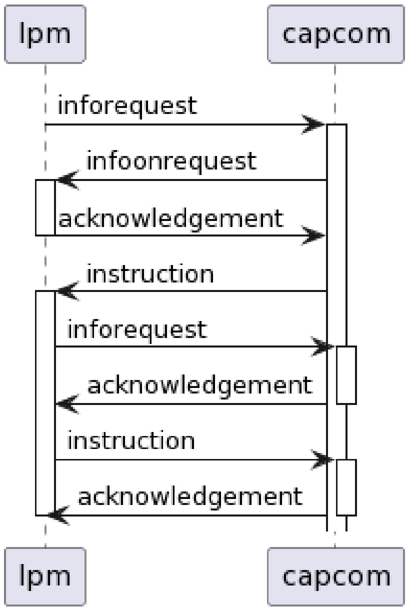

Figure 7. *Pattern #469*

CAPCOM responds by providing the requested information and confirming its receipt with an acknowledgement. This showcases closed-loop communication, a key feature for maintaining clarity and ensuring tasks are understood and executed correctly. The pattern describes a cyclic exchange between CAPCOM and LPM, where CAPCOM conveys instructions to LPM regarding the operational workflow. Each instruction by CAPCOM is met with an information request from LPM, which may indicate step-wise task completion or the need for ongoing confirmation at each process stage. A sequence of acknowledgements and further instructions characterises this cycle of information requests by LPM and instructional responses from CAPCOM. The pattern reflects a disciplined and systematic approach to task management and demonstrates a well-structured and meticulous communication protocol between the crew members.

Lastly, the third most recurrent pattern in the pre-crisis dataset (#468) shows a coherent and structured flow of communication. The LPM's request initiates a chain of CAPCOM responses progressing from acknowledgement to instruction. This interaction sequence exemplifies a procedural communication framework and demonstrates how information seeking within a team triggers a structured series of informative and directive responses critical for task continuation and operational coherence. **Figure 8** presents pattern visualisation.

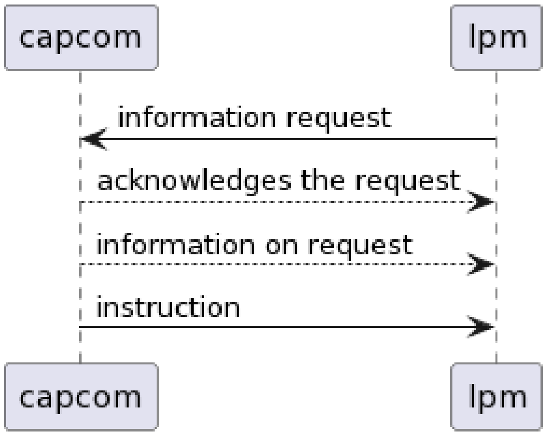

Figure 8. *Pattern #468*

Overall, examining pre-crisis coordination patterns reveals a foundation of procedural communication and the prevalence of explicit coordination, illustrating the team's systematic approach to mission management.

The Most Recurrent Patterns During the Accident

In the t-pattern diagram during the accident, a distinct transformation in the coordination patterns of the Apollo 13 team becomes evident, marking a departure from the pre-crisis communication strategies. As illustrated in the diagram (**Figure 9**), this shift is characterised by an increased reliance on more complex and explicit coordination mechanisms. Unlike the relatively streamlined and direct patterns observed before the accident, the during-accident scenario revealed a heightened complexity in communication, with a notable surge in the frequency and intricacy of explicit coordination actions. This change could underscore the team's adaptive response to the emergent challenge, emphasising a more dynamic and elaborate exchange of directives, information requests, and confirmations to navigate unforeseen circumstances effectively.

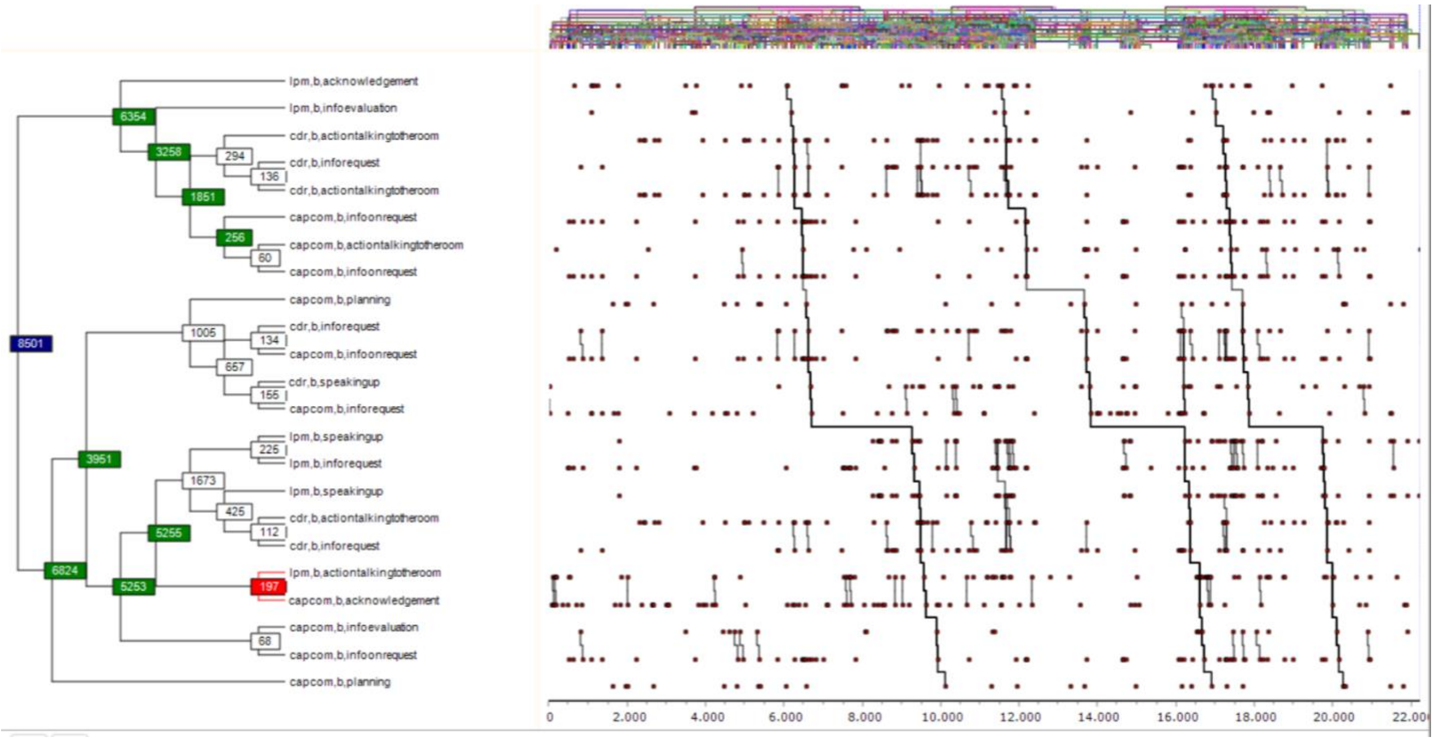

Figure 9. *T-Pattern Diagram For Dataset During Accident*

In this dataset, three patterns were identified as prominent, each reflecting a distinct approach to crisis management through explicit coordination mechanisms. Pattern #8501 stands out due to its complexity, with a length of 23, making it the most intricate and demanding pattern observed, and it dominates the analysis, accounting for 57% of the total period. Pattern #6824 follows, with a length of 15, representing a significant portion of the coordination effort at 42% of the analysis time. Lastly, pattern #3951 has a length of 14 and encompasses 40% of the total analysed duration. Together, these patterns vividly illustrate the adaptive coordination strategies the Apollo 13 team deployed in the aftermath of the accident.

The development of more intricate coordination patterns (compared to the pre-accident dataset) involves more explicit coordination behaviour. As such, the most prominent pattern for the analysed dataset (#8501) reveals a complex process of communication, information exchange, and decision-making among the three roles: CAPCOM (spacecraft communicator), CDR (James A. Lovell Jr.) and LPM (Fred W. Haise Jr.). The observation of how actors switch coordination behaviours underlines the team's adaptation to the unfolding crisis, highlighting how each team member's role and communication style evolve in response to the immediate needs and complexities of the situation. It emphasises the iterative nature of planning and information processing, with each role having specific contributions and responsibilities. The pattern emphasises proactive communication (speaking up), implicit action coordination (actiontalkingtotheroom), and the importance of recognition and evaluation in collaborative environments (acknowledgement; infoevaluation). **Figure 10** demonstrates the relationship between actors in the pattern. The pattern consists of four main parts:

1. *Information and Acknowledgement Loop*: The initial part suggests an interaction where LPM and CAPCOM acknowledge and evaluate information, possibly provided by CDR or resulting from CDR's actions (like actiontalkingtotheroom). This suggests a scenario where communication and information verification are crucial, leaving no room for error.

2. *Planning and Requesting Information*: The sequence involving planning and infoonrequest suggests that CAPCOM plays a role in planning and requests information from CDR, who in turn might seek additional information or clarification (inforequest). This indicates a collaborative planning process where different roles contribute information and feedback.

3. *Speaking Up and Action Talking:* The repetition of speakingup and actiontalkingtotheroom indicates scenarios where roles need to voice concerns, take the initiative, provide updates, or request information actively. This behaviour could reflect a move from waiting for directive approval to a dynamic where team members, driven by their expertise and understanding of their roles, take charge of decision-making. For instance, when CDR or LPM engages in speaking up or action talking to the room, it precedes or follows information being shared or instructions being given, suggesting that these proactive actions

are pivotal in setting the stage for decision-making or clarifying the next steps. The interaction of these proactive behaviours with other coordination behaviours suggests a distributed leadership model where command and control are fluid and based on the immediate needs of the crisis.

4. *Feedback and Evaluation*: The pattern of information evaluation followed by planning activities suggests a feedback loop where information is evaluated, leading to planning or adjustments in plans based on the evaluated information.

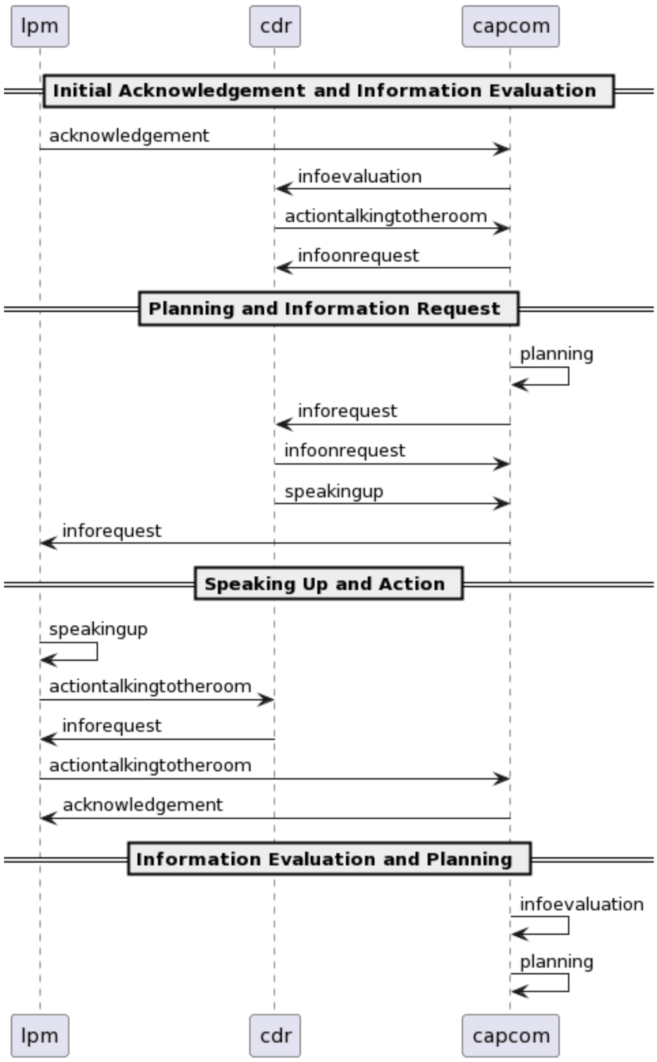

Figure 10. *Pattern #8501*

The second most prominent pattern (#6824) presents a nuanced tapestry of interactions among CAPCOM, CDR, and LPM, revealing the complex coordination and communication flows. This pattern elucidates a dynamic, multi-stage process of decision-making, information exchange, and strategic planning, underscored by the collaborative efforts of the team members. **Figure 11** represents the pattern visualisation. The pattern begins with CAPCOM

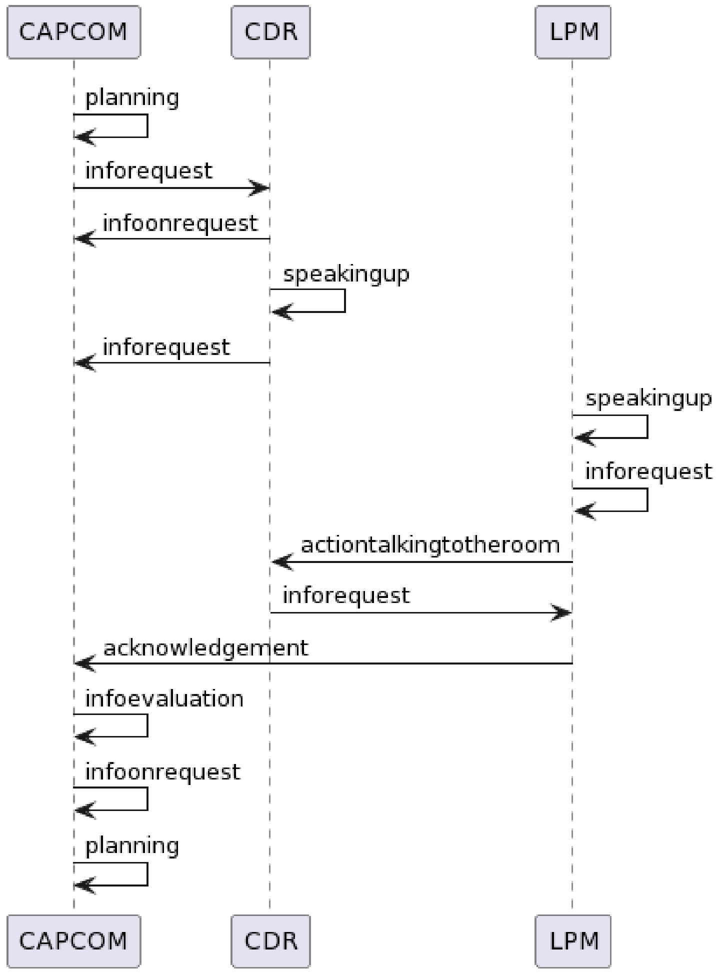

Figure 11. *Pattern #6824*

undertaking a planning stage, suggesting an initial phase where strategic decisions are being formulated. Following the planning initiation, CAPCOM requests information from CDR, signalling the beginning of an iterative information exchange cycle crucial for refining the strategic plan. CDR responds, indicating a reciprocal and responsive communication flow. This is followed by an internal deliberation within CDR - indicated by a speaking-up action -

perhaps signalling a review or reconsideration, which prompts another round of information solicitation from CAPCOM, denoting an iterative process of clarification and refinement. Parallelly, LPM partakes in an analogous cycle of internal communication, marked by a series of speaking-up and information requests. This sequence may reflect LPM's parallel process of decision-making or strategy development, mirroring the actions taken by CDR. As the interaction unfolds, LPM's action talking to the room, involving CDR, suggests a shift from implicit to explicit coordination. In this collaborative space, LPM and CDR's interchange, culminating in CDR's renewed information request, underlines the dynamic nature of information sharing within the team. LPM's acknowledgement to CAPCOM potentially signifies a resolution or validation of the information cycle, establishing a loop of confirmation/aligning the action between the parties. The pattern concludes with CAPCOM engaging in an info evaluation, followed by an acknowledgement, and circling back to planning. This pattern reflects a responsive planning approach where CAPCOM integrates evaluated information into subsequent strategic considerations.

Lastly, the third most recurrent pattern in the during-crisis dataset (#3951) commences with CAPCOM engaging in a planning stage. This outset is promptly followed by an information request from CDR aimed at CAPCOM. CAPCOM's response to this inquiry provides the requested information and acts as a catalyst for the CDR to speak up, potentially

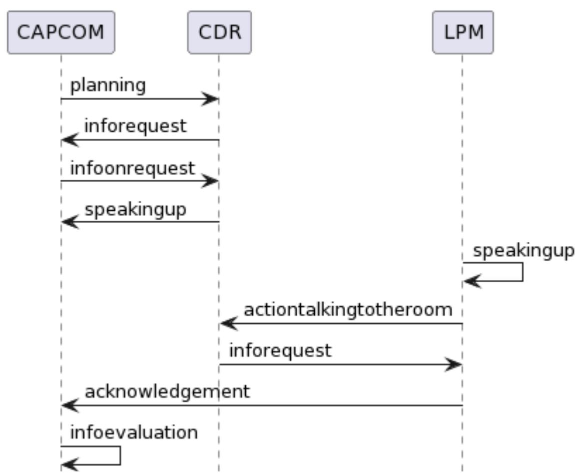

Figure 12. *Pattern #3951*

voicing concerns or proposing adjustments to the initial plan, reflecting a dynamic interplay of communication and strategy refinement. Simultaneously, the LPM engages in a parallel process of contemplation, marked by speaking up. This behaviour suggests a phase of internal decision-making or consideration. LPM’s contributions prompt further discussions with the CDR, illustrating the collaborative essence of crisis management and decision-making within the team. The pattern culminates with CAPCOM undertaking an evaluation of the information. This evaluation signifies an iterative loop of assessment and adjustment, emphasising how the continuous exchange of insights and updates directly shapes and informs the mission’s strategic direction and planning efforts. The visualisation of the relationship between actors in the pattern is shown in **Figure 12.**

Discussion

This study was designed to explore how action teams equipped with resilience capabilities successfully manage crises. By analysing the coordination behaviour during the Apollo 13 mission, the study aimed to reveal the specific mechanisms that enabled the team to navigate the severe challenges posed by the onboard explosion. The study was driven by the question: How do the coordination dynamics within a resilient action team shift before and during an unfolding accident? Study findings indicate significant quantitative and qualitative differences in coordination behaviours, underscoring a shift towards complex coordination.

The study highlights significant differences in the team's coordination behaviours during the crisis compared to the before-accident period. During normal operations, patterns were typically shorter and more routine, reflecting the established protocols and predictability of tasks. For example, the most prominent pattern from the normal phase involved routine checks and updates between team members (following a sequence of giving instructions → information request → information on request → acknowledgement). This type of pattern aligns with more routine operations where tasks are well-defined and actions are performed according to a set protocol. Such patterns ensure efficiency (Salas et al., 2005) and reduce the cognitive load (Sweller, 1988) on team members by leveraging familiar, repeated interactions that facilitate smooth operational flow.

However, during the crisis, the research revealed a marked increase in the complexity of coordination, as evidenced by the lengthening of patterns and the increased proportion of pattern duration in the total. Such changes demonstrate a shift towards more elaborate and prolonged coordination efforts, which likely developed as an adaptation mechanism to maintain team functioning under heightened stress. For instance, the most prominent pattern observed during the crisis phase involved a complex sequence of information exchange, multiple information requests, updates, and repeated confirmations. This pattern is characterised by frequent iterations where team members repeatedly cross-checked and confirmed information, ensuring accuracy and immediate responsiveness. This pattern emphasises reliance on thorough and detailed communication to navigate the uncertainty and urgency introduced by the crisis.

Furthermore, the study revealed significant changes in team coordination during the crisis phase as compared to the normal operations phase, particularly on how team members adjusted their actions after evaluating new information - a process hereinafter referred to as *action calibration*. This concept, while inspired by crisis management literature, is used here to specifically illustrate the iterative process of realigning actions based on new or updated information during the Apollo 13 mission. Action calibration involved a robust iterative process of evaluation, planning, and execution, highlighting its crucial role within the crisis management framework. For example, the most frequent pattern from the crisis phase involved sequences of exchanges of updated situational assessments, followed by planning action and then action calibration, meaning that team members were continuously reassessing and adapting their strategies to meet the rapidly evolving conditions. This shift was starkly contrasted with the pre-accident phase, which is characterised by straightforward procedural dialogues.

It is also noteworthy that there was a shift toward a more collaborative and proactive approach during the crisis phase. This shift is exemplified by an increase in behaviours such as speaking up, which enabled Apollo-13 team members to actively contribute and voice their concerns. Such behaviours not only demonstrate a psychologically safe environment, indicative of a culture of openness and trust but also enhance the team's adaptive capacity and foster cohesion among members.

With regard to exhibited behaviours, both explicit and implicit, there was no significant shift; both before and during the crisis, the team predominantly engaged in explicit coordination. The pre-crisis dataset was characterised by procedural dialogues, where only explicit coordination behaviours were observed. Conversely, the crisis dataset also primarily featured explicit coordination behaviours, though these were notably more complex. However, during the crisis, "action-related talking to the room" particularly stands out as an example of implicit behaviour, exemplifying "sensemaking" behaviour (Waller, 2008). This behaviour helps teams act quickly and effectively by collectively interpreting and explaining information from the environment (Weick, 1995). It is also noteworthy that the methods of analysis applied in this study might only partially capture implicit behaviours, which are often unspoken and not easily discernible from a transcribed dataset.

Theoretical Implications

The findings from this study offer nuanced contributions to the theoretical underpinnings of team dynamics and crisis management. By examining the coordination behaviour patterns within the Apollo 13 mission team, this research aligns with and expands upon existing theories regarding team adaptability and resilience in action teams.

The increased complexity of coordination patterns during the crisis phase demonstrates the team's ability to employ various behavioural strategies and responses to deal with the unfolding crisis. This complexity indicates that the team does not rely on a single, fixed approach but is able to adjust its behaviour dynamically. In essence, this complexity reflects the team's ability to synthesise diverse information, draw on different skills and respond flexibly to challenges (Ishak & Ballard, 2012). Such versatility is critical to adaptability, enabling the team to respond effectively to new, uncertain or rapidly changing environments (Ishak & Ballard, 2012; K. E. Weick & Sutcliffe, 2007). The Apollo 13 team's ability to dynamically adjust their coordination strategies in response to an unforeseen crisis exemplifies the concept of resilience as graceful extensibility, which Woods (2018) describes as the ability of systems to extend their performance beyond usual limits in response to crisis. The findings of this study thus provide empirical support for theoretical models that highlight resilience as a critical ability of effective action teams (Edmondson, 2003; Woods, 2018).

However, Stachowski et al. (2009) found that more effective teams experience less complex coordination patterns, which contradicts these findings. Nevertheless, it can be argued that the discrepancy observed by Stachowski et al. (2009) regarding the effectiveness of teams and their coordination complexity can be attributed to the context-specific nature of team dynamics. In environments where procedures are well-established and tasks are predictable, less complex coordination patterns may indeed correlate with higher effectiveness due to the efficiency and clarity they bring (Marks et al., 2001). However, in crises like the Apollo 13 mission, the increased complexity of coordination patterns reflects a necessary adaptation mechanism. This complexity enables teams to leverage a broader array of behaviours, strategies, and information-processing capabilities to navigate the unpredictability and multifaceted nature of their challenges (Burke et al., 2006). Thus, while Stachowski et al. (2009) suggest that more effective teams exhibit simpler coordination patterns, our findings illustrate that in high-stress, uncertain environments like the Apollo 13 mission, a more complex coordination framework is beneficial and necessary. This study adds to existing research by demonstrating that the level of coordination complexity depends significantly on the context, specifically the stability versus volatility of the environment. Future research should explore the thresholds of coordination complexity in various contexts to better understand when complexity enhances versus hinders team effectiveness.

Moreover, during the accident, the Apollo-13 team exhibited a behavioural sequence where information evaluation was followed by planning, which can indicate the information evaluation triggers the action calibration. In team learning research, this iterative process is seen as a foundational element of adaptive learning, where teams cyclically assess information, plan responses, and adjust actions based on new insights (Edmondson, 1999). This reflective cycle enhances the team's adaptability in real time and also contributes to the development of shared mental models. These models are collective understandings of tasks, processes, and environments that are crucial for coordinated action, providing a unified operational framework that all team members can refer to in making quick, coherent decisions (Cannon-Bowers et al., 1993; Decuyper et al., 2010; Wilson et al., 2007). Consequently, the complexity of such patterns underscores the team's capacity for continuous learning and adaptation, reflecting a high level of collective intelligence and situational awareness that enables the team to navigate complex situations with agility and precision.

The occurring speaking-up behaviour followed by information request and information evaluation behaviours indicates that team members actively participate in proactive behaviours. Such sequences are often linked to high levels of psychological safety, enabling members to voice ideas, questions, and concerns without fear of negative repercussions, fostering an environment ripe for innovation and adaptive learning (Edmondson, 1999). Furthermore, this behaviour aligns with the concept of transactive memory systems, where teams effectively leverage individual expertise through shared communication and understanding, optimising performance and adaptability in complex tasks (Ellis et al., 2007). Thus, the pattern of speaking up, followed by information requests and evaluation, underscores the team's capability to dynamically adjust and refine their strategies, contributing to a resilient performance against the unfolding crisis.

By exploring the dynamics between explicit and implicit coordination strategies during the unfolding crisis of the Apollo 13 mission, this research also contributes to the evolving discourse on the most effective forms of coordination in action teams. In contrast to the prevailing emphasis on the efficiency of implicit coordination in seamless team performance (Rico et al., 2008, 2011), the findings suggest a central role for explicit coordination in the Apollo 13 scenario. This distinction highlights the context-dependent nature of coordination effectiveness and extends theoretical models by demonstrating the situational need for explicit over implicit coordination mechanisms to ensure clarity and mutual understanding (Kozlowski & Ilgen, 2006; Salas et al., 2000).

Practical Implications

By examining the changes in coordination patterns during the Apollo 13 mission's onboard explosion, this research sheds light on the mechanisms underpinning the team's resilience and effectiveness in managing the crisis. Thus, the increased complexity of coordination patterns and the role of action calibration and proactive behaviours provide actionable insights. These results could be considered when developing team training learning modules and communication frameworks for high-stressful environments. Emphasising adaptive coordination strategies and establishing communication protocols that underpin precise information exchange can significantly bolster team responsiveness and efficacy in emergent conditions. Importantly, including study insights into simulation training that incorporates a variety of scenarios is beneficial for preparing teams for unexpected challenges and enhancing their ability to apply theoretical knowledge in practical situations (Ishak & Ballard, 2012).

Moreover, the study highlighted the critical role of psychological safety, evidenced by an increased frequency of "speaking up" behaviours during the crisis. This behaviour indicates a psychologically safe environment where team members feel empowered to express concerns and share information freely. The presence of such behaviours suggests that the Apollo 13 crew operated in an organisational climate that supported open dialogue, mutual trust, and collaboration - key factors that enhance team resilience and innovation. This study dimension prompts further research to explore how psychological safety contributes to team performance and to identify effective strategies for cultivating such an environment in high-stakes settings.

Furthermore, this study could be of practical relevance for action teams across various sectors, including emergency response, healthcare, aerospace, and beyond. The importance of the information evaluation cycle for action calibration observed in the study is underscored by its ability to facilitate rapid, informed decision-making in dynamic environments. Uitdewilligen & Waller (2018) research supports this by noting that high-performing teams spend more time in the information-evaluation and information-structuring phases, enabling them to make decisions more effectively during the decision-making phase. This cycle ensures that teams respond to immediate challenges with continually refined strategies based on the latest, most accurate information available, thereby enhancing overall team adaptability and effectiveness in crises. Thus, including evaluation/reflection activities into an action team training program could be beneficial for enhancing their performance. Such metacognitive interventions aim to enhance the team's collective awareness of their own cognitive processes. They can involve activities that promote reflection, self-assessment, and planning for future learning and development, which can be later translated into action (Ellis et al., 2007; McCarthy & Garavan, 2008).

Limitations and Recommendations for Future Research

There are a few limitations that could be accounted for in future research into coordination patterns. One primary limitation is the scope of the analysed dataset, which included only six hours before the accident and six hours during the accident; the entire mission transcript consists of approximately 144 hours of space-to-ground audio and was not analysed. This limitation could result in missing critical behavioural patterns that were not captured within the analysed timeframe. To address this limitation, a comprehensive analysis of the full Apollo 13 mission transcript, which involves multiple actors and audio channels, could be considered. Conducting this type of in-depth coding analysis could provide a more complete understanding of the coordination dynamics throughout the mission. It could reveal additional patterns of explicit and implicit coordination, variations in communication as the crisis continues, and how these might have evolved into the crisis management strategies observed during different critical phases of the mission. However, this type of in-depth coding analysis is labour-intensive and could require collaboration among multiple researchers.

The second limitation relates to the use of THEME software. While THEME utilises a variety of statistical tests that enable granular, time-sensitive analysis, it does not provide a user-friendly experience for data analysis. The software's last update in 2017 left some of its features outdated, including its limited capability to visualise pattern strings (the connections between events that form the pattern). Furthermore, the absence of a comprehensive user manual complicates navigation within the software. The challenge was partially mitigated by employing the PlantUML visualisation tool, which facilitated the visualisation of patterns, thereby aiding the communication of study findings. However, future research should consider integrating THEME with more modern and user-friendly visualisation tools like PlantUML or developing plugins that enhance its data representation capabilities. Such enhancements would not only improve usability but also extend the analytical power of THEME by making complex data sets more accessible and easier to interpret.

Third, the T-pattern analysis conducted in the current study was limited to the three most recurrent patterns for each analysed mission phase. This methodological choice, while facilitating a focused examination within the limited duration available for the study, inherently restricts the breadth of the analysis. It potentially overlooks other significant patterns of coordination that may have been critical to the mission's success. This selection approach inevitably introduces a risk of selection bias, where less frequent yet potentially pivotal interactions might not be captured. To overcome this limitation, future investigations would benefit from a more extensive analysis that includes a broader array of patterns. This expanded approach would allow for a deeper dive into team coordination's multifaceted nature, potentially unveiling subtle but strategic behaviours that could contribute to the team's adaptability and resilience during crises.

Fourth, the study's reliance on audio transcript for retrospective analysis fails to capture non-verbal cues and implicit behaviours that may play a critical role in the team's coordination efforts. Research has shown that multi-modal design approaches, including visual and physiological measures, provide a more comprehensive understanding of behavioural dynamics, including implicit behaviours (Morris et al., 2006). Particularly, the use of wearable technology to capture physiological responses can offer valuable insights into the underlying emotional and cognitive states of team members, thus enriching our understanding of implicit coordination (Pentland, 2010; Endedijk et al., 2018). Future research could benefit from real-time observational studies or simulations with wearable technology to provide a more holistic view of team coordination dynamics, including non-verbal communications and tacit knowledge exchanges.

Future research should also investigate the role of Transactive Memory Systems (TMS) in enhancing team adaptability and resilience. The observed efficacy of the Apollo 13 team's coordination raises questions about the underlying factors that enabled such adaptive changes. TMS, where team members deeply understand each other's expertise, roles, and responsibilities, could significantly facilitate efficient information exchange and task delegation (Edmondson et al., 2007; Ellis et al., 2007). Exploring how teams develop and utilise TMS in high-pressure environments might provide valuable insights into the mechanisms that underpin effective team coordination and crisis management.

Conclusion

This study explored the coordination behavioural patterns of the Apollo 13 mission team before and during an onboard exposure, with the primary aim of understanding how these patterns contributed to the team's success in managing an unexpected crisis. The findings demonstrate that the Apollo 13 team increased the complexity of coordination patterns and effectively utilised action calibration and proactive behaviours during the crisis.

This study has contributed new knowledge to the field of team dynamics in several ways. First, it has provided empirical evidence supporting the statement that increased complexity in coordination patterns is a sign of team adaptability in crises. This aligns with and expands upon existing theories regarding team adaptability and resilience in high-stakes environments like space missions. Second, the research underscored the importance of proactive communication strategies, which are critical for fostering an environment conducive to effective team coordination and rapid problem-solving.

Methodologically, this study has advanced the analysis of team coordination dynamics by employing a temporal approach to study coordination behaviours as they unfold during crises. This approach has highlighted the dynamic changes in team coordination and has provided an understanding of the sequential and adaptive nature of team coordination. Additionally, to enhance this time-sensitive, granular analysis, the study integrated the use of PlantUML, a visualisation tool that enabled a more comprehensive examination of complex patterns. This combination of temporal analysis with visualisation techniques suggests a methodological pathway for future studies that require detailed pattern recognition and analysis, particularly those utilising mission transcripts as primary data sources.

In conclusion, the Apollo 13 mission is a compelling case study for examining the impact of coordination dynamics on team performance during crises. The insights derived from this study deepen our understanding of the mechanisms underpinning effective team coordination.

As research continues to employ analytic techniques to explore team coordination dynamics in real-time, we can better equip action teams across various sectors to manage crises effectively, ultimately bolstering their resilience when faced with unforeseen challenges. This exploration not only aids in preparing teams but also contributes to the theoretical and practical frameworks concerning team dynamics in crisis management.

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Appendix A

Vvt.vvt Table

actors
cmp
CAPCOM
cdr
LPM

b_e
b

verbalacts
instruction
planning
speakingup
actiontalkingtotheroom
monitoring
providingassistance
inforequest
infoevaluation
infoonrequest
gatherinfo
infotalkingtotheroom
infowithoutrequest
callout
acknowledgement
other

Appendix B

Before the accident. Pattern strings for #483, 469 and 468

#483

(CAPCOM, instruction (((LPM, inforequest (CAPCOM,infoonrequest CAPCOM,acknowledgement)) CAPCOM,instruction)((CAPCOM,instruction CAPCOM,acknowledgement) CAPCOM,instruction)))

#469

(((LPM,inforequest (CAPCOM,infoonrequest CAPCOM,acknowledgement)) CAPCOM,instruction)((CAPCOM,instruction CAPCOM,acknowledgement) CAPCOM,instruction))

#468

((LPM,inforequest (CAPCOM, infoonrequest CAPCOM, acknowledgement)) CAPCOM, instruction)

Appendix C

During the Accident. Pattern strings for #8501, 6824 and 3951

Pattern#8501

((LPM,b,acknowledgement (LPM,b,infoevaluation ((cdr,b,actiontalkingtotheroom (cdr,b,inforequest cdr,b,actiontalkingtotheroom))(CAPCOM,b,infoonrequest (CAPCOM,b,actiontalkingtotheroom CAPCOM,b,infoonrequest)))))(((CAPCOM,b,planning ((cdr,b,inforequest CAPCOM,b,infoonrequest)(cdr,b,speakingup CAPCOM,b,inforequest)))((((LPM,b,speakingup LPM,b,inforequest)(LPM,b,speakingup (cdr,b,actiontalkingtotheroom cdr,b,inforequest)))(LPM,b,actiontalkingtotheroom CAPCOM,b,acknowledgement))(CAPCOM,b,infoevaluation CAPCOM,b,infoonrequest))) CAPCOM,b,planning))

Pattern #6824

(((CAPCOM,b,planning ((cdr,b,inforequest CAPCOM,b,infoonrequest)(cdr,b,speakingup CAPCOM,b,inforequest)))((((LPM,b,speakingup LPM,b,inforequest)(LPM,b,speakingup (cdr,b,actiontalkingtotheroom cdr,b,inforequest)))(LPM,b,actiontalkingtotheroom CAPCOM,b,acknowledgement))(CAPCOM,b,infoevaluation CAPCOM,b,infoonrequest))) CAPCOM,b,planning)

Pattern#3951

((CAPCOM,b,planning ((cdr,b,inforequest CAPCOM,b,infoonrequest)(cdr,b,speakingup CAPCOM,b,inforequest)))((((LPM,b,speakingup LPM,b,inforequest)(LPM,b,speakingup (cdr,b,actiontalkingtotheroom cdr,b,inforequest)))(LPM,b,actiontalkingtotheroom CAPCOM,b,acknowledgement))(CAPCOM,b,infoevaluation CAPCOM,b,infoonrequest)))

Appendix D

Use of Generative AI

During the preparation of this work, the author utilised ChatGPT 3.5 and Grammarly to ensure grammatical accuracy and maintain consistent language use throughout the document. These tools were employed to refine the text and enhance readability. After using these tools, the author reviewed and edited the content as needed and took full responsibility for the publication's content.