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A Model of Human Variability in Viable Ship Design

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Submitted by

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14. ABSTRACT
It is generally acknowledged that decisions made during the research and development of ship design drive the total cost of ship ownership. Further, the largest component of the total cost of ship ownership is the cost of the crew. The need to better account for the human operator continues and the ONR CMP-FY13-02 Simulation Toolset for Analysis of Mission, Personnel, and Systems (STAMPS) is the most recent effort to incorporate new advances in human centered design into the ship design process. The current process of integrating human factors into naval ship design deconstructs the ship's design into individual ship systems and missions (MIL-STD-46855A). These systems and missions are then further deconstructed with information and process flow charts to trade off studies and analysis is used to allocate functions between the operators and technology. This is then followed by task analysis to assess required manning levels, training needs, critical time requirements, etc. which finally results in the development of ship manning documents and a naval system training plan. This technical report examines the role of a team within the system and the factors that influence team performance under various operating conditions.

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Team performance, Intact teams, Performance decay, Human performance mediators, Performance model, Viable system, Requisite variety, System resilience

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Executive Summary

Decisions made during the research and development of ship design drive the total cost of ship ownership; the cost of the crew contributes significantly to the total cost of ship ownership. The ONR CMP-FY13-02 Simulation Toolset for Analysis of Mission, Personnel, and Systems (STAMPS) supports the continuing need to better account for the human operator and incorporate new advances in human centered design into the ship design process.

This technical report examines a specific aspect of the STAMPS project, namely, the role of a team within the sociotechnical system and the factors that influence team performance under various operating conditions. An overview of team formation and emergence is provided. Person and situational factors that impact collective performance by teams are reviewed, as are the various methods for defining and measuring team effectiveness. Degraded effectiveness is discussed from the perspectives of decay of individual task performance by team members as contributory to decay of collective performance; decay of collective task performance by teams; mitigating decay of collective task performance by teams; and skill gaps, reallocation of workload, and backup behavior. A case is made for human operators as a source of system resilience, given their ability to contribute flexibility, adaptability, and evolution to the system. These operators are capable of prioritization and task switching, adapting to change or turbulence in the system, engaging in Naturalistic Decision Making and Recognition-Primed Decision Making, enabling soft evolution in the system, and contributing variety as conceptualized in the Viable System Model. These factors contribute to greater resilience in the overall sociotechnical system.

Introduction

It is generally acknowledged that decisions made during the research and development of ship design drive the total cost of ship ownership. Further, the largest component of the total cost of ship ownership is the cost of the crew. This correlation of ship design and manning levels to total ownership cost has led the Navy to pursue multiple initiatives to reduce the manning of ships over the past decades and generally spurred the advancement of the development of Human System Integration (HSI) tools that better incorporate understanding of human needs in early ship design. The Office of Naval Research (ONR)/Surface Combatant for the 21st Century (SC-21) Science & Technology Manning Affordability Initiative's Human Centered Design Environment was a key early advocate for the development of better tools and analytical methods to incorporate the needs of human operators into the engineering of ship design (see Figure 1). The need to better account for the human operator continues and the ONR CMP-FY13-02 Simulation Toolset for Analysis of Mission, Personnel, and Systems (STAMPS) is the most recent effort to incorporate new advances in human centered design into the ship design process.

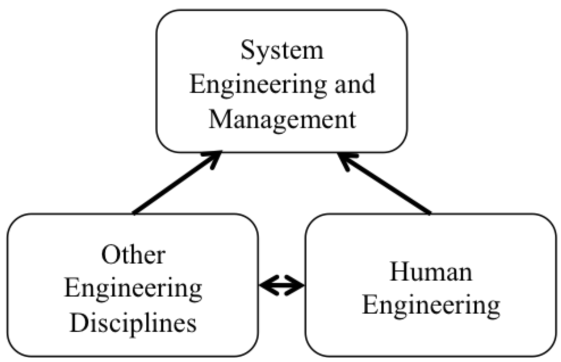

Figure 1. Relationship of System Engineering and Human Engineering (Adapted from Naval Surface Warfare Command, 2001)

The current process of integrating human factors into naval ship design deconstructs the ship's design into individual ship systems and missions (MIL-STD-46855A). These systems and missions are then further deconstructed with information and process flow charts to trade off studies and analysis is used to allocate functions between the operators and technology. This is then followed by task analysis to assess required manning levels, training needs, critical time requirements, etc. which finally results in the development of ship manning documents and a naval system training plan. The ONR STAMPS research team is attempting to improve this process by creating and integrating the HSI analysis with technical system designs so that ship design and manpower teams can better estimate the manning needs of the proposed ship design.

Deconstructing ship designs to assess the human role in the system or the mission tends to view human variability as a source of error. Technological systems are already prone to software and hardware failures that result in a predicted technological system availability (A_o). If the human operator employing the system is perfectly trained and focused on their task, then the predicted A_o of the system may be achieved. However, if the human factors (task loading, response time, training, attention, etc.) are not optimal, than system availability is degraded. The

U.S. Navy's current process is to assume that the as-designed crew is fully manned, trained, and motivated rather than to introduce human variability into the ship design process.

This view of human error comes from the underlying theoretical models that make assumptions about how errors occur. A common model employed in assessing total system error is the sequence-of-events or "domino" model developed by Heinrich in 1931 to explain the causes of industrial accidents (Hollnagel, Woods, & Leveson, 2006). In this model, errors are seen as a resulting from a chain of events and are prevented by breaking the chain of events. The model can be developed with significant complexity as various branches in the chain of events are considered but ultimately it relies on a deterministic model of events (see Figure 2). Tools such as Failure Modes and Effects Analysis and bottom-up event tree analysis are examples of methods employing this model.

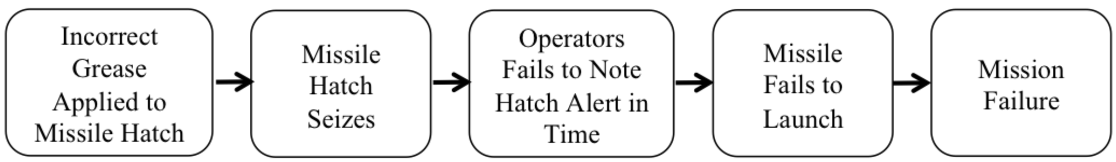

Figure 2. Domino Theory of system failure

A second model employed in assessing total system error is the epidemiological or "Swiss Cheese Model" of system failure first proposed by Reason in 1990 (Hollnagel et al., 2006). In this model, errors occur as actions by humans or the environment (active conditions) interact with latent conditions in the technological system to cause errors. It is called "Swiss cheese" because each layer in the model is viewed as a slice of Swiss cheese with holes in the defenses of the total system caused by either active conditions (human variation) or latent conditions (features of the system). Total system errors occur when the active and latent conditions line up in such a manner that a chain of events leading to system error is allowed to occur (see Figure 3). The Swiss cheese model lends itself to top-down fault tree analysis. Event tree analysis and fault tree analysis (and the combination of the two in probabilistic risk assessment) form the basis of many of our current HSI tools (National Research Council, 2007).

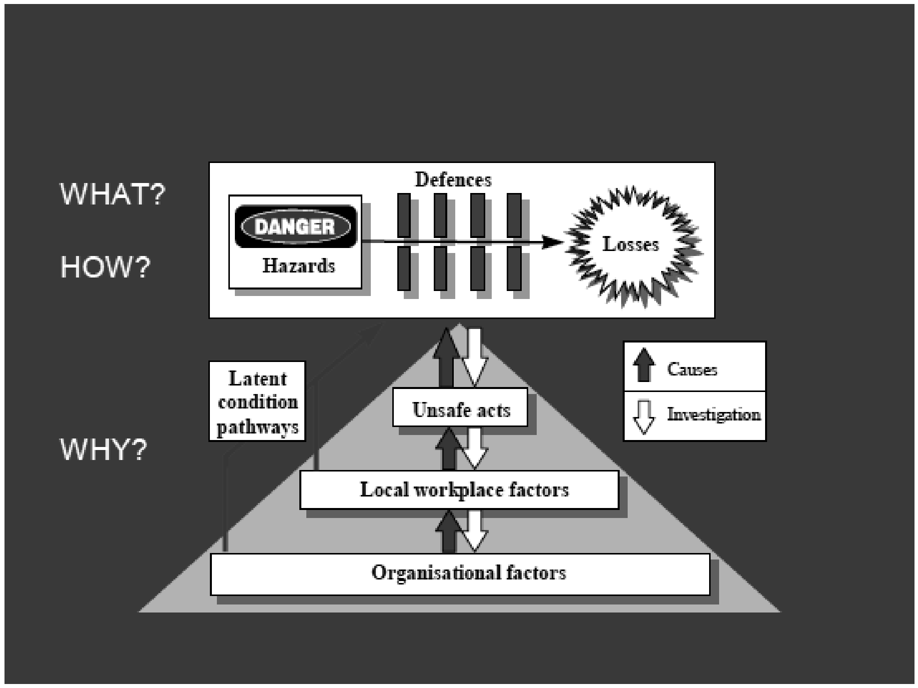

Figure 3. Swiss Cheese Model of system failure (Reason, Hollnagel, & Paries, 2006)

If we solely view human variability as a source of error, then the question quickly becomes how far can we reduce the manning of the ship and sustain safe and effective operations. The human engineers in the HCDE inevitably take up the role of trying to ensure that any anticipated crew reductions can be borne by the total system with tolerable reliability.

There is a complementary view that is emerging in reliability science that views human variation not only as a source of error and failure but also as a source of safety and mission success (Rasmussen, 1990; Rochlin, 1999; Sutcliffe & Vogus, 2003; Hollnagel, Woods & Leveson, 2006; & Weick & Sutcliffe, 2007). The source of this new view is based upon the science of complexity. Socio-technical systems (like a ship) are complex adaptive systems and, therefore, not simple enough to be analyzed by deconstructing the ship's functions, assessing risk, and adding up the numbers. Complex adaptive systems are truly more than the sum of their parts, a view that is especially important when the system (ship and crew) must be ready to confront unexpected and new challenges in combat and at sea. In this new view, human variability is a source of ship strength and adaptivity. The measure of a system's ability to succeed while adapting to a changing environment is called viability. This perspective of viability tends to view human variability as a source of resilience in contributing to safe and effective operations. Therefore, the need for better HSI tools must encompass both the demands of reduced cost (human variability as risk) and resilience (human variability as a contributor of safe and effective operations).

Problem Statement: Tools for analyzing human system integration in ship design tend to view human variability as a source of risk. Human variability must also be seen as a source of resilience. New tools are needed to ensure that features in the ship design enhance the viability of the total system and the resilience of the crew to adapt in ways that contribute to ships safety and mission success.

Applicable Studies: There is little argument about the growing complexity of naval operations (see Naval Operational Concept, 2010) but few studies have examined the impact of complexity on naval teams and the need to engineer resilience into total ship design. Steed, Marquet & Armbruster (2010) explored the role of growing complexity on submarine operations and called for advances in developing tactical information system design to develop a more human-centered approach. Nemeth, Wiggins, Strouse, Crandall & Connor (2011) examined the role of command and control in contributing to the resilience of naval expeditionary forces.

Naval Relevance: Failure to properly account for the human component in ship design can have significant negative effect on naval forces. The recent "Balisle Report" (2010) levied much of the responsibility for the negative trend of U.S. Surface Force readiness on inadequate fleet manning. Ship and shore manning levels were reduced by a series of initiatives such as the Optimal Manning Initiative that reduced surface ship manning levels by as much as 18%. The result of inadequate ship and shore manning combined with reduced inspections, reduced training, and reduced material support to create a decade of decay in Surface Force readiness.

Study Purpose: In 2008, Sheridan reviewed the basic ideas of both traditional risk engineering and the new field of resilience engineering and concluded that resilience engineering concepts complement traditional risk analysis methodologies but noted that the field had not yet yielded useful operational methods. The purpose of this study is to begin to address this research gap by proposing a new model of human performance that combines the perspectives of complex systems and more traditional human factors concepts. Our goal is to test the proposed model with U.S. Navy case studies to explore concepts of human variability in viable ship design.

Sociotechnical systems

A ship can be viewed as a complex sociotechnical system consisting of a variety of subsystems (e.g., manpower, operations, technology/"systems"). The logistical and engineering rationale for this viewpoint is concerned with allocating resources, organizing information, and providing coordination between subsystems and entities. The ship as a whole must respond to mission or task execution orders, as well as take direction regarding safety and protective systems. As a sociotechnical system, the ship should be viewed in light of the principles suggested by Cummings and Worley (2001):

1. Compatibility: The system should be designed to match its objectives, and should incorporate both technical and social or psychological considerations.
2. Minimal critical specification: Essential elements of the system should be specified and non-essential elements of the system should not be specified. This allows for the greatest amount of flexibility within the system, as specifying non-essential elements of the system limits the ability of the system to adapt to changing situational or environmental conditions. Providing minimal critical specification increases the degrees of freedom afforded to decision makers in the system, and allows alternative transition pathways to achieve goals and objectives. Minimum critical specifications function as macro-ergonomic constraints, and may entail such factors as: (1) Members of the organization understand how to conduct mega-tasks. They have the necessary knowledge and skills to engage in relationships with other organizational members that result in the emergent property mega-tasks. (2) The critical knowledge and skill requirements of a job role or billet are known, and organizational members have proficiency in the task elements that define their job roles or billets. (3) Organizational members have or can easily access the resources that are required for the achievement of mega-goals but are not task specific.[1]
3. Variance control: Variance refers to unanticipated, unplanned for events that can critically impact system outcomes, and should be minimized to the degree possible. It is important to address not just the consequences of variances, but the sources of variance as well.
4. Boundary location: Boundary location refers to the boundaries between organizational departments, between organizational departments and the organization, and between the organization and the environment. Sociotechnical design stresses that boundaries should not disrupt the sharing of information, knowledge, data, and learning. Such interference can be reduced by adjusting boundaries.
5. Information flow: Information flow relates to the dissemination of information in the system. Organizational information can be used for control, records, and action. Information that is used for control may involve an information bottleneck at a point of authority; it is important that information is not involved in an abuse of authority for control. Information utilized for records must be appropriately safeguarded to prevent exploitation. The appropriate dispersion of information to members of the organization with a need to know supports effective action or performance, as opportunities for variance due to misinformation from external sources are reduced. Envelopes of competency should be assessed to ensure that the appropriate individuals are seeking and

[1] These constraints are very similar to the assumptions used by the U.S. Navy Manpower Analysis Center when establishing the requirements for developing ship designs.

providing information and data. Members of the organization in different work domains will have different information needs passed on individual departmental or team responsibilities and capabilities, and varying levels of expertise.

6. Power and authority: Members of the organization who have a need for certain resources, such as materials or equipment, should have access to and authority over those resources. Additionally, individuals who have access to and authority over resources should have responsibility for them and demonstrate discretion in their use. Essentially, members of the organization should have responsibility for the resources required to perform their tasks.
7. Multifunctional principle: This principle refers to the adaptability or flexibility of the organization. Often, certain facets of the system will have to adapt to other facets. This may be accomplished by adding new roles, which may change hierarchies, communication, or the allocation of resources. Alternately, the system can adapt by changing existing roles, which tends to be less disruptive because it likely does not alter the established chain of command or communication links.
8. Support congruence: This principle refers to the match between reward systems and management philosophy. Namely, aspects of performance and responsibility that are required and evaluated should be reinforced and rewarded. For example, in some systems, rewarding individual efforts may not be consistent with the management philosophy.
9. Transitional organization: Transitional organization involves the actions and activities that should take place when an organization is in a state of change. For example, an alternative to screening out individuals for a new job role is the self-selection of individuals. Allowing organizational members to determine if they want a new job role can aid in the process of change and improve the effectiveness of training due to increased motivation.
10. Incompletion: The principle of incompletion recognizes that the operational environment is dynamic, and stresses the importance of ongoing evaluation and redesign. A mechanism for constant monitoring should be in place, along with a continuous capability to start the process of change and redesign. Stability is treated as an illusion and as merely an instant between transitions.

The sociotechnical system approach assumes that the organization, in this case the ship, is itself a system that represents the functions and goal-directed behaviors of the people and technology within in. This approach also assumes that the organization or ship, as a system, is open to influences from the environment and situational context. Boundary management of the sociotechnical system refers to the process by which the organization has the freedom to function, adapt, and evolve, while exchanging inputs and outputs with the environment or operational context.

Team formation and emergence

Given the frequency of change or turbulence within systems, increased flexibility in response to changes in the external environment are necessary in order to maintain viability. This may be best supported by a diverse range of knowledge, skills, experience, and perspectives derived from a range of people constituting a team. A team may be better equipped to adapt to change or turbulence because collectively it possesses a broader range of response alternatives than does an individual. Scholtes, Joiner, and Streibel (1996) assert that team performance will exceed individual performance when the task is complex; creativity is needed; fast learning is required; more efficient utilization of resources is necessary; the situation is ambiguous; high commitment is desirable; a plan requires the cooperation of other people in order to be implemented; and/or the task or process is cross-functional.

A good deal of research regarding teams has general agreement on how a team is defined. There is frequent reference (e.g., Bassett-Jones, 2005; Eppler & Sukowski, 2000; Castka, Bamber, Sharp, & Belohoubek, 2001; Proehl; 1997) to the definition provided by Katzenbach and Smith (1993b), who asserts that "a real team is a small number of people with complementary skills who are committed to a common purpose, set of performance goals, and approach for which they hold themselves mutually accountable" (p. 45).

Tuckman (1965) proposed a four-stage model of small group development, in which a group progresses in a linear sequence from disorganization through conflict to the development of group cohesion and the eventual formation of an effective team. McGrew, Bilotta, and Deeney (1999, p. 229-230) describe the four stages of the "forming, storming, norming, and performing" process as follows:

- Forming: Group members begin by testing the boundaries of interpersonal and task behaviors, orienting themselves to each other and to the task at hand. At the same time, dependency relationships are established with the leaders, other group members, and preexisting standards.
- Storming: As the group more clearly defines its boundaries, members begin showing resistance to group influence and to the requirements of the tasks. Conflict and polarization around interpersonal issues grows. Heightened emotional responses to interpersonal issues are turned against the task itself.
- Norming: Resistance falls as interpersonal and task-related issues are resolved. A sense of group develops, roles are accepted, and standards of behavior evolve. Group members are open to the expression of opinions and ideas.
- Performing: Structural issues have been resolved and are now supportive of task performance. Interpersonal structure is the mechanism by which task activities are accomplished. Roles become functional and, as needed, flexible. Group energy is directed constructively toward the task rather than destructively toward each other (Tuckman, 1965)

Tuckman and Jensen (1977) proposed a fifth stage as an extension of the original model termed adjourning, which address the systematic closure of a team that has fulfilled its purpose.

Tuckman's model of team development and dismantling is viewed as an orderly life cycle process with the aim of effective performance in the achievement of a particular goal.

McGrew, Bilotta, and Deeney (1999) elaborated on existing team development research to address the decay phase of an intact team. The authors note that inherent to the life cycle process is a decline stage, which has a direct impact on team performance just as the growth stage does. When an emergent team has served its purpose and accomplished the objective with which it was charged (*e.g.*, a quality improvement team achieving measurable improvements in an organization or a fire team extinguishing a fire), an adjourning process is likely to follow the performing phase. McGrew, Bilotta, and Deeney (1999, p. 230-231) propose the following extension to Tuckman's (1965) model to incorporate the adjourning phase:

- De-norming: Over the years, there is, within the team, an instinctive drift back toward previous patterns of behavior that must be counteracted through continual norming behavior. Drift originates in changes in the team environment, in changes in project scope, size, or personnel. Even changes in personal priorities can undermine the established standards of behavior within the group. In many ways, the performing stage is a knife edge or saddle point, not a point of static equilibrium. Norm observance can drift among established team members as well as new. New members are not always familiarized with group standards. There are few software development groups that support a formal concept of apprenticeship or initiation. The most experienced or technically adept team members are often reassigned or lured away to newer, more challenging, or higher priority projects. Original team members who are left behind sense a loosening of the social web that had enabled the group to reach a high level of performance and they seek shortcuts to minimize the impact of their increasing workloads. With new members come new ideas that older group members feel attack the established order and require a defensive response. The expression of ideas and opinions becomes less open and begins to move underground. Previously accepted roles are rejected and often unilaterally redefined by the new members who, through assertion or neglect, decide what work or responsibilities they will accept.[2]
- De-storming: This is a reverse play of the storming phase that began abruptly and then, as group resistance broke down, faded into a comfortable acceptance. De-storming, in contrast, raises the group's level of discomfort gradually as norming behavior declines, as group cohesion weakens, and as resistance to group influence grows. Heightened interpersonal emotions are once again turned against the task itself. When the discomfort level has built up enough, the group explodes in open conflict and polarization of the membership, and moves rapidly into the final stage.

[2] This is a topic suitable for further research. Naval teams reach a high level of proficiency as they are "normed" in the pre-deployment and early parts of the deployment cycle. However, over time, they may become vulnerable to performance "drift" with negative consequences.

- De-forming: Boundaries are aggressively re-explored and redefined in a struggle for control of pieces of the group. It is not uncommon to see even small teams become balkanized as each person claims for himself or herself those pieces of the group's overall responsibilities that he or she is willing to accept. The pieces no one will accept are abandoned. Group members begin isolating themselves from each other and from their leaders. Performance declines rapidly because the whole job is no longer being done and group members little care what happens beyond their self-imposed borders.

The proposed extension addresses team decay with regard to the dismantling of a team. Research has also examined how the performance of a team can decay while the team itself remains theoretically intact.

Team performance

A great deal of previous research has examined the various factors that contribute to team performance in complex operational environments. Frequently, outcome measures seek examine collective performance of an entire system; however, traditional approaches may fail to capture individual elements that contribute to performance. Assessments may treat portions of the system as a "black box" or limit evaluations to subsystems such as a particular human-machine interface or a single criterion such as workload. Previous research has examined, in relative isolation, various factors that contribute to team performance including: cooperation (Johnson & Johnson, 2000), cognitive ability (Morgan, Salas, & Glickman, 1993) personality (Johnson & Johnson, 2000), trust (Anderson & West, 1996), group efficacy (Seijts, Latham, & Rotman, 2000), task versus emotional focus (Gully, Incalcaterra, Joshi, & Beaubien, 2002), communication processes (Johnson & Johnson, 2000), and shared team goals (Katzenbach & Smith, 1993a). Essens (2000) asserts that a more holistic evaluation is necessary to diagnose positive and negative influences that produce some composite result.

Essens (2000) examined the interaction of individual and team performance in ship command centers, which are an example of a complex system where information from various domains must be aggregated and acted upon. The system involves human information processing, decision making, and decision execution; these functions may be supported by various tools and technologies, and take place in a context that is dynamic and may change over varying time horizons. In order for a complex system to function effectively, subsystems composed of multiple people and technologies must aggregate information and align processes in order to achieve task goals. Essens (2000) notes that four factors play a critical role in complex system performance under high levels of information load, time stress, and time complexity: individual information processing, team management, communication load, and distribution of tasks. These factors contribute to the competition for resources between individual and team processes. Essens (2000) asserts that when individuals become overloaded, team members will first shed tasks that are demanding and that do not lead toward direct feedback[3]; collective team performance is likely to suffer most under such conditions.

Predicting collective task performance by teams: Person factors

Roth (1992) has defined collective task performance by a team as the ability of the team to achieve the performance requirements of the task or objective with which the team has been charged. As such, a method of predicting team performance of a collective task involves the identification and assessment of likely deficits in the relevant performance capabilities of the team. Bass (1982) developed a model that views team performance generally as the goodness of fit between the skills and knowledge available to the team and the skills and knowledge required for effective performance to achieve a given task or objective. The model classifies sources of performance demands and compares them with the team's capability to meet the demands and

[3] Recent concerns over test cheating scandals in the military may be linked to this "shedding" effect. In the conflicts between group and individual tasks, taking tests is a personal task. If the likelihood of negative feedback is low (i.e. not getting caught), this task may be shed.

perform to standard. Roth (1992, p. 4) notes three sources of performance determinants adapted from Bass' (1982) model:

1. The determinants of generic performance demands for a team task, in terms of the skills and knowledge required (in the abstract) to perform the task.
2. The determinants of the present capability of a specific team to bring the needed skills and knowledge to performing a team task.
3. Variables that influence the skills and knowledge required as well as the skills and knowledge available to a team for a specific performance of the task.

The maximal capability of a team to apply skills and knowledge during collective task performance is considered to be the aggregate of the attributes of the members of the team. Specifically, the relevant attributes are considered to be team members' aptitude, general experience at respective billets or job roles, and experience as members of the intact team; team roles and formal team structure may be influenced by team members' aptitude and general experience, and are likely to themselves influence how the team task-organizes (Roth, 1992).

Predicting collective task performance by teams: Situational factors

Collective task performance by a team does not occur in a vacuum; *in situ* performance of collective tasks is likely to be affected by the context in which it occurs. Situational conditions may alter a team's ability to express its collective skills and knowledge and therefore impact the team's ability to successfully perform a task or achieve an objective. Roth (1992) notes that contextual conditions for Army collective tasks involve Mission, Enemy situation, Troops (available), Terrain (and weather), and Time available (for planning tasks); this summary of situational conditions is referred to as METT-T. METT-T conditions can impact team organization, task organization, task requirements, individual performance of component tasks that support collective task performance, and the overall effectiveness of collective task performance.

Predicting collective task performance by teams: An integration of person and situational factors

Roth (1992) provides a model of the determinants of task performance that integrates elements of Bass' (1965) model and accounts for both person and situational factors (see Figure 4).

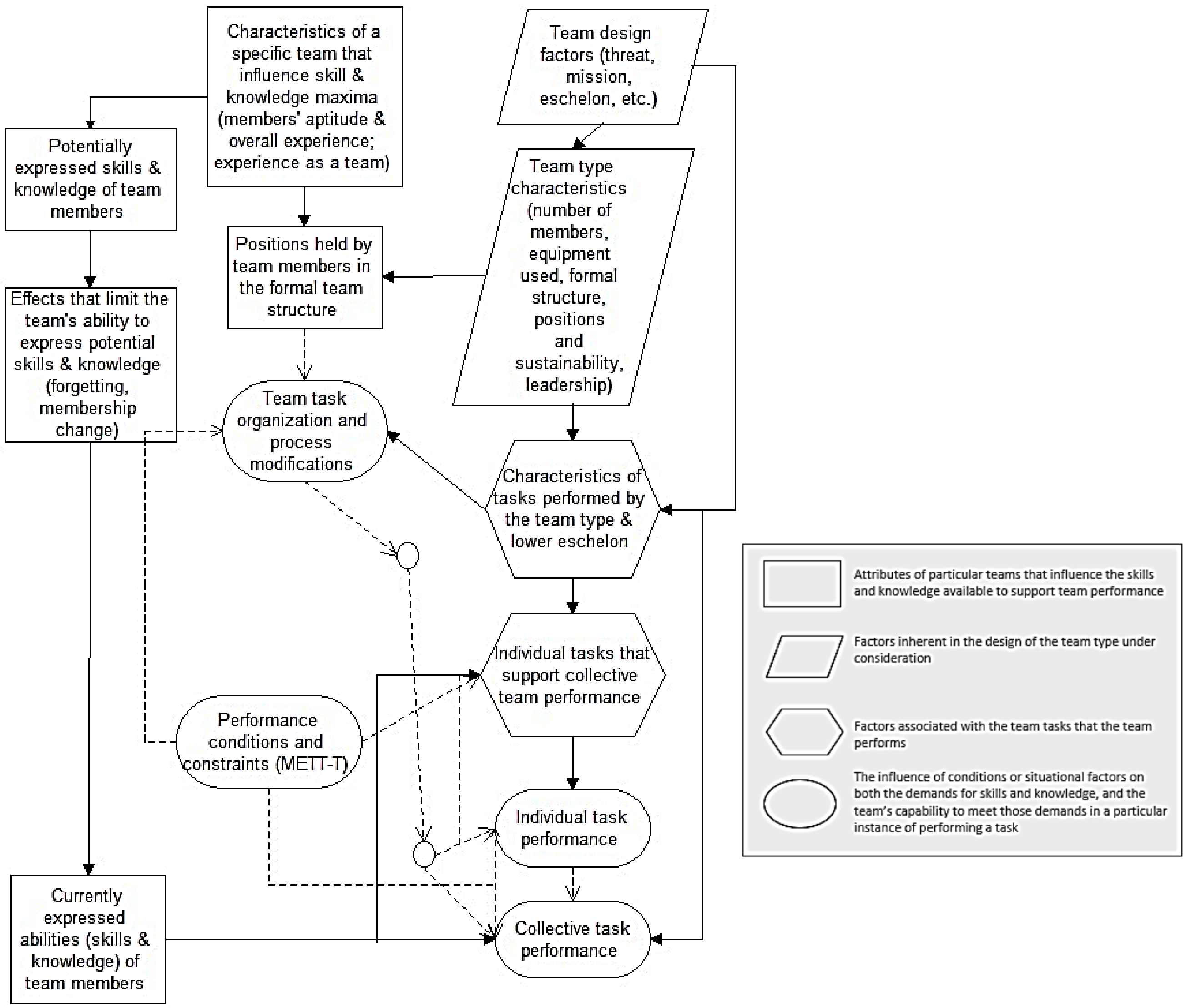

Figure 4. A model of the determinants of collective task performance (Roth, 1992, p. 5)

Defining and measuring team effectiveness

The increasing frequency with which organizations are employing teams to accomplish work tasks that had previously been fractioned and delegated to individuals has spurred an ever increasing focus on the examination and assessment of collective performance. There are dozens of existing measures that assess team attributes and dynamics. Specific areas of interest include such elements as team building, developing interpersonal relationship skills, selection of team members, assessing team cognition, identifying team issues, and rating team efficiency (Salas, Cooke, Kiekel, Stout, Bower, & Cannon-Bowers, 2003). Team variables that are assessed with the aim of diagnosing or predicting those elements include personality, cooperation, team trust, cognitive ability, team efficacy beliefs, task versus emotional orientation, communication processes, and shared goals (Anderson & West, 1996). There are various approaches to the development of such measures and such work is undertaken by both industry and academia. The purpose, validity and reliability, and theoretical and conceptual underpinnings vary from tool to tool.

Consultant-developed instruments tend to focus on dimensions consequential to performance that are also most amenable to improvement via consultant-based interventions. Wageman, Hackman, and Lehman (2005) note that while these tools generally have high face validity and provide feedback on team dynamics that users find interesting and informative, there is a general lack of empirical support. Frequently the measures are developed based on the experiences and observations of practitioners rather than by incorporating established theory and research. Consultant-based instruments are infrequently employed in academic research; thus they lack unbiased reliability and validity studies that would support their inclusion in an examination of team behavior, dynamics, and performance.

Alternately, there are a variety of scholar-developed instruments that measure team attributes, dynamics, behavior, and performance that have been assessed under formal laboratory conditions and whose reliability and validity have been well established. However, these instruments tend to be narrower in scope, with a focus on the research interests of the respective developers. Scholar-developed instruments tend to take a considerable amount of time for completion; even so, they generally do not provide a robust team diagnosis and important factors may not be captured by the tool. For example, both Mohr (1971) and Pearce and Gregersen (1991) developed instruments to assess team task interdependence using multi-item Likert-type scales; because neither measure adequately captures the cooperation demands of particular team tasks, subsequent revisions to each of the scales were more context specific (Wageman, Hackman, & Lehman, 2005). Because of the context specificity required by these measures to capture cooperation aspects of team performance, a standard measure and corresponding norms failed to emerge.

Wageman, Hackman, and Lehman (2005) assert that the Team Diagnostic Survey (TDS) overcomes the challenges inherent to consultant-developed and scholar-developed instruments by providing a robust diagnosis of team behavior, dynamics, and performance across a variety of contexts in a short form that is empirically validated. A thorough examination of the instrument's psychometric properties supports its inclusion in academic research. The availability of norms for different types of teams and organizations support the employment of the TDS in the field as well. The team profile generated by the TDS can be an effective means for assessing a team's standing on the conditions and dimensions that foster team effectiveness (Wageman, Hackman, & Lehman, 2005).

Hackman and Wageman (2005) have defined team effectiveness as a three dimensional construct: (1) Effectiveness is considered to be present when the output of the team system, be it a product, service, or decision, meets or exceeds the criteria for quantity, quality, and timeliness. (2) Team members' capability to perform together is enhanced by the social processes involved in team performance. Teams are considered effective when the degree of team intactness is greater at the conclusion of a task or following the achievement of an objective than when the team initially commenced performance. (3) Membership in the team supports the learning and wellbeing of individual team members; membership in the team does not frustrate, alienate, or deskill team members. The second and third dimensions of Hackman and Wageman's (2005) definition of team effectiveness can be assessed using the TDS (Wageman, Hackman, &

Lehman, 2005). The TDS views the team as a semi-autonomous social system that evolves over time and in context into an intact entity, and identifies both the strengths and weaknesses of a team. The TDS diagnoses the enabling conditions that increase the likelihood that a team will perform effectively and assesses the effectiveness of team processes, the quality of relationships between team members, and individual team members' motivation and satisfaction. Wageman, Hackman, and Lehman (2005) assert that effective team performance that produces satisfactory outcomes is a result of the synergistic effect of three processes: (1) the amount of effort extended by the team as a whole in completing a task or achieving an objective; (2) the alignment of the strategies employed by the group with the task at hand; and (3) the collective knowledge and skills contributed by members of the team. A team that puts forth sufficient effort, employs an appropriate strategy for task completion or achievement of an objective, and possesses sufficient knowledge and skills is likely to achieve a high score on the first dimension of Hackman and Wageman's (2005) model of team effectiveness.

More generally, Zigon (1997) proposed guiding principles for the assessment of collective team performance, rather than endorsing a particular instrument. In order to most effectively measure team performance in a way that supports actionable feedback, Zigon (1997, p. 38) advocates that performance measures should include:

- A statement of the results the team will be working to achieve with measures and performance standards for each result
- Statements of each individual's results, with measures and performance standards for each result
- A clear picture of the priorities and relative importance of the team and individual results
- A plan for how to collect and summarize performance data, so the team and individuals will know how they are performing compared to the performance standards

With regard to assessing the general success or failure of a team, Church (1998) asserts that collective performance by a team may not necessarily be best measured at the team level. Rather, evaluating the performance of a team within an organization may require an examination at the higher organizational level of analysis. Regardless, the chief aim of performance measures should be enabling the team to understand what they ought to do in order to improve their performance.

Performance decay

Decay of individual task performance by team members as contributory to decay of collective performance

Collective performance may be considered the aggregate of the individual contributions of team members. Individual performance must be considered in evaluating possible outcomes with regard to team task performance. Campbell (1990) proposed a model of performance that captures the various dimensions of non-domain specific performance. Within this model, task specific behaviors refer to the substantive tasks that distinguish one objective from another; alternately, non-task specific behaviors refer to those tasks that do not pertain specifically and only to a particular job or objective. Interpersonal dimensions are also of importance, particularly the individual’s proficiency in effectively communicating information and the expression of helping behaviors or backup behaviors when tasks are interdependent and performance is collective. The interpersonal dimension may refer to interactions that are either task specific or non-task specific. The degree to which individuals commit to a particular task, and in some cases their job role in general, is deemed effort, and may refer to either normal operating conditions or extraordinary circumstances. The remaining factors of Campbell’s eight factor model are not necessarily applicable across work domains. These factors involve personal discipline to the degree that peripheral behaviors do not negatively impact performance, a supervisory or leadership component, and managerial or administrative duties that support the organization or system as a whole but do not involve direct supervision.

The performance of tasks imposes skill and resource requirements and demands on all members of the team to some degree. Degradation of individual capacities contribute to overall decay of collective performance, though this process may be mitigated to some degree by sufficient skill, knowledge, and functional overlap between team members. The factors that contribute to performance decrements may be environmental, situational, interpersonal, physiological, or psychological.

For example, individual endurance when wearing full firefighting PPE may be limited to less than 10 minutes in a high heat stress environment (US Navy, 2006). The maximum time for a firefighter to function in full firefighting PPE is 30 minutes. Beyond these time limits, fatigue and heat stress or heat strain may become unacceptable risks that result in performance degradation and threaten the safety of the team member individually and the team as a whole.

Individual task performance may also be hampered by problematic communication strategies. For example, members of a fire team generally exchange information with one another via normal voice communications. When voice amplifiers are available and employed, they may be provided to some members of the fire party. Voice amplifiers attach to a firefighter’s breathing mask and projects his voice, precluding the need for loud shouting by the firefighter in order to be heard through is face mask. When available, it is suggested that voice amplifiers are supplied to at least 10 members of the fire party including the scene leader, the attack team leader, two attack nozzlemen, two hosemen, two investigators, a messenger, and an electrician (Navy, 2006). Team members may also communicate with one another via radio equipment. However, in a high heat stress environment, there are limitations of radio equipment that must be realized and accounted for. For example, exposing the radio to high heat will cause a frequency shift (Navy, 2006). While personnel generally carry radios in a pocket of the FFE to reduce heat exposure, over time the high heat from a major fire will cause the radio unit to malfunction. As such, the attack team leader is advised to communication with the scene leader using "best available means" (Navy, 2006, p. 555-7-59). Attack team members are also likely to experience degraded communication abilities in a severe environment, as the primary focus will be on breathing, survival, and the immediate primary task at hand. The attack team leader may not utilize radio communications effectively when working in severe conditions and/or under high levels of stress. In such situations, the scene leader is expected to initiate actions as necessary in the absence of communications from and with the attack team. The scene leader can acquire information about the fire attack via a messenger dispatched to the attack team when radio communications are insufficient. When any of the various communication strategies employed by an individual team member are insufficient for or improperly aligned to a given task, individual work may suffer. Individual task performance that degrades under potentially stressful circumstances may contribute to degraded overall team performance. This is particularly likely in situations requiring distributed team decision making, whereby team members must interact in a timely fashion to communicate critical information (Urban, Weaver, Bowers, & Rhodenizer, 1996).

In a more generalized context, Campbell (1990) suggests that individual differences in performance and the rate at which performance degrades are a function of three primary determinants: motivation, declarative knowledge, and procedural knowledge and skills. Motivation refers to the direction, intensity, and persistence of volitional behaviors in support of task completion and the achievement of a given objective. The individual elects to expend effort, chooses the level of effort to expend, and determines the duration for which he can and will persist in the expenditure of that level of effort. Declarative knowledge refers to the individual's knowledge about the requirements of a given task, including knowledge of the relevant principles and facts. Procedural knowledge and skills involve knowledge of how to execute the elements of a given task; this may include relevant cognitive, perceptual, or interpersonal skills.

Decay of collective task performance by teams

Previous research has also acknowledged that elements of team performance may decay while a team remains theoretically intact. Robbins and Finley (1996) propose that teams fail due to mismatched needs, ambiguous goals, unresolved roles, poor decision making, personality conflicts, poor leadership, inadequate feedback and/or information, improper reward systems, deficient team trust, and/or unwillingness to change. Katzenback and Smith (1993b) provide a similar summary of factors that contribute to collective performance decrements, noting a weak sense of direction; insufficient or unequal commitment to team performance; gaps in critical skills; and external confusion, hostility, and/or indifference. Critical skill gaps results from a lack of training or unsuitable team composition (Castka et al., 2001).

Alternately, Roth (1992) asserts that moderating factors include skill decay and team membership changes. Skill decay refers to the deterioration of skills and knowledge when they have not been practiced for an extended period of time; this may have deleterious effects on collective task performance. A lack of practice of individual task-supporting skills and knowledge may also lead to skill decay that negatively affects collective task performance. Skill decay is considered to contribute to a reduction in the maximal expression of knowledge and skills by a team.

Alternately, collective skills and knowledge may decay as a result of changes in team membership. These changes may be the result of absolute changes in team membership (turnover) or changes in the positions held by team members (turbulence). Higher levels of turbulence (Eaton & Neff, 1978) and turnover (Forgays & Levy, 1957) have been shown to have a negative effect on team performance. Turnover in leader positions has been demonstrated to have a more detrimental effect than turnover in positions that are less specialized and function more to fulfill general manpower requirements (Trow, 1964; Ziller, 1963). Changes in team membership are considered to contribute to a reduction in the maximal expression of knowledge and skills by a team. Greater stability in team membership is considered beneficial to collective team performance.

Roth (1992) proposed a series of taxonomies to organize and classify factors believed to impact team performance. Because team have a variety of attributes which may vary according to team type or over time, it is important to take a holistic accounting of performance determinants. Roth asserts that the variables of interest include number of members (size), type of formal or informal organizational structures or communication patterns, permanence, tasks performed by the team, the types of individual skills required for team task performance, technical support or equipment used in team performance, amount of experience working together, and numerous other dimensions (Dyer, 1984; Denson, 1981; Dyer, Trimble, & Finley, 1980).

Taxon 1 describes the attributes proposed by Roth (1992, p. 10-17) to impact the sensitivity of a team to performance change. This taxon includes the following elements:

- team size (number of members)
- formal organizational structure- sub-teams
- member substitutability- position redundancy in the team’s structure
- more position redundancy yields a smaller impact of turbulence, turnover, and skill & knowledge decay without practice on team performance
- equipment used by the team
- tasks performed by the team and team members
- leadership
- the total sensitivity score for a team type can range from zero to 12. A score of zero indicates a relatively small impact on performance change of either forgetting or membership change for a team type. On the other end of the continuum, a score of 12 would be interpreted as indicating a relatively high level of sensitivity to performance change as a result of both forgetting and membership change.

The respective influences of these elements are summarized in Table 1 (Roth, 1992, p. 18):

Table 1. The attributes proposed to impact team sensitivity to performance change

	Influence of the attribute on effects of the primary performance predictors	
Attribute	Influence on skill decay	Influence on turnover and turbulence
Team size	Larger size increases effects on performance	Larger size decreases effects on performance
Number of sub-teams in formal team structure	Larger number of sub-teams increases effects on performance	Larger number of sub-teams increases effects on performance
Position redundancy in formal team structure	Greater redundancy decreases effects on performance	Greater redundancy decreases effects on performance
Number of equipment items used by team type	Larger number of equipment items increases effect on performance	Larger number of equipment items increases effect on performance
Number of collective tasks performed by team type	Larger number of tasks increases effects on performance	Larger number of tasks increases effects on performance
Number of individual tasks performed by team type	Larger number of tasks increases effects on performance	Larger number of tasks increases effects on performance
Number of leaders in formal team structure	Larger number of leaders decreases effects on performance	Larger number of leaders decreases effects on performance

Taxon 2 describes the characteristics of collective tasks proposed by Roth (1992, p. 19-27) to influence team performance:

- number of task steps
- established versus emergent tasks
- sub-teams in task performance
- individual task performance
- coaction versus interaction in task performance

  - A coative task is one where all unit members or sub-teams perform similar or identical activities simultaneously, generally under central direction or leadership. Communication tends to be unidirectional, from the team leader to team members. Team members tend to adapt their activities in a similar way as a result of directions.
  - An interactive task is one where individual team members or sub-teams perform different activities, often asynchronously. Communication in interactive tasks tends to be multidirectional, and sub-teams or individual team members may respond to communications or directions in different fashions.
- potential for compensation or correction in task performance
  - A key characteristic of team behavior and performance is the ability of one member of a team to compensate for less than adequate performance of other members (George, 1979; Dyer, 1980). This can include providing guidance or corrections to the behavior of another team member, or what has been termed "load balancing" (performing part or all of a task in another member's stead) (Lanzetta & Roby, 1956).

The respective influences of these elements are summarized in Table 2 (Roth, 1992, p. 29):

Table 2. The characteristics of collective tasks that influence team performance

	Influence of the attribute on effects of the primary performance predictors	
Attribute	Influence on skill decay	Influence on turnover and turbulence
Number of task steps (subtask and standards)	More steps increases effects on performance	More steps increases effects on performance
Established versus emergent rating of task	More emergent increases effects on performance	More emergent increases effects on performance
Average number of sub-teams per subtask	Larger number increases effects on performance	Larger number increases effects on performance
Number of individual tasks performed in collective task	Larger number of tasks increases effects on performance	Larger number of tasks increases effects on performance
Coactive versus interactive rating of task	More interactive rating increases effects on performance	More interactive rating increases effects on performance

Rating of potential for compensation or correction in task performance	Higher rating increases effects on performance	Higher rating increases effects on performance

Taxon 3 describes the specific team sensitivity to performance change proposed by Roth (1992, p. 27-31):

- aptitude
  - Experimental studies of retention of skills and knowledge association with military type tasks indicate that higher-aptitude (as indicated by Mental Category) personnel typically learn to criterion level more rapidly and retain more learned material over a given retention interval. These results are specific to individual tasks. An alternative explanation is that higher aptitude personnel learn more than lower aptitude personnel during initial skill and knowledge acquisition, but that the rate of decay for all levels of aptitude is the same. Whichever explanation is chosen, the result is the same: higher aptitude personnel retain more of what they have learned, and perform more proficiently, over a given retention interval, than do lower aptitude personnel
- training and experience
  - In terms of skill and knowledge development, training and experience can be thought of as providing initial and additional opportunities to learn, or to develop effective and elaborated knowledge representation and recall structure (KRRSs). The combination of formal and informal training, and experience on the job, may lead to overlearning; that is, additional learning that takes place after the initial task criterion has been reached. The degree of overlearning has been cited as an extremely important determinant of long-term retention. Overlearning has also been associated with the development of KRRSs that are more resistant to forgetting.
  - When considering team performance, the authors distinguish between two elements of team members' training and experience: (1) overall training and experience as a member of the military, and (2) training and experience as a member of the team. The higher the rate of turnover, the less likely it is that all members of a team will have developed and retained the critical teamwork-oriented knowledge and skills necessary to perform collective tasks at a high level of proficiency, other factors being equal.
  - The other element of training and experience relates to overall history as a military member. In general, training and experience are correlated with a number of characteristics of a military member: total length of service, paygrade, and Skill Level within MOS. Of these, the paygrade of team members probably reflects qualities of most interest from the authors' point of

view. Paygrade is highly correlated with assigned MOS Skill Level (for enlisted personnel), which indicates proficiency in certain tasks specific to an MOS, or completing training designed to produce proficiency in those tasks. Therefore, paygrade can be thought of as directly related to particular competencies in job performance.

- A composite metric is used for this variable, for two reasons. First, it is desirable to reflect the multidimensional nature of team member characteristics. As with aptitude, both the average and the highest among the team should be represented in a metric. Second, a composite metric allows for including both officer and enlisted personnel. This cannot be done with some other possible measures, such as Skill Level (officers do not have assigned Skill Levels). The metric is computed by averaging four values:
  - The average paygrade of all enlisted personnel assigned to the team;
  - The paygrade of the highest-ranking enlisted member of the team;
  - The average paygrade of all officer personnel assigned to the team; and
  - The paygrade of the highest-ranking officer assigned to the team
- The denominator should reflect the number of figures used to compute the numerator. For example, if no officers are included in the formal structure of the team type of interest (as with an Infantry squad), then only the two values for enlisted personnel should be added to make the numerator of the equation, and the denominator should be two.
- This metric is insensitive to the number of personnel actually assigned to a team. This enables comparing experience among teams some of which may be understrength, or experiencing shortfalls of grades of assigned personnel to the authorized grades for their positions. However, it should be used only to make comparisons among teams of a given type. Teams of different types should not be compared using this metric, because the attributes associated with the design of different team types vary.

The respective influences of these elements are summarized in Table 3 (Roth, 1992, p. 29):

Table 3. The specific team sensitivity to performance change

Attribute	Influence of the attribute on the effects of forgetting
Aptitude metric	Larger metric reduces effects on performance
Turnover rate per month (Experience as a team)	Larger rate increases effects on performance
Overall military experience of team members (Paygrade metric)	Larger metric reduces effects on performance

Shanahan, Best, Finch, and Sutton (2007) subsequently examined the behavioral, cognitive, and motivation factors that influence team performance. This research integrates elements of Roth's (1992) discussion of the role of training as a team. Shanahan and colleagues assert that efficacious team performance is supported by a common understanding of team members' intent, an accurate knowledge of each member's roles and responsibilities, situation awareness, and effective communication and collaboration. This perspective asserts that in addition to behavioral processes, emergent cognitive or motivational states of the team—such as situation awareness and team cohesion—strongly mediate the alignment of team processes with contextually driven task demands. Emergent team states are considered to be dynamic and fluctuate as a result of the team's situation, inputs, processes, and outcomes. Emergent states function as both inputs and outputs in the conceptualization of team effectiveness, as they are a product of team experiences and processes and moderate subsequent team experiences and processes. Shanahan and colleagues employ the conceptual framework presented by Kozlowski and Ilgen (2006, p. 79) to demonstrate the recursive nature of the team system (see Figure 5).

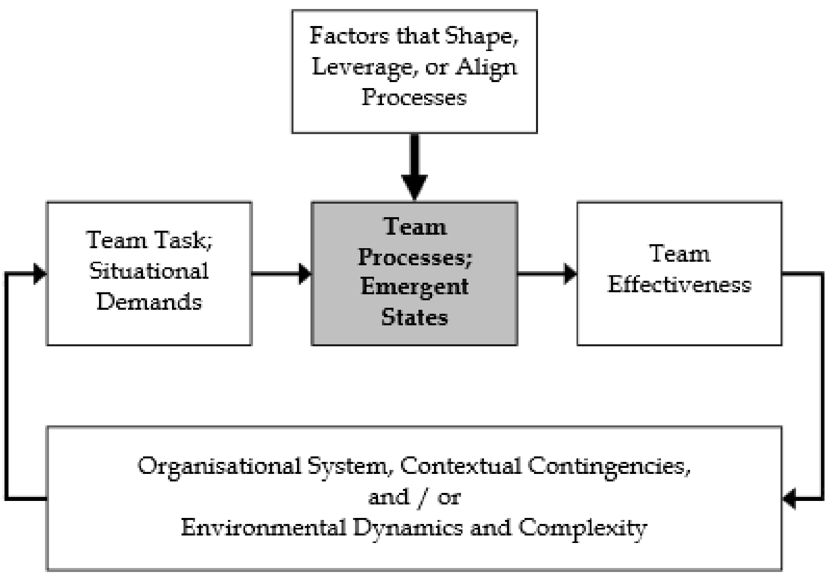

Figure 5. Conceptual framework of team effectiveness (Kozlowski & Ilgen, 2006, p. 79)

Shanahan and colleagues (2007, p. 2) summarize the factors contributing to team performance in Table 4:

Table 4. Behavioral, cognitive, and motivational dimensions underlying team performance (Shanahan et al., 2007, p. 2)

Behavioral processes	Cognitive structures and processes	Motivational processes and states
Information exchange Communication	Mental models Transactive memory	Collective efficacy Cohesion

Monitoring behavior Supporting behavior Leadership and initiative Coordination Cooperation Assertiveness Decision making Adaptability	Situation awareness	Trust

There are a variety of skill dimensions and subskills that contribute to emergent states. For example:

Table 5. Teamwork skill dimensions and subskills (Shanahan et al., 2007, p. 5)

Skill dimension	Sub skills
Adaptability	Flexibility Compensatory behavior Dynamic reallocation of functions
Shared situation awareness	Situation awareness Shared problem-model development
Performance monitoring/feedback	Intra-member feedback Mutual performance monitoring
Leadership/team management	Task structuring Mission analysis Motivation of others
Interpersonal relations	Conflict resolution Cooperation (interpersonal)

	Assertiveness Morale building (behavioral reinforcement) Boundary spanning
Coordination	Task organization Task interaction Timing and activity pacing
Communication	Information exchange Consulting with others
Decision making	Problem assessment Problem solving Planning Metacognitive behavior Implementation (jurisdiction)

Smith-Jentsch, Zeisig, Acton, and McPherson (1998) provide a detailed description of some of the processes included in Shanahan and colleagues' (2007) conception of the factors underlying team performance. Information exchange is comprised of employing information from all available sources, passing information to the appropriate parties in a timely fashion, and providing holistic situation updates. Communication involves utilizing appropriate language and phrasing, ensuring the completeness of reports, avoiding wordiness and excessive chatter, and communicating in a clear, audible tone of voice. Supporting or backup behavior includes monitoring for errors and taking corrective action as appropriate, and offering and requesting backup as a compensatory mechanism to equally distribute workload among team members. Leadership and initiative involves providing guidance and suggestions to others, as well as communicating clear and appropriate priorities. Brannick, Prince, Prince, and Salas (1995) provide more elaborate descriptions of other processes included in Shanahan and colleagues' (2007) conception of the factors underlying team performance. Assertiveness is described as a team member's willingness to make, act on, and defend decisions, and to ask questions when additional information is required. Brannick and colleagues coming decision making and mission analysis as a single teamwork dimension, with the accompanying definition that this factor involves employing sound judgment to choose the best course of action based on available information, as well as seeking information and allocating and monitoring resources. Adaptability is defined as altering a course of action as appropriate given changing conditions, enacting an appropriate change of action, and maintaining constructive behavior under stress.

Situation awareness involves the identification of problems, maintenance of accurate perceptions of the external environment, and detection of situations that require corrective action. Leadership is defined as the direction and coordination of the activities of other team members and monitoring their performance. Communication involves clearly and accurately dispatching and acknowledging information, instructions, and commands.

Various dimensions and sub-dimensions proposed by Shanahan and colleagues (2007) contribute to a general class of cognitive constructs referred to as mental models. Mental models describe and explain how information and knowledge are represented in the mind (Klimoski & Mohammed, 1994). Salas, Sims, and Burke (2005) assert that "mental models are what individuals use to organize or encode information such as the dynamics of the environment in which they are embedded and the response patterns needed to manage these dynamics, the purpose of the team, and the interdependencies among team members' roles" (p. 565). Mohammed, Ferzandi, and Hamilton (2010) describe the antecedents, outcomes, and moderators of TMMs in Figure 6. Factors such as the tenure and experience of team members have been noted as determinants of convergent TMMs. For example, Smith-Jentsch and colleagues (2001) found that Navy personnel holding higher ranks and with longer time in the service tended to have more similar TMMs; individuals with longer time in the service also had more accurate TMMs. When a team is composed of a greater percentage of members with high team experience, greater agreement with regard to TMM schema exist (Rentsch & Klimoski, 2001). Similarity in education and organization level and percentage of recruited team members also contribute to teamwork schema agreement; similarity in gender and age did not have a relationship with TMM agreement (Rentsch & Klimoski, 2001). Edwards, Day, Arthur, and Bell (2006) found that the general mental ability of the team positively predicts mental model similarity for the taskwork domain, and predicts accuracy even more strongly.

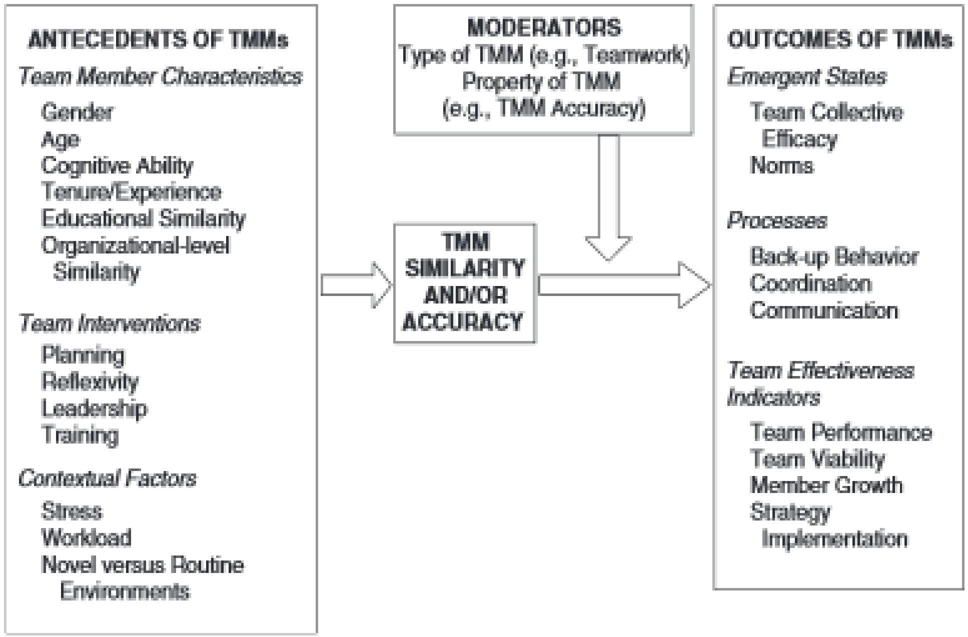

Figure 6. A sampling of antecedents, outcomes, and moderators empirically investigated in the TMM literature (Mohammed, Ferzandi, & Hamilton, 2010, p. 892)

Team mental models (TMMs) describe and explain how key elements of a team's relevant context or situation are shared across team members; TMMs reflect the team members' shared, organized understanding and mental representation of skills and knowledge about key situational and contextual factors (Mohammed, Ferzandi, & Hamilton, 2010). Mohammed, Ferzandi, and Hamilton (2010) illustrate the similarities and differences between TMMs and other team cognition constructs in Table 6.

Table 6. Team Mental Models (TMMs) compared to other team cognition constructs (Mohammed, Ferzandi, & Hamilton, 2010, pp. 882-883)

Dimension	Team Mental Models	Transactive memory	Group learning	Shared/Team situation awareness	Strategic consensus

Definition	Team members' shared, organized understanding of knowledge about key elements of the team's relevant environment (Klimoski & Mohammed, 1994)	Cognitively independent system for encoding, storing, and retrieving information that combines the knowledge possessed by each individual with a shared awareness of who knows what (Wegner, 1987)	Processes and outcomes through which groups acquire, share, and combine new knowledge through experience (Argote, Gruenfield, & Naquin, 1999)	Sharing among group members concerning the meaning and projected status of environmental events (Wellens, 1993)	Shared understanding of strategic priorities among managers (Kellermanns, Walter, Lechner, & Floyd, 2005)
Academic roots	Psychology (industrial-organizational, cognitive)	Psychology (social, cognitive)	Organization-al behavior	Aviation, human factors, cognitive psychology	Strategy, decision making
Properties	Similarity, accuracy	Agreement, accuracy, specialization of expertise	Similarity	Similarity, accuracy	Similarity
General content domain	Taskwork & teamwork knowledge	Taskwork knowledge	Teamwork knowledge	Taskwork knowledge	Beliefs

Specific content domain	Equipment, work procedures and strategy, awareness of member responsibilities and role interdependencies, understanding of teammates' preferences and skills	Task-based expertise	Acquiring new knowledge, asking for help, reflecting on errors, seeking feedback, and creating new practices and procedures	Perception of environmental elements, comprehension of current situation, projection of future status	Strategic ends, means, and priorities, strategic commitment
Degree of sharing emphasis	Sharing as overlapping	Sharing as distributed	Sharing as overlapping	Sharing as overlapping	Sharing as both distributed and overlapping
Elicitation technique	Paired comparison ratings, concept maps, card sorts, qualitative techniques	Collective recall measures, behavioral observation, surveys (e.g., Lewis, 2003)	Surveys, qualitative techniques (e.g., interviews, observation)	Surveys (freeze probe, real-time problem self-rating), observer ratings, indirect performance measures, eye tracking	Surveys (questions about scenarios, understanding or importance of specific strategies)
Structural representation	Pathfinder, multidimensional scaling, UCINET, concept maps, card sorts	None	None	None	None
Samples & tasks typically investigated	Laboratory student teams performing computer simulations, action teams in a variety of field settings	Laboratory student teams performing assembly tasks, MBA project teams, industry teams	Qualitative and quantitative field research on a variety of team types	Military and aviation personnel in field settings or performing simulations	Top management teams, management decision-making teams

Representative studies	Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000; Lim & Klein, 2006; Marks, Sabella, Burke, & Zaccaro, 2002; Rentsch & Klimoski, 2001	Austin, 2003; Lewis, 2004; Liang, Moreland, & Argote, 1995; Moreland & Myaskovsky, 2000	Edmonson, 1999; Edmonson, Winslow, Bohmer, & Pisano, 2003; Wong, 2004; Zellmer-Bruhn & Gibson, 2006	Artman, 2000; Banks & McKeran, 2005; Prince, Ellis, Brannick, & Salas, 2007; Wellens, 1993	Ensley & Pearce, 2001; Kilduff, Angelmar, & Mehra, 2000; Knight et al., 1999

When the members of an intact team have a shared mental model of both taskwork and teamwork, the team is considered to be more prepared to anticipate the needs and actions of other team members (Cannon-Bowers, Salas, & Converse, 1993). Collective task performance will benefit from well-developed TMMs, as they allow team members to have similar or shared interpretations of information, expectations about future events, and causal accounting or explanations for a situation. TMMs can contribute to more effective team situation awareness, as a strong TMM allows a team to have a shared conception of what is currently happening, what is expected to happen in the future, and the reasons for these occurrences. This allows individual team members to better predict the needs of other team members and the team as a whole based on an understanding of both the situation and other team members' individual knowledge and skills. TMMs support better team coordination of action and adaptive behaviors that enable a team to make better decisions and demonstrate more effective performance in response to task demands (Mohammed, Ferzandi, & Hamilton, 2010).

Marks, Mathieu, & Zaccaro (2001) assert that TMMs are emergent properties of a team, and represent cognitive "properties of the team that are typically dynamic in nature and vary as a function of team context, inputs, processes, and outcomes" (p. 357). While the inputs to a TMM are based on the perceptions and cognition of individual team members, the result of TMMs is a common knowledge structure that influences collective performance. TMMs were originally proposed as being composed of four non-independent content domains: knowledge about technology and tools (equipment model); understanding of procedures, strategies, and contingency plans (task model); awareness of the responsibilities, role interdependencies, and communication patters of team members (team interaction model); and understanding of team members' preferences, skills, knowledge, and habits (team model) (Cannon-Bowers, Salas, & Converse, 1993). Subsequent research addressing TMMs has collapsed the four content domains into two dimensions: teamwork and taskwork (e.g., Mathieu, Heffner, Goodwin, Salas, & Canon-Bowers, 2000). From this viewpoint, the teamwork aspects of TMMs involve the interpersonal interaction requirements and knowledge and skills of team members; the knowledge aspect of the TMM includes declarative, procedural, and strategic knowledge (Rouse, Canon-Bowers, & Salas, 1992). The interpersonal aspects of effective teamwork include respect and trust; protection and support; open dialogue and communication; common goals; shared values and beliefs; a subordination of individual objectives to those of the team; and distributed leadership (Kets De Vries, 1999). This belief structure is contrasted to a knowledge structure that refers to a descriptive situational state that regards the state of nature believed to be true. Taskwork, the second dimension of the collapsed TMM, involves task and work goals and performance requirements.

A great deal of previous research has established a positive relationship between shared TMMs and effective team performance (e.g., Marks et al., 2000; Marks et al., 2002; Mathieu et al., 2000; Lim & Klein, 2006; Rentsch & Klimoski, 2001; Smith-Jentsch et al., 2005). The emergence of a TMM has also been found to demonstrate a positive relationship with various team processes (Matheiu et al., 2000) including team back-up behavior and quality (Marks et al., 2002), coordination (Marks et al., 2002), and communication (Marks et al., 2000). Additionally, higher degrees of sharedness of TMMs has been shown to result in greater collective efficacy at task performance (Mathieu, Rapp, Maynard, & Mangos, 2010), strategy implementation (Gurtner, Tschan, Semmer, & Nagele, 2007), engagement (Miles & Kivligham, 2008), and less attention to time (Waller, Gupta, & Giambatista, 2004). The formation and emergence of effective TMMs is considered to evolve as a result of and be motivated by training (Cannon-Bowers, 2007). Salas, Cannon-Bowers, and Johnston (1997) assert that the chief purpose of team training is "to foster in team members an accurate and sufficient mental representation of the team task structure, team role, and the process by which the two interact (p. 362). Training interventions such as self-correction, team interaction training, computer-based, and cross-training have been found to increase the similarity and/or accuracy of TMMs (Mohammed, Ferzandi, & Hamilton, 2010).

With regard to collective functions supported by TMMs, Shanahan and colleagues (2007) note decision making as a behavioral process that contributes to team performance. Decision making by a team is a complex process. Orasanu (1990) asserts that there are four components to complex team decision making: situation assessment, metacognition, shared interpretations of the decision situation, and resource allocation. The continual management and allocation of resources among team members differentiates team decision making from individual decision making (Salas, Dickinson, Converse, & Tannenbaum, 1992). Resource allocation involves monitoring the resource needs of each team member, and distributing resources among team members in such a way as to maximize the collective performance of the team. Resource needs may vary based on team structure, which refers to the fractioning of the collective team task into component pieces of information and capabilities, and the delegation of these constituent portions to individual team members.

With regard to the decision making element of collective task performance decay, there are tendencies that occur during group decision making that may contribute to degraded outcomes. The expected benefits of group or team problem solving and decision-making—including a variety of perspectives, a dampening of decision biases, increased decision reliability, and more information regarding possible alternatives (Aldag & Fuller, 1993)—may decompose when either group polarization or groupthink occur. The general conception that any collective decision-making process is superior to individual decision-making is faulty; characteristics of the group or team itself can either drive the manifestation of such phenomenon or inoculate against it.

Group polarization involves the phenomenon whereby groups to make decisions that are more extreme than the initial inclinations of individual group members. Group polarization drives the attitude change on an individual level; choice shift refers to the collective attitude change of the group (Meyers & Lamm, 1976). Over the course of deliberation, group members move toward a more extreme position relative to members' pre-deliberation tendency. Group polarization may also result in a significant shift in collective risk tolerance.

Sunstein (2002) asserts two underlying mechanisms that produce group polarization: (1) social influences on behavior, and (2) limited "argument pools" and the trajectories along which they lead group members. Because social homogeneity can be detrimental to meaningful deliberation, it is important that groups or teams have sufficient diversity. An intact team may be less vulnerable to normative influence in group deliberation, as members may be less likely to engage in social comparison and seek acceptance and favorable perception by the group because relations between team members and cohesion are already established. Ad hoc teams may be more susceptible to group polarization and choice shift, as members are more likely to take a position that is similar to everyone else's but more extreme in order to gain acceptance from the group.

An additional tendency that can manifest in group decision making is the phenomenon of groupthink, whereby a group may fail to adequately consider the available information in an objective manner if they are overly focused on maintaining group cohesiveness. Groupthink is more likely to emerge within a group that is highly cohesive, isolated from alternative perspectives, and has highly authoritative leaders who provide stringent direction. In an effort to reduce friction within the group, individual members may fail to share unique information or unique information may not be weighted appropriately due to the manner in which it is communicated. When a competent team member fails to appropriately disagree within the course of problem solving, process loss may occur. Groupthink can be minimized when a team engages in assertive communication. Hunt and colleagues (2007) note that task achievement may depend on a team member's ability to call attention to anomalies in the process or to speak up when he believes something might be going wrong. Assertive communication entails the acknowledgment that all team members may have valuable input regardless of hierarchies within the team, and that dissention can be voiced in a respectful manner without fear of retribution; assertive communication will reduce groupthink and improve decision-making, as a greater variety of information will be available for consideration.

Previous research has examined acute factors that effect team decay in a considerably more compressed window of time. For example, Mahan, Elliot, Dunwoody, and Marino (1998) assert that sleep loss, continuous performance, and delayed feedback on performance are common features of complex operational environments that have a tendency to degrade performance. Specifically, these factors have consistently led to slowed reaction time, a failure to respond when necessary, incorrect responses, slowed high level cognitive functioning, degraded working memory, and decrements in the execution of knowledge (US Congress Office of Technology Assessment, 1991; Mahan, 1992; Mahan, 1994; Hammond & Doyle, 1991; Dinges, Whitehouse, Orne, & Orne, 1988). Mahan and colleagues (1998) reviewed the specific effects of delayed feedback on performance, noting that feedback reduces human out-of-the-loop effects and may even attenuate the effects of some physiological stressors in complex judgment tasks (Searcy, 1994). Delayed or absent feedback has also been implicated as a cause of the loss in control of the execution of information in complex multi-informational integration tasks (Mahan, 1994; Hammond, 1996). Immediate feedback on the quality of judgments enhances a decision maker's sense of implicit control over information (Mahan, Kirschenbaum, Jilg, & Marino, 1998). Implicit computation and explicit computation are both necessary for complex judgment tasks involving uncertainty that require multiple-cue integration. While some analytical deliberation and application of rules or algorithms is necessary for making judgments, there is also an intuitive component in the decision making process which involves an intuitive holistic assessment of the decision situation. This implicit control over information, discrete from conscious awareness and explicit control over information, is enhanced by immediate feedback on judgment quality and effectiveness (Mahan et al., 1998). In the absence of immediate feedback, particularly when coupled with fatigue, a decision maker's ability to control the execution of information becomes degraded. Teams may dissociate from common, normative judgments over time in the absence of feedback that allows them to calibrate the validity of their judgments; teams and team members may progressively institute policies or rules that are uniquely invalid (Mahan et al., 1998). These outcomes may result in part from degraded TMMs under increased levels of stress and workload, or when the context or situation is novel as opposed to routine. For example, Ellis (2006) found that the similarity and accuracy of team interaction mental models decreased in light of acute stress.

Urban, Weaver, Bowers, and Rhodenizer (1996) also examined more intuitive type decision making, generally referred to as naturalistic decision making, by teams in complex environments. Complexity may be the result of information ambiguity, rapid change and evolution of information, high time pressure, high workload, or some combination of these features (Orasanu & Salas, 1993). Urban and colleagues (1996) examined the effects of team structure, time pressure, and resource demand on team performance and communication over time. Teams under high time pressure performed significantly worse in general compared to the performance of teams in the baseline and high resource demand conditions. Interestingly, while collective team performance was degraded under high time pressure, it was found that teams in this condition responded more quickly to the demands imposed by individual monitoring tasks. This finding indicates that under time pressure, an increased focus on individual tasks may have contributed to poorer collective performance. Increased awareness of strategies that emerge under high time pressure may enable team members to shift their focus from individual task performance to collective team performance, which in turn may support the adoption of strategies that maximize team performance. Training interventions may mitigate the detrimental effects of time pressure on team members' allocation of attention to component tasks. Stout, Salas, and Carson (1994) have asserted that training regarding individual resource allocation (e.g., time sharing) might be a necessary antecedent to improving team resource allocation performance.

Consistent with previous research, Urban and colleagues (1996) found a significant effect of workload on communication, such that teams under high levels of workload demonstrated reduced communication. Teams in the high resource demand condition maintained general performance levels comparable to those of teams in the baseline workload condition. However, high resource demand teams did demonstrate reduced communication regarding the availability of team resources. Communication regarding resource availability was not impacted by time pressure. Team structure did exert a significant impact on communication regarding the availability of resources. Nonhierarchical teams, in which all team members had identical information and capabilities for performing the team task, asked more questions about the availability of resources and made more statements about the demand for resources than did hierarchical teams, in which each team member except the team leader performed similar functions within different domains. Resource availability questions involve the discernment and location of resource deposits that allow a team to respond to task demands. Resource demand behaviors involve diagnosis of the requirements of the task situation. Hierarchical teams asked more questions and made more statements regarding resource exchange. Nonhierarchical teams performed generally better than hierarchical teams. Hierarchical teams demonstrated degraded performance under high workload conditions, while nonhierarchical teams did not. Urban and colleagues (1996) propose that nonhierarchical teams may employ increased communication behaviors in order to support situation awareness, given that this team type involves a more autonomous structure. Hierarchical team members have reduced autonomy of interactions inherent to this team type. As such, it is possible that they are able to simplify the situation assessment strategy in their communication and simply exchange resources among themselves, thus increasing the number of communications to this effect. The findings of Urban and colleagues (1996) suggest nonhierarchical team performance requires communication that provides situation awareness; hierarchical teams benefit more so from communication aimed at supporting resource exchange. Further, the structure type of a team is likely to influence the coping strategies that a team employs to offset workload effects.

Essens (2000) also discussed the potentially negative effects of high workload, a condition asserted to be relative standard in operational command centers and other workplace environments. Over time or due to the situation, workload levels may exceed some critical threshold of processing capacity, of an individual or a team. When workload exceeds the limits of individual or team processing capacity, performance is likely to suffer; the individual or team has been charged with achieving some task or goal that it cannot handle in the time allotted. Increased workload may also reveal inequities in the distribution of workload; depending on team members' roles and responsibilities, some individuals may be overloadedper during a critical situation while others may have few functions. In this scenario, it might be said that some resources are being underutilized while others are being over expended. An unequal distribution of workload or consistent overload not only impacts individual and collective team performance from an operational perspective, these factors may also contribute to negative feelings and accordingly poorer performance if a team is consistently performing below expectations or standards due to workload issues. Performance of a team is positively correlated to its group-efficacy beliefs (Seijits, Latham, & Rotman, 2000); thus, if the team believes it will not do well, performance will be poorer. The potential for reallocation of tasks to underutilized team members as a compensatory mechanism will partially be a function of the structure of the team, the degree of overlap in skill sets and knowledge between team members, and the presence and accessibility of a TMM that allows for an understanding of other team members' roles and responsibilities.

Alternately, high levels workload may be compensated for via load shedding, as opposed to redistribution. When workload reaches some critical threshold, parallel or secondary tasks may be shed or delayed. There is a tendency toward first shedding those tasks that are demanding and do not lead toward immediate feedback or direct success or that hinder performance of an individual's most crucial tasks (Essens 2000). In some cases, team tasks may be viewed as secondary to individual tasks, and may be shed or postponed. Driskell, Salas, and

Johnston (1999) found that stress led to a restricted focus, whereby individual team members narrowed attention from a team perspective to a more individualistic perspective. A team perspective will incorporate a firm understanding of the task, an agreed upon standard of performance, a deadline, a tacit understanding of the limits of the work being undertaken, and a clear definition of the stakeholders (Robbins & Finley, 1996). An understanding and acceptance of these factors relays the relative importance of the collective task at hand and the expectations for performance. Since team perspective is a significant predictor of team performance, loss of team-level perspective under stress is detrimental to collective performance. The degree to which a narrowed, self-focus will degrade team performance may be partially influenced by which team members are affected, and their individual roles and responsibilities. Essens (2000) asserts that a particular danger arises when a team leader has responsibilities beyond the direction, control, and coordination of team members; if the team leader engages in directly accountable tasks and compensates for high workload by shedding tasks that support collective team performance, this may result in the breakdown of the team and team performance. The scope of work becomes increasingly narrowed, with the focus on a limited subset of tasks that at best include the central and most critical tasks. Communication generally decreases, as it may be viewed as a secondary responsibility or nonessential to critical task performance. The tolerance of the individual or team for errors in performance increases, as error correction comes at a time and effort cost that an individual or team may be unwilling or unable to afford. In addition, supporting or backup behaviors, such as error monitoring and response, and the redistribution of workload between overloaded and under-loaded team members, are likely to decrease under stress along with other backup and prosocial behaviors.

Cohen (1978, 1980) found that stress may lead individuals to neglect social or interpersonal cues and demonstrate decreased sensitivity toward others as a result of stress-induced attentional narrowing. As attention becomes increasingly narrowed, an individual will first ignore less relevant peripheral task cues; more relevant and central task cues will subsequently be ignored as attention becomes increasingly focused. As such, aspects of task performance that require attention to and processing of a wide range of cues are more susceptible to degradation under stress (Driskell, Salas, & Johnston, 1999). Collective tasks require team members to attend to both individual and team-level tasks, and to engage in coordination and communication toward the aim of collective performance. Given that attention to social or team cues will diminish as an individual's focus narrows under stress, team perspective is reduced and collective performance will decay.

Team members whose breadth of attention has narrowed and who have become more self-focused under stress are less likely to engage in compensatory strategies such as the redistribution of workload or coordination with other team members; conversely, they are more likely to adopt a narrower, individualistic perspective of task activity (Driskell, Salas, & Johnston, 1999). Driskell, Salas, and Johnston (1999) found that after partialing out the effects for team perspective on team performance, both group interdependence and stress were no longer significant predictors of performance. Team perspective is proposed to be crucial to collective performance, and may in fact be a conduit via which stress and group interdependence moderate performance. There was a mediating effect of team perspective, such that the effects of stress and team interdependence on performance were primarily the result of their effects on team perspective. It is unlikely that the team will be able to sustain effective operations under such conditions, and collective task performance is likely to decay.

Mitigating decay of collective task performance by teams

Generally, effective performance by teams is supported by an amalgamation of factors. Hunt, Shilkofski, Stavroudis, and Nelson (2007) elaborate on nine characteristics associated with high-performing teams (see Table 7).

Table 7. Characteristics associated with high-performing teams (Hunt, Shilkofski, Stavroudis, & Nelson, 2007, pp. 303-305)

Characteristics	*Influence on team performance*
Situation awareness (SA)	Team performance is improved when team members continually assess their environment and update each other in a process called "shared cognition," so that they are making decisions based on current information and can have a shared mental model of the current state of affairs and an updated plan of action with contingencies. SA allows team to maintain a big picture view of situation. Effective military and aviation teams have higher SA than low-performing teams.
Leadership	An effective team leader can command the team and values input from team members. Flattening the hierarch improves safety because information can flow in both directions, whereas leaders who maintain an authoritarian type of leadership reinforce large authority gradients, creating unnecessary risk. A leader should try not to perform procedures unless the procedure is essential and no one else is capable of doing it. Stepping back and keeping a bird's eye view allows the leader to take in and process more information and contributes to situational awareness.
Followership	The nonleader members of the team are called followers. Good followership is just as important for good team functioning as good leadership. Followers need to know their individual role on the team but also contribute to overall team functionality. They must contribute to situational awareness by verbalizing observations about changes in the environment, ideas about diagnosis, to decrease the leaders' workload if necessary, and finally to help the leader avoid mistakes (e.g., the team leader might focus on an incorrect diagnosis and apply the wrong rule (treatment) owing to a fixation error, or be incapacitated, hence everyone in the team should always be alert). Finally, followers must not assume that the leader knows everything and should feel obligated to share observations that might impact outcome.
Closed loop communication	Closed looped communication is used to ensure that a message that was sent is heeded and understood, and involves the sender initiating a message, the receiver receiving the message, interpreting it, and

	acknowledging its receipt, and the sender following up to insure the intended message was received.
Critical language and standardized practices	Critical language refers to the use of a catch phrase that means something to every member of an organization and requires specific action (standardized practices). [For example,] United Airlines develops the CUS program, for "I'm concerned, I'm uncomfortable, this is unsafe, or I'm scared," and is adopted within the culture as meaning "we have a serious problem, stop and listen to me." Another example of a standardized approach to improve the effectiveness of communication is SBAR (situation, background, assessment, recommendation). This is a tool that gives an outline of how awareness and education regarding the fact that nurses, physicians, and other clinicians are taught to communicate in very different styles.
Assertive communication	Safe patient care [or other effective team performance] may depend on the ability of a team member to speak up and get the attention of other team members when they believe something might be going wrong. This is more likely to happen if a team member believes speaking up will not be held against them. A recurrent phrase is that people can still show deference to expertise, but speak up in a non-threatening and respectful manner. The idea is all team members may have valuable input, regardless of rank. The "hint and hope" model has been described as a common and dangerous way of trying indirectly to communicate with other team members.
Adaptive behaviors	Teams whose members are flexible and perform as needed to optimize team functioning and demonstrate adaptive behaviors are those that can truly benefit from the synergy of an effective team. Examples of adaptive behavior that optimize team functionality include: (a) team members ask for help when overloaded; (b) team members monitor each other’s performance to notice any performance decreases (mutual performance monitoring); or (c) team members take an active role in assisting other team members who are in need of help (backup behavior). An essential component to the above actions happening is trust among team members.

Workload management	Workload management is dependent on team members demonstrating adaptive behaviors. This principle requires (1) proper allocation of tasks to individuals; (2) avoidance of work overloads in self and in others; (3) prioritization of tasks during periods of high workload; and (4) preventing nonessential factors from distracting attention from adherence to protocols, particularly those relating to critical tasks.
Debriefing	Debriefing is the process of reviewing a simulation or real event after it is complete to optimize any lessons that can be learned. When using simulation as a teaching tool, simulation with no debriefing and feedback does not result in effective learning. In terms of real events, teams that debrief themselves afterward have been shown to be higher performing.

Alternately, Rickards and Moger (1999) identify seven factors that distinguish high performing teams from lower performing teams: strong platform of understanding; shared vision; creative climate; ownership of ideas; resilience to setbacks; network activators; and learning from experience. Colenso (2000) asserts that high performing teams are defined through preconditions (e.g., purpose, empowerment, support, objectives) and characteristics (interpersonal skills, participation, decision making, creativity, managing the external environment). Katzenbach and Smith (1993b) propose that a strong sense of personal commitment on the part of team members is what distinguishes high performing teams from teams with poorer performance outcomes. This results in higher standards of performance, more robust approaches to tasks, greater mutual accountability, more interchangeable and complementary skills among team members, and a greater sense of collective purpose. Sharp, Hides, Bamber, and Castka (2000) propose six enablers of high performing teams: team member competencies; skills, processes, tools, and techniques; interpersonal skills, communication, personality preferences; value system; shared vision, purpose, goals, direction; and organizational values including openness. Additionally, collective task performance in uncertain, time-constrained, emergency situations is supported by TMMs, particularly when explicit communication is difficult (Cannon-Bowers, Salas, & Converse, 1993; Orasanu & Salas, 1993).

Skill gaps, reallocation of workload, and backup behavior

Smith-Jentsch, Zeisig, Acton, and McPherson (1998) assert that backup behaviors may be protective against performance decay under high levels of workload. These behaviors include error monitoring and response, and a redistribution of workload as necessary to compensate for unequally disseminated workload or overloaded team members. Backup behaviors can mitigate collective performance decay when some team members are under high load.

Greater interdependence leads to a broader team perspective; conversely, stress leads to a narrowing of team perspective (Driskell, Salas, & Johnston, 1999). Team perspective is crucial to effective team performance. In order to maintain effective task performance in situations when effective teamwork is essential, restructuring the task to make it less demanding (e.g, by delegating subtasks) may support effective collective performance by allowing team members to maintain attention to critical task and interpersonal or team cues. Essentially, preserving sufficient attentional resources to maintain team perspective, perhaps through the restructuring of the task demands or environment, supports effective collective performance. Alternately, team perspective may be preserved under stress if it has sufficient subjective importance to team members. Wickens (1996) asserts that stress-induced attentional narrowing may be mediated by subjective importance such that prioritized cues and information are attended to to the exclusion of data with lower perceived priority. While it is often the case that teamwork behaviors such as communication and coordination are perceived by team members as having lower priority than individual, high-accountability tasks, interventions that emphasize team perspective may alleviate team decay under stress (Driskell, Salas, & Johnston, 1999). Team building and the reinforcement of the interrelation of team members and the interdependent nature of team tasks may reduce the detrimental effects of stress on team performance.

Critical skill gaps results from a lack of training or unsuitable team composition (Castka et al., 2001), and may reduce the potential for interdependence because of insufficient knowledge and skills. Castka and colleagues (2001) assert that gaps in knowledge and skills may be overcome via training and personal development. Domains to be addressed via training and development include (Caskta et al., 2001, p. 129):

- Interpersonal and joint skills: dealing with conflict, dynamics of teamwork, how to conduct meetings, effective decision making, communication skills, effective record keeping
- Analytical and statistical skills: problem-solving methods, improvement techniques, basic quality control skills
- Improvement techniques, creativity approach, systems thinking
- Technical skills: related to a particular job

Minimizing skill gaps increases the potential for the reallocation of tasks to underutilized team members under conditions of high load or stress. The capacity for reallocation is partially a function of the structure of the team, the degree of overlap in skill sets and knowledge between team members, and the presence and accessibility of a TMM that allows for an understanding of other team members' roles and responsibilities. As a situation develops, additional resource requirements may emerge, and resources may need to be reassigned to meet operational demands. A team with a capacity for some degree of reallocation of workload among its own members may be less vulnerable to the detrimental effects of load shedding under stress, as slack in the system may allow for stabilization of collective performance.

Further complicating the process of reallocation is the fact that some resources are synergistic; for example, a helicopter and a pilot may together constitute a resource, just as an intact team of firefighters and their associated equipment might constitute a resource. The contributions of an individual worker to a dynamic operational situation may be negligible if that person does not possess adequate skills, knowledge, experience, and TMM understanding. An inexperienced, unskilled, or unincorporated individual may in fact function as a liability to the team if he does not have an understanding of the roles and responsibilities of team members and the skills and knowledge to supplement or complement collective task performance. The addition of supplemental intact teams, however, will more likely meet the resource requirements generated by an evolving operational situation, as long as coordination between teams is achieved. This will require multi-agent planning to maximize the utility of the additional resources (Airy, Mullen, & Yen, 2009). Each team may have individual tasks and goals, but interdependencies between goals must be addressed. As such, the integration of multiple resource agents requires both coordination and planning (de Weerdt & Clement, 2009). This may involve a higher level leader providing task assignment or coordinated resource allocation for teams sharing common resources.

Human operators as a source of system resilience: Team flexibility, adaptability, and evolution

When addressing the flexibility and adaptability of a team, it is important to consider the dexterity of the team with regard to reacting or responding to unexpected change and whether the degree of structure of the team supports effective performance in a given environment. A change, variation, or disturbance in a system may not necessarily be amenable to prediction. As a result, the specific actions that teams must take to complete a task or satisfy a goal would also no longer be amenable to prediction, because the team must oppose or accommodate the disturbance in the system. As such, the team may need to resolve ambiguity in the situation based on its own subjective perceptions, performance criteria, and experience. Ad hoc interactions among team members may emerge, particularly when routine problem-solving methods are inadequate for the current decision situation and existing knowledge must be reinterpreted and reevaluated. When examining the flexibility and adaptability of a team, it is necessary to account for not just prescribed procedures and strategies, but also the strategies that operators employ to process information in light of expertise, perceived work load, perceived cognitive burden of using a particular strategy over another, and the specific information needs of a particular strategy. The system should not overconstrain the individuals and teams working within it, but rather support reduced cognitive workload by making task-relevant aspects of available data more salient and usable. The implementation of work constraints that limit available options rather than strictly focus on prescribed protocols for task completion can support team flexibility, adaptability, and evolution. The conditions that allow a team to respond to unforeseen change or a novel situation can be incubated in the degrees of freedom afforded to an operator. These degrees of freedom allow for alternative transition pathways between the current state and a state in which tasks and goals have been achieved. During a spontaneous event situation, a team may fail to complete all prescribed steps toward goal achievement, but the task may be executed in a manner that best suits the specific context, constraints, and demands of the situation.

Unexpected change may result from environmental developments or situational developments, such as time pressure or fatigue, that put pressure on an existing routine or process. This provides windows of opportunity for new configurations of goal-oriented behaviors to emerge. The decision-making that occurs in such situations is an example of naturalistic decision making. The accommodations and actions that support a collective response to a spontaneous event must be generated online. Cognitively retrieving and implementing formal protocols will be ineffective, as the pattern of change or disturbance in the system is likely unique and characterized by its own set of contingencies. This situated context means that the same set of team behaviors may have different effects at different times. Therefore, teams may need to engage alternative transition pathways in order to achieve the same task goal depending on the situated context. This is referred to as context-conditioned variability or situated action.

Prioritization and task switching

Human operators are viewed as both a source of vulnerability and a source of strength within a complex sociotechnical system. Human operators possess an inherent flexibility and adaptability that allows them to adopt compensation strategies which faced with a structurally imperfect system. When a system is confronted with a situation for which it is not equipped, human operators first try to compensate by putting forth extra effort. When workload reaches some critical threshold, operators engage in task prioritization and parallel or secondary tasks may be shed or delayed to free up all available resources for the performance of the task or tasks perceived as most critical. Essens (2000) notes that while workload is a commonly employed criterion when assessing system functioning, it does not provide a measure of the quality of the work. In order to evaluate the quality of task performance, the demands of an operational situation must be accounted for. These demands may include parallel or secondary tasks; in this case, performance quality also involves prioritization and effective task switching as appropriate to context.

Adapting to change or turbulence in the system

When operating within the confines of a complex sociotechnical system, information from various domains must be combined and acted upon (Essens, 2000). The context in which information processing, decision making, and decision making are occurring is dynamic and situational demands may change over varying time horizons. Cues from the environment will provide information to an individual or team about situational demands that must be met in order to achieve task goals. In decision situations involving complex systems, it is possible that scenarios will arise whereby system inputs will exceed acceptable ranges and the system will no longer perform in a predictable manner. While a system may function in a linear, desirable manner under light or moderate workload, it may behave in a nonlinear, unpredictable manner under heavy loads. Geels and Schot (2007) note that there are five general types of change that can disrupt performance within a system (see Figure 7):

- *Regular change*: corresponds to environments that regularly experience a low intensity, gradual change
- *Hyperturbulence*: corresponds to environments that feature a high frequency of high-speed change in one dimension
- *Specific shock*: corresponds to environmental changes that are rapid and high in intensity, come rarely, and are relatively narrow in scope; a specific shock may dissipate and disappear after a while, returning to baseline, or it may lead to a structural stepwise change, as represented by the two arrows in the above figure
- *Disruptive change*: corresponds to changes that occur infrequently, develop gradually, but have a high-intensity effect in one dimension
- *Avalanche change*: occurs very infrequently, but is of high intensity, of high speed, and simultaneously affects multiple dimensions of the environment; avalanche change leads to permanent changes in the environment (Geels & Schot, 2007, p. 404)

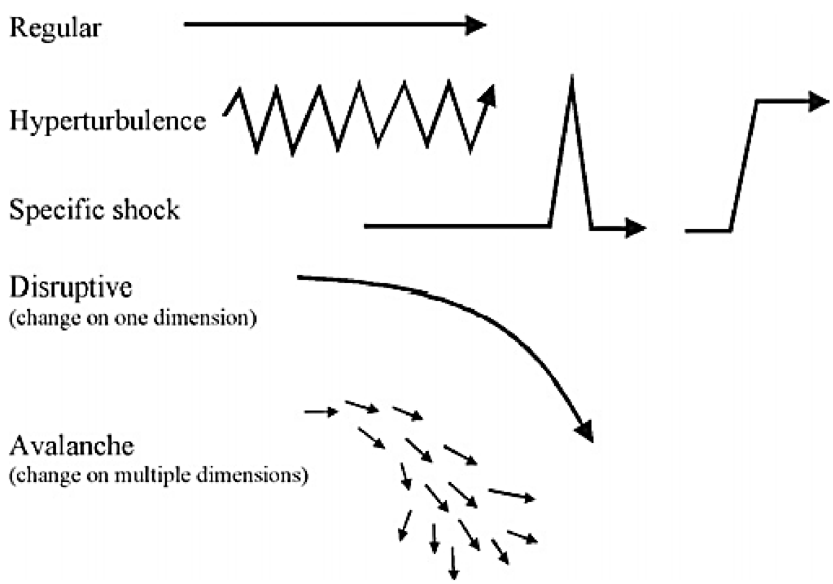

Figure 7. Change and disruption in a system (Geels & Schot, 2007, p. 404).

Change may result from environmental or situational developments that put pressure on an existing routine or process, which then provides windows of opportunity for novelties and new configurations emerge, having taken advantage of these "windows of opportunity." The system may or may not re-stabilize following a disruption or change. Recovery from change will result in a dynamically stable socio-technical system, as ongoing processes continue on different dimensions. In line with Cummings and Worley's (2001) "Incompletion Principle" of sociotechnical systems, stability can be viewed as an instant between transitions.

Generally, when a complex, sociotechnical system is operating in a linear, predictable fashion, each activity (process) is controlled by internal and/or external factors. There are conditions that must exist in order for an activity to produce the correct outputs and achieve task goals. These conditions are specified by controls, such as the availability of data or objects; controls may also refer to the actions, policies, regulations, and/or macro-organizational constraints that direct the goal-directed activity/process. Each activity or process requires one or more mechanisms and/or resources that support the successful completion of a goal-directed activity but are not in any way changed by it. Each process or activity may have multiple inputs, outputs, and controls. The four elements to be identified and mapped to describe a process are inputs, outputs, resources, and controls. Many complex systems are recursive, meaning that systems within the greater sociotechnical system are capable of both generating and absorbing complexity, and are adaptive to change. Feedback loops may result in changes to the relationships between system components and/or the creation of new interdependencies and alternative transition pathways to task completion and goal achievement (Fulscher & Powell, 1999). Feedback loops may illustrate opportunities for soft evolution. Soft evolution refers to the social or organizational evolution with respect to technological artifacts, and may capture the alternative transition pathways that evolve from expertise with a system and/or reliance on heuristics. Hard evolution refers to the evolution of technological artifacts, such as changes to hardware, software, or other elements of technology. Changes to these tools or resources may result in alternative transition pathways that support extant or new objectives.

Soft evolution and Naturalistic Decision Making: Adaptive decision making in ambiguous or time-pressured situations

Soft evolution may occur when system constraints have been exceeded and the system is behaving in a nonlinear fashion. Individuals and teams who possess an accurate mental model of the sociotechnical system as a whole as well as an accurate TMM that captures the respective skills and knowledge of team members may engage in spontaneous or non-prescribed actions with the aim of increasing recoverability and controllability of the system. Actions undertaken by individuals or teams with expertise regarding the system that fall outside the boundaries of prescribed, rational protocols may constitute a specific type of decision making referred to as naturalistic decision making (NDM). Klein and Klinger (1991) note that the defining features of situations involving NDM include uncertainty, ambiguity, and missing data; shifting and competing goals; dynamic and continually changing conditions; action-feedback loops; time stress; high stakes; multiple players; organizational goals and norms; and experienced decision makers. When a system is operating outside of its operational competency envelope, expert decision makers may attempt to recover the system from graceless degradation without the benefit of ample time or definitive information. Naturalistic decision making (NDM) is intended to examine and describe how individuals make decisions "in the wild," or in complex real-world settings. This theory is contrasted in many ways with more classical approaches, such as Multi-Attribute Utility Analysis or Decision Analysis. Classical approaches focused on logic, analytics, and systematic weighting of cues to determine an optimal decision. Gigerenzer and Goldstein (1996), however, note that the human decision maker does not have unlimited time, information, or processing capabilities, a sentiment echoed by Cooksey (2001) in his note regarding the importance of "understanding constraints on, and capabilities of, decision makers" (p. 362). This is particularly relevant when the degradation of a complex system may have critical consequences. In such situations involving ambiguous information and time pressure, most decision making that takes place cannot operate in accordance with the constraints described by classical approaches. As such, the Naturalistic Decision Making approach evolved as a means of examining how individuals actually make decisions, particularly in complex and cognitively or affectively demanding situations.

Klein and Klinger (1991) note several defining features involved in NDM: (a) ill-defined goals and ill-structured tasks; (b) uncertainty, ambiguity, and missing data; (c) shifting and competing goals; (d) dynamic and continually changing conditions; (e) action-feedback loops (real-time reactions to changed conditions); (f) time stress; (g) high stakes or significant personal consequences for mistakes; (h) multiple players; (i) organizational goals and norms; and (j) experienced decision makers (p. 17). These features function to the detriment of classical decision making approaches, which deteriorate when decisions must be made under time stress because of the complexity of the analysis and weighting operations. Further, classical approaches "lack the flexibility for handling rapidly changing conditions. It is difficult to factor in ambiguity, vagueness, and inaccuracies when applying analytical methods" (Klein & Klinger, 1991, p. 16). The adaptability inherent to naturalistic decision making by human operators is contrasted starkly with the rigidity of automated system responses to inputs. System performance will degrade, often gracelessly, when the inputs exceed the standardized values incorporated into its design; conversely, when a system is confronted with a situation for which it is not equipped, human operators engage in compensatory mechanisms to attempt to recover system functionality. NDM involves process orientation, situation-action matching decision rules, context-bound informal modeling, and empirical-based prescriptions (see for elaboration, Lipshitz, Klein, Orasanu, & Salas, 2001). This approach to rapid and adaptive decision making functions beyond the limits imposed in classical decision making, as employed by protocols and automated systems, which adheres to strict rules, employs algorithms for cue weighting, is not amenable to rapidly changing situations, and frequently fails when inputs involve ambiguous or missing data.

Recognition-Primed Decision making: The role of team situation awareness and experience

A particular form of NDM that is relevant to decisions made by teams in complex contexts involves the Recognition-Primed Decision (RPD) model. This method of decision making involves recognition and the implementation of a discernible response as a primary decision making strategy (Klein & Klinger, 1991). Bond and Cooper (2006) note that "recognition-primed decision making theory describes the decision processes of experts in time-bound emergency situations and is the foundation for a model of emergency decision making" (p. 1023). Recognition entails the availability of information regarding the task type, goals, which cues should be discriminated and monitored, and reasonable expectations about the course of events. Klein (1993) proposes several features that distinguish RPD from normative or classical decision making:

- The RPD model focuses on situation assessment rather than judging one option to be superior to others.
- The RPD model describes how people bring their experience to bear on a decision.
- The RPD model asserts that experienced decision makers can identify a reasonably good option as the first one they consider, rather than treating option generation as a semi-random process, requiring the decision maker to generate many options.
- The RPD model relies on satisficing (Simon, 1955) rather than optimizing—finding the first option that works, not necessarily the best or optimal option.
- The RPD model focuses on serial evaluation of options and thereby avoids the requirement for concurrent deliberation between options that marks the focus on the "moment of choice."
- The RPD model asserts that experienced decision makers evaluate an option by conducting mental simulations of a course of action to see if it will work, rather than having to contrast strengths and weaknesses of different options
- Finally, a recognitional strategy enables the decision maker to be continually prepared to initiate action by committing to the option being evaluated. Formal strategies require the decision maker to wait until the analyses are completed before finding out which option was rated the highest" (p. 143-144).

It is likely that RPD is supported by situation awareness, a common understanding of team members' intent, an accurate knowledge of each member's roles and responsibilities, and effective communication and collaboration, the same factors which support general team efficacy (Shanahan et al., 2007). Team situation awareness specifically is likely a strong contributor to effective RPD, as SA involves the identification of problems, maintenance of accurate perceptions of the environment, and detection of situations that require corrective action. Klein (1993) asserts that "There seem to be four important aspects of situation assessment: (a) understanding the types of goals that can be reasonably accomplished in the situation, (b) increasing the salience of cues that are important within the context of the situation, (c) forming expectations which can serve as a check on the accuracy of the situation assessment (i.e., if the expectancies are violated, it suggests that the situation has been misunderstood), and (d) identifying the typical actions to take" (p. 142). Team or shared SA involves a collective discernment and understanding of the meaning and projected status of the situation (Wellens, 1993), and is supported by a strong TMM (Cannon-Bowers, Salas, & Converse, 1993). As the team monitors the evolution of the situation, it can then make modifications to the selected response as dictated by the current situation, and can modify the response as conditions change. RPD functions particularly well under conditions of time pressure, when generating and systematically evaluating a large set of alternatives would involve an investment of time not available to the decision maker. Klein and Klinger (1991) note that "RPDs are marked by an absence of comparison among options. They are induced by a starting point that involves recognitional matches that in turn evoke generation of the most likely action" (p. 18). Bond and Cooper (2006) emphasize that RPD focuses on a situational assessment rather than an options assessment. An experienced team making decisions in an unstable environment can continuously monitor and process performance data, and make decisions for the adaptation or evolution of team behavior to meet situational demands. Expert teams engaging in RPD can respond both efficiently and effectively based on previous knowledge and experience when prescriptive or normative decision rules no longer apply to a system functioning outside its competency envelope and thus outside the scope for which the system was designed. Thus, in operational settings where the situation is ambiguous and creativity is needed, the adaptability of a cohesive, experienced team is advantageous over automation and its normative decision rules given the team's ability to identify acceptable courses of action to satisfy plausible goals.

In order to engage in RPD, the decision maker must possess sufficient expertise in a domain area to match a situation with an appropriate course of action, as well as the necessary experience with a system to know what affordances can be made and what constraints exist. An intact team with a strong TMM benefits from an understanding of the collective knowledge and skills possessed by the team as a whole, and thus has the advantage of a broader range of experiences and consequently a more diverse set of potential responses. Thus, a team with a larger repertoire of capabilities has a greater capacity for implementing system recovery even when the system itself is complex. This team characteristic may be a protective factor against collective performance decay when the viability of a system is challenged by deteriorating environmental conditions.

Viable System Model

The Viable System Model (VSM) addresses five main functions within an adaptive system. These elements include:

- the units that perform that tasks of the organization
- the units that coordinate and schedule the units that perform tasks, including allocating space and equipment, and enforcing rules and procedures
- units that function as “middle management,” making resource bargains with the units that perform tasks by making resources available in exchange for commitments to achieve specific objectives
- units that are responsible for long-range planning and the design of new products and services
- units that manage the interactions between middle management units and long-range planning units, and that determine the identity of the organization and its governing principles and norms

The various units or elements that are identified within the Viable System Model together function to manage variety.

Variety refers to the number of different possible states in a system. For example, a light switch has a variety of two (states On and Off), while a single-digit display has a variety of 10 (states 0, 1, 2, 3, 4, 5, 6, 7, 8, 9). An n-digit display has a variety of 10^n. Variety expands rapidly in conjunction with increased system complexity. Many complex systems have variety that is effectively mathematically infinite. For a system that is continuously variable, for practical purposes the variety is determined by the just noticeable difference (JND) in states that can be discriminated by an observer. The number of possible states the system can be in depends on the observer. As such, the variety of a system depends on its context and the capabilities or capacities of the operator who is observing the system.

In order cope with the great amount of variety in the environment or a complex system, the human perceptual system attenuates, or filters, the variety within the environment (see Figure 8). Variety attenuators are derived from human physiology, individual endowments, and social conditioning. The variety attenuators serve as filters that do not merely reduce the amplitude of signals coming from the environment, but rather select relevant aspects of signals and discard irrelevant aspects. Variety can also be attenuated as a function of job roles, whereby various individuals within an organization have various responsibilities, such as monitoring particular aspects of the external environment or maintaining adherence to regulations. The system can cope with or maintain relative stability within its environment, as long as it can successfully absorb the variety from the environment, by attenuating incoming variety and amplifying its own variety back to the environment. Control or stability can be obtained only if the variety of the system is at least as great as the variety of the situation to be controlled.

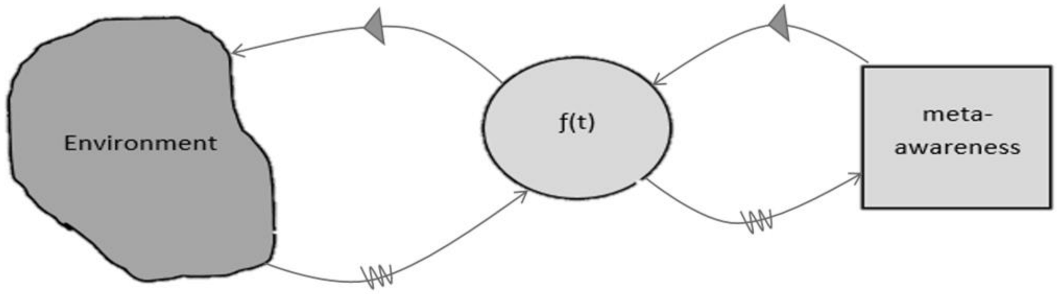

Figure 8. Viable System Model

A key aspect of the Viable Systems Model (VSM) is that it is a recursive structure; each system within the viable systems model is also a viable system (see Table 8).

Table 8. Overview of system elements in VSM

System 1	Elements concerned with performing the key transformations of the organization
System 2	Information channels that enable System 1 elements to communicate between each other and allow System 3 to monitor and coordinate System 1 activities
System 3	Consists of structures and controls that establish rules, resources, rights, and responsibilities of System 1 and provides interface with Systems 4 and 5
System 4	Elements which look outward to the environment endeavoring to understand how the organization needs tto adapt to remain viable
System 5	Creates policy decisions within the organization as a whole to balance demands from different organizations and provides direction for the organization as a whole

The VSM provides a framework for diagnosing and steering interactions within a system and between a system and its environment, with the aim of producing effective structural mechanisms that support the continued existence of the system within its environment. The VSM focuses on the emergent organization or system, rather than only local or global processes, in a given environment. This model emphasizes connectivity, and reveals the structural context that can either support or hinder interactions between various elements of the system as they encounter decision situations or problematic conditions. While the interconnectivity within a given system is an important feature within VSM, another defining characteristic within this framework is the ability of the system to maintain a separate existence as a result of a capacity for problem solving. A viable system must be capable of responding to both familiar and unanticipated events driven by the environment; this requires a capacity to evolve and adapt to changing environments and environmental demands. The VSM acknowledges that a spontaneous event may cause turbulence within the system, but the fundamental attribute of viability lessens the vulnerability of the system and increases the likelihood of recovery. In this way, a viable system is more adaptive to change, whether it is gradual or acute. Affording individual or team elements within the system sufficient degrees of freedom with regard to allowable actions to respond to an environmental stimulus increases viability. These actions should occur within the bounds of practical constraints that ensure that macro-organizational objectives are achieved and the well-being of system elements or the system as a whole are not compromised. For example, constraints should be in place that minimize borrowing from safety or drift into failure when system elements engage in tradeoffs or task shedding in order to maintain a specified level of performance during overload.

The VSM asserts that recurrent interactions between elements of the system in a particular context produce specific relations. These interactions may involve direct communications, such as routine conversations, or indirect communications, such as the coordination of actions as an outcome of the organizational context or culture; team mental models are an example of such an outcome, whereby recurrent interactions between elements of the system contribute to mutual trust and understanding of team members' roles and responsibilities. The relations formed by interactions between system elements provide an organization with its unique identity. As such, when these relations are altered by variations in organizational or team membership or roles, the identity of the organization can change. Alternately, organizational or team membership may change, but if analogous relationships are retained, the organizational identity is maintained.

In addition to identity as an emergent property of the organization, structure also emerges from communication or interaction mechanisms that enable various elements of the system to function as a collective whole. The elements that permit the organization to function together as a whole can include the various roles that individuals fill and the units or teams that they form. Both individual roles and teams are resourced by a variety of technologies, including tools and materials. It is the stable relations that allow for the amalgamation of the roles or teams and their associated technologies that define the structure of the organization. The structure of the organization can be viewed as a network of stable but dynamic communications or organizational processes; informational processes that support or facilitate such communications constitute structure. Informational processes and relations must co-evolve along with the variety in the system's environment in order to maintain viability. A system that is sufficiently flexible, adaptive, and equipped with diverse but coordinated human and technological resources so as to effectively respond to the variety present in its environment is said to have requisite variety.

Requisite variety: Collective knowledge and skills, and the resulting repertoire of capabilities for implementing system recovery

The law of requisite variety was first identified by Ashby (1956); Buckley (1968) defines requisite variety as "variety within a system must be at least as great as the environmental variety against which it is attempting to regulate itself" (p. 495). Variety refers generally to the number of possible or potential states in a situation. The Law of Requisite Variety asserts that when the complexity or variety inherent to a given context or environment exceeds the capacity of a system, the system cannot sustain performance and will decay or fail. A system has requisite variety when its repertoire of capabilities and capacities is at least as broad as the maximal number of different stimuli it may encounter in its environment. Requisite variety moderates a system's capability for response through its ability to detect in an environment information that conditions action. Weick (1979) asserts that systems with requisite variety have a greater capacity for adaptation and viability because they "align their actions and beliefs retrospectively and achieve an unequivocal behavior orientation with regard to a greater proportion of the environment… No one is ever free to do something he can't think of" (p. 193). Ashby (1958) notes that while an individual has some limited capacity, the capacity of a team is significantly greater.

A system without requisite variety is not viable. In order for a team to possess requisite variety and be viable, it must be capable of a number of responses that exceeds environmental variability. In order for variety to be expressed, macro-organizational constraints must be met; those elements upon which a team expressing variety depends, such as technologies or time, must be available and working properly. Greater variety enables a system or team to detect more patterns and information within an environment; variety in an environment is defined by the just noticeable differences between various states. The number of possible states of an environment depends on the observer, as very subtle, non-detectable differences in the situation will not alter the response of the individual or team. The perceptual capabilities of the individual or team attenuate the variety in the environment (Hilder, 1995). The variety of possible states of a situation may range from desirable to undesirable; Zelany (1986) defines control of a system as the "ability to elicit desirable states" (p. 269).

Greater variety within the team enables the generation of a broader range of strategies for response with the aim of bringing the system back under control. However, it is important that variety does not become cumbersome in its complexity and excessive structure. Excessive variety in fact reduces agility and dexterity with regard to reacting to contextual changes, and is equally problematic to insufficient variety that results in oversimplified and ineffective responding. Excessive variety may occur, for example, when a team grows too large and it is difficult to manage structure, relations, and information processes. Appropriate requisite variety in teams is considered to evolve from the emergent property of cohesion and adaptation, whereby the team and its processes co-evolve along with the environment. For a given set of objectives in a particular context, some optimal degree of variety will exist. When a team with insufficient variety is confronted with a situation that exceeds its capabilities, there are two potential coping mechanisms to attempt to re-stabilize the system. The team can increase the variety in the regulator (Ashby, 1958); for example, additional equipment or resources may be requested, or additional individuals with supplementary skills and knowledge may be incorporated into the system. Alternately, the variety in the system being regulated may be attenuated or reduced; for example, the incorporation of additional time or information may compensate for some of the contextual or environmental complexity. Time can be considered a resource itself or a means of increasing capability. The contextual or environmental system may be redefined so that it is manageable; this may be accomplished by modifying the objectives or goals that the team is attempting to accomplish in that context or environment. Risk tolerance should be viewed as a system constraint, and should not be modified in order to compensate for contextual or environmental complexity.

Shifting risk tolerance is involved in drift into failure. As a result of limitations in time, information, and information processing capacity, individuals, teams, and organizations "learn to 'safely' borrow from safety while achieving gains in other areas" (Dekker, 2005, p. 26). Drift into failure cannot take place without the team or organization "learning" where such affordances can be taken. As such, systems that are generally poor at learning or adapting may have the benefit of being less likely to drift into failure. These small departures from safety prescriptions or protocols, when met with success in the form of no incidents or obvious costs to safety, may serve as new anchors from which subsequent safety departures will be made. Team leaders or team members readjust the baseline from which decisions are made and this becomes the new anchor from which adjustments are made. This process engenders drift into failure, the accumulation of latent risks and hazardous conditions that have the potential to contribute to or cause an accident. While it is difficult to implement and enforce macro-ergonomic constraints to prevent drift into failure, the development of organizational resilience can mitigate its harmful effects. Dekker (2005) defines organizational resilience as "a capability to recognize the boundaries of safe operations, a capability to steer back from them in a controlled manner, a capability to recover from a loss of control if it does occur. This means that human factors and system safety must find new ways of engineering resilience into organizations, of equipping organizations with a capability to recognize, and recover from, a loss of control" (p. 45).

System resilience

Furniss, Back, Blandford, Hildebrandt, and Broberg (2011) define resilience as "the ability to recover from some unexpected event, or to avoid accidents happening despite the persistence of poor circumstances" (p. 2). Sheard and Mostashari (2008) note five aspects that should be considered within the resilience framework: time periods, types of resilient system, events requiring resilience, required resilience actions, and preserved qualities (see Figure 9).

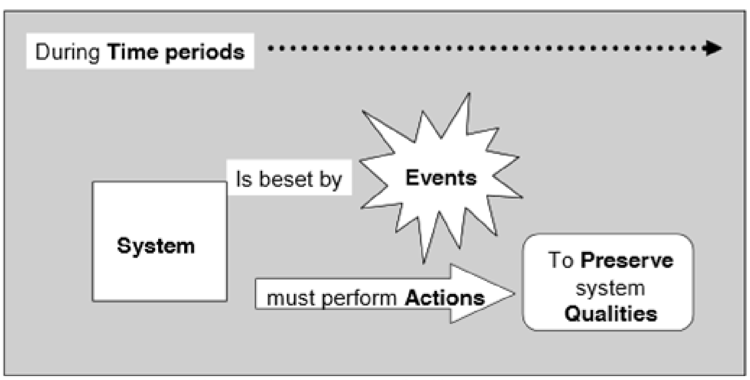

Figure 9. System resilience framework

These elements involve survival of the system during and beyond an event, with or without the need to sustain operations and work toward objectives during the event itself. Following the event, the system recovers to a steady state, which may be either the state in existence prior to the event or a newly configured but stable state that supports the completion of tasks and objects. Sheard and Mostashari (2008) elaborate upon the elements involved in the resilience framework:

- Time periods: In literature these usually appear implicitly, noted by terms such as "before" or "prior to," "during" or "while," "following" or "after," and "proactive" and "reactive" (see Figure 10)
- System: system (general), technical system (system of systems, engineering system), ecosystem, organization, enterprise (sociotechnical systems, infrastructure system), person, people plus nature, or network
- Event: disturbance (disruption, perturbation), change (external and internal change), environmental change, shocks, harm (harmful agent, adversity), mishap (accident), network disconnection, failure, loss, trauma

- Required action: adapt, prevent, resist/counter/withstand/cope with, adjust, survive/endure, sustain/maintain/retain, absorb, respond, reorganize, tolerate, mitigate severity of, gracefully degrade, recover/bounce back from/return to equilibrium
- Preserved qualities: function, structure, state/regime, identity, feedbacks, objectives, operations, processes, controls. Things that are allowed to change include: operating mode, internal configuration, sometimes internal structure (self-organization) (p. 2)

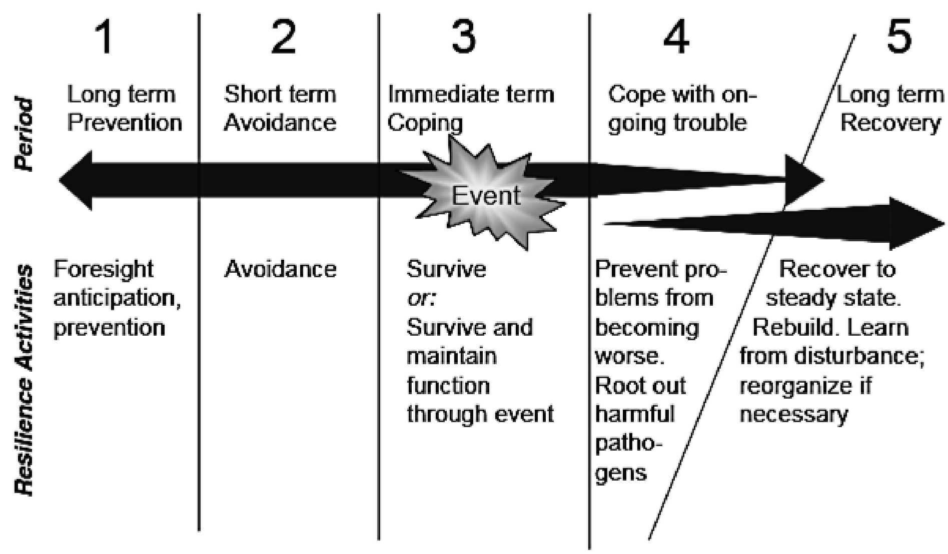

Figure 10. Time periods

Sheard and Mostashari (2008) propose characteristics of resilience that are specific to each of the five time periods described in Figure 7. It is often the case that only some and not all of these levels will occur at a given time.

1. Long-term prevention (Foresight and prevention): This involves prediction, anticipation, or planning for disturbances in order to prevent loss of control or other undesirable outcomes. This is done by deliberate anticipation of future changes in the environment that may affect the system's ability to function along with a willingness to prepare against these changes even if the outcome is. Long-term prevention requires identification and management of long-term risk.
2. Short-term avoidance: This refers to management of dangers that could affect the system in near real-time. Avoidance occurs by keeping safety systems up to date.
3. Immediate-term coping: Survive. Cope with problems, usually sudden problems. In some cases, a resilient system or enterprise must continuously operate through the emergency, possibly with degraded functionality. To survive, the system must respond (or react), quickly and efficiently, to regular disturbances and threats, must recover from loss of control, and must shun or resist harmful influences.
4. Cope with ongoing trouble: In addition to surviving the event, resilience requires that the system or enterprise prevents a bad situation from becoming worse. The system must continue to endure harmful influences; one way is to seek and root out latent

pathogens. This may require continuous monitoring for irregular disturbances and threats, and revision of the basis for the monitoring.

5. Long-term recovery: This means to recover from something bad once it has happened. The system or enterprise must learn from the disturbance (add information to the system function repertoire, like an immune system does) and rebuild itself when necessary. The system may reorganize to adapt to harmful influences (p. 3).

To the degree possible, systems should be designed in ways that anticipate and resist turbulence in the system; however, this engineering approach does not protect against unforeseen perturbations. Systems designed with inherent resilience have reduced vulnerability to unanticipated events due to requisite diversity, efficiency, adaptability, and cohesion. System resilience can be promoted when individuals and teams are experienced and well-trained, as these factors enable better coping with unexpected events (Furniss et al., 2011). The resilience repertoire of a team consists of a set of skills, knowledge, practices, and attitudes. In order for the repertoire to be successfully implemented when coping with system turbulence, the team must be supported by appropriate resources, system characteristics, and organizational structures. This requires engineering, design, and manpower staffing practices that consider the ship as a complex sociotechnical system composed of a variety of subsystems. This approach supports the appropriate allocation of resources, disbursement of information, and coordination between various subsystems of the ship. Because the ship as a whole is tasked with objectives, it is important that requisite variety exist within each level of the recursive system in order achieve and maintain effective performance in a range of states and under a variety of conditions.

The emergent model

In the context of a sociotechnical system that consists of a multitude of elements and recursive systems, factors emerge based on previous research that together constitute a proposed model of performance (see Figure 11). The nature or structure of a task will determine which and how HPM (Human Performance Modifiers) will impact performance. If the components of a collective task are independent, the average of team members' capacities on a HPM (*e.g.*, fatigue, collective experience) can be used to determine the influence of that particular factor on performance. If the components are dependent/cooperative, a "lowest common denominator" approach is likely more prudent, whereby the team will be capable of performing at the level of the least competent or resource-equipped team member with regard to a given HPM. HPMs proposed by previous research to have a significant impact on collective performance include fatigue, intactness of the team (with regard to familiarity and experience with fellow team members, technologies and equipment, and the overall system), training, motivation, and physical characteristics such as strength.

Performance outcomes for collective task performance can be viewed in terms of system viability. The team must possess requisite variety with regard to both "people resources" and "technology resources." People resources involve aptitude, adequate cognitive capacity, adequate physical capacity, skills and knowledge, experience at a billet or job role, and experience as part of an intact team. The team must have adequate collective knowledge, skills, and abilities in order to have a resulting repertoire of capabilities necessary for maintaining system stability or implementing system recovery in order to restore system stability. Task characteristics and situational factors will affect the degree to which individual and collective knowledge, skills, and abilities can be expressed. Relevant technology resources must be functional and accessible. People resources and technology resources must be available and coordinate in time and space in order to achieve objectives and preserve system qualities. Within the STAMPS framework, the description of "work" links people, technologies, and the environment in time; tasks supporting objectives occur in a specific environment at a specific time and are performed by a specific billet or team and/or technology. In order to determine which HPM are applicable and to determine whether satisfactory performance of the work has occurred, tasks must have descriptions of criticality and structure (independent versus coordinated/dependent) and a clear delineation of what constitutes accomplishment of a given outcome objective.

If the sociotechnical system possesses the necessary elements and capabilities to preserve the qualities of the system (*e.g.*, function, structure, identity, operations, processes, controls, states, feedbacks, and objectives), the system as a whole may be considered viable. Recovery and stability must be achieved within the bounds of given criterion, such as within a defined time standard or latency for collective task completion to a specified degree of accuracy. These standards must be achieved for both planned, anticipated objectives and unplanned events. When the sociotechnical system as a whole, including its teams, does not possess requisite variety, performance cannot be sustained and will decay or fail. This occurs when the repertoire of capabilities and capacities of the sociotechnical system is not as broad as the maximal range of stimuli and conditions it encounters in its operating environment. Insufficient levels of various HPM, such as cognitive and energetic resources or training, will reduce a system's capability for adaptation and viability because the operators within the system are unable to meet the requirements for maintaining or restoring system stability. The selection of adequately rested, trained, and experienced operators to teams supports viability by endowing the team with the required collective knowledge, skills, and abilities to adequately perform collective tasks in support of system stability and mission objectives. This team must be equipped with diverse but coordinated technological resources in order to maintain sufficient flexibility and adaptability when responding to the variety present in the operating environment.

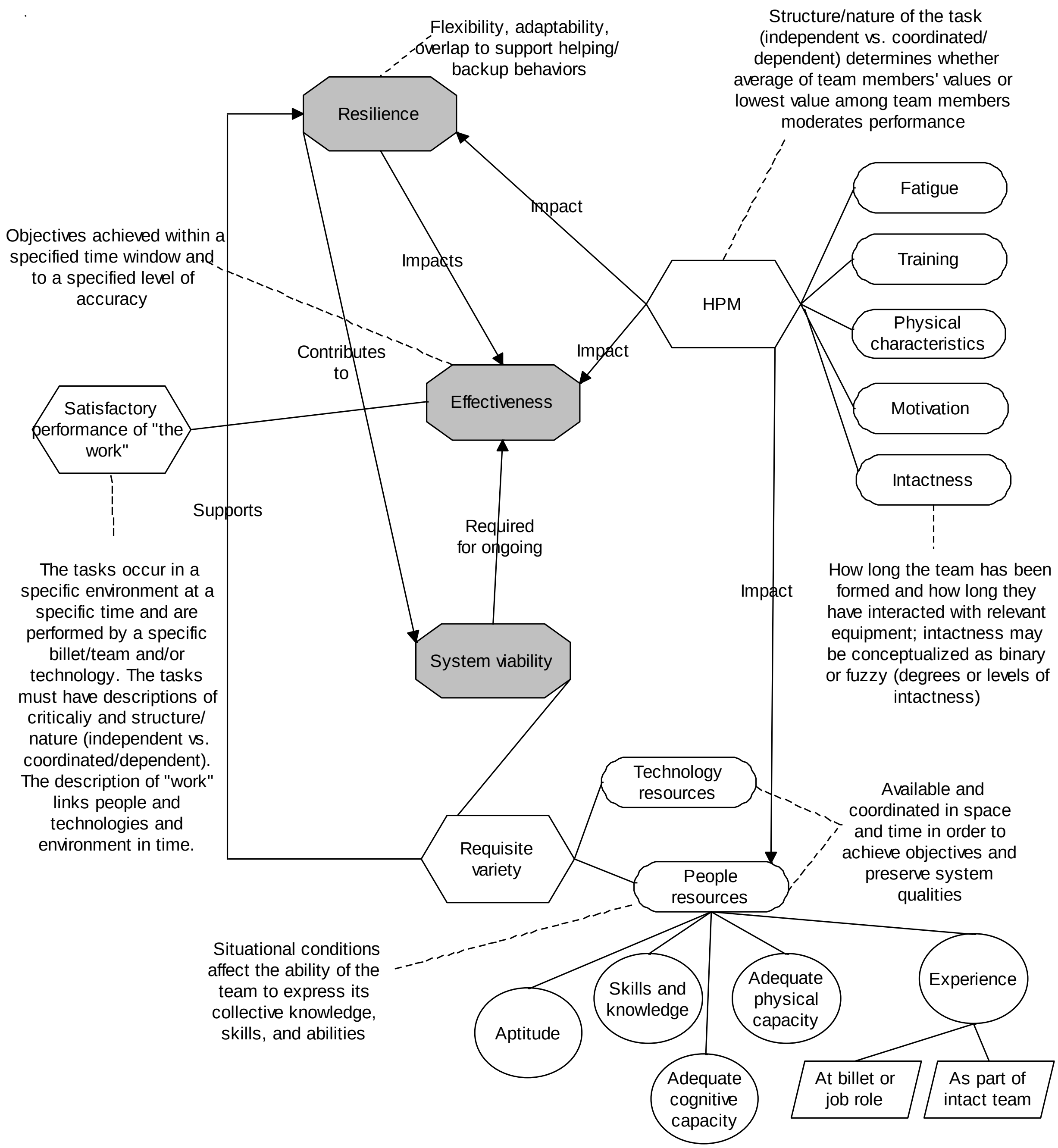

Figure 11. Emergent Model of Human Performance

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