Simulating Team Cognition in Complex Systems: Practical Considerations for Researchers

Michael McNeese Nathan J. McNeese Tristan Endsley James Reep and Peter Forster

Abstract In contemporary society, teamwork is prominent as a critical component in many complex environments. Much of the success of teamwork is coupled with both team cognition and the contextual surround that a team is required to perform in. Over the last thirty years there have been various formulations of team simulations that represent team cognition and the context in various ways—some more bene cial than others. This paper examines numerous practical considerations, lessons learned, and insights developed over speci c team simulations that our research group has engaged with over the years.

Keywords Team cognition Simulation and modeling Cognitive science

1 Introduction

Teams and teamwork have long been prevalent in many complex environments (aviation, command and control, healthcare, transportation, cyber) resulting in both successes and failures. In response to the importance of teamwork, team performance has been studied through a variety of methods and numerous technologies have been developed for augmenting collaborative activities. While teamwork has legitimately been inspired from cognitive perspectives [1, 2], teamwork is highly coupled to built and social environments (i.e. contextually-bound) [3, 4]. Yet, it has been the case that frameworks and simulations signi cantly under-represent real world practice, culture, and socio-political variables in the study of teams.

M. McNeese ( ) T. Endsley J. Reep P. Forster
The Pennsylvania State University, Old Main, State College
PA 16801, USA
e-mail: mmcneese@ist.psv.edu

N.J. McNeese
Arizona State University, Tempe, AZ 85281, USA

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1 1 Historical Background

This paper begins with the goal of retrospectively examining multiple simulations the rst author has utilized for research, helped to develop, and/or validated over a thirty-year period. In this section, we will overview the team simulations we have developed and/or used, and what they have afforded researchers in terms of theory, models, and connected technologies. As one examines this historical strand of simulations it is insightful to note that the evolutionary pattern extends from primarily cognitively-bound tasks to becoming increasingly more contextually-bound [5]. This was not random, but resulted from interviews, concept mapping, and qualitative studies of real world operators and teams within given elds of practice (e.g., emergencies, crisis management, AWACS command and control airborne operations, intelligent analyst workers, cyber security) [6]. Hence development of team simulations has increasingly favored inclusion of context, perception and pickup of information directly, and even cultural speci cations. Likewise, the evolutionary and in many cases extraordinary development of technology has also extended cognition from inside-the-head to be more distributed across time and context (see distributed cognition [3]; macrocognition, [7]. Indeed, current studies from our laboratory are heavily grounded in these research areas [8]. The objective of this paper is to take a broad look at these simulations and determine (1) What has been gained through research (i.e., what areas of cognitive science have been the focus for team simulations)?; (2) What are some of the salient considerations that have emerged?; and (3) What lessons learned and insights are valuable for other researchers?.

2 Emergent Complexity in Teamwork Simulation/Modeling

Practical teamwork is often tied to macrocognitive challenges [7] and often involves learning across time, getting to know teammates and how to compensate for individual differences, understanding team-to-team interdependencies, facilitating information sharing through limited visualization and communication, integrating cultural differences, and overcoming human-system integration limitations, to name a few. Indeed, the goal of understanding cognition within this broader team milieu has been paramount to enable designs that improve usefulness, adaptability, and resilience as the context unfolds.

Much of our work is historically related to the *Dynamic Decision Model* [9] in which individual decision-making is expanded into teamwork considerations. This resulted in a dynamic, intellective team decision-making simulation named TRAP [10], standing for Team Resource Allocation Problem. Within this simulation, time-contingent team interdependencies determine outcomes dependent on the joint success of human information processing strategies of each team member. TRAP was used to study cognitive variables (workload, biases, and information sharing) and technological impacts on team performance variables (e.g., use of large group displays). TRAP was typical of experimental psychology tasks but was computer-based and produced interactive opportunistic problem solving at the team level. In this sense, TRAP really focused on each team member being aware of analytical values underlying specific targets and fusing/sharing that information within the team milieu. TRAP integrated abstract thinking with emerging and uncertain information associated with "tasks", given specified team resource interdependencies. Its built-in complicatedness creates cognitive complexity. However, the simulation lacked a rich, applied, real world context and that limited its effectiveness. Also, TRAP studies were "one and done" and looked only "within a team" not "across teams". While this remains very typical of many team cognition experiments today, the approach unfortunately limits understanding of learning and dynamics within and across teams given multiple exposures to tasks and context.

The simulation CITIES [11] was developed in part to address TRAP weaknesses and afford a realistic setting for teamwork, information sharing, and team situation awareness by simulating teamwork between police and fire teams in crisis response. While different in context, it still maintained the strong underlying experimental psychology nature of TRAP. Of note is that CITIES was designed to look at team situational awareness (SA), specifically when distributed teamwork required technological means to coordinate/communicate (video teleconferencing, telephones, email, avatars were compared for performance gains). Recent work has expanded this into the NeoCITIES crisis management simulation [12], incorporating a wide array of cognitive, technological, communication, and information elements within studies, and also affording team-to-team interaction and longitudinal work with teams. Today, NeoCITIES exists as a sophisticated client-server information architecture utilizing an adaptive group interface for information display. NeoCITIES represents the logical congruence of TRAP and CITIES and is a prototypical team simulation environment. Other recent similar simulations, such as those involving UAVs, have detailed interactive team cognition in complex and dynamic domains with promising results [5, 13].

While NeoCITIES has been a very flexible simulation and has elements of cognition and context structured into task resource allocation problems, it still presents a relatively well-defined event structure that is dependent on emergent situations that are provided to participants. From that perspective—(like its predecessors) it emphasizes emergent team decision making with fairly well defined roles. Many theories and variables have been studied within this framework with much exactitude and thoroughness (see next section). However, it does not particularly capture the more ill defined situations that require a team to find, define, explore, and solve emergent problems. The Jasper task (developed as part of a broad series at Vanderbilt University) has been utilized to (1) emphasize problem solving tasks in teamwork (both distributed and collocated), (2) continue to place emphasis on collaborative technologies that facilitate learning, information sharing, and awareness, and (3) greatly increase the focus on contextualist, perceptual-based learning through the use of video-based macrocontexts [15]. Macrocontexts effectively blend cognitive and contextual elements, but provide opportunities for direct pickup of information, affording advances in problem ideation and solution (affordances, scaffolds) giving a unique excursion into very real world situations as demonstrated through Jasper's video-based story problems. Jasper was also predicated on foundational D = RxT physics problems as an underlying mathematical pretext. Therein, it was unique and enabled different kinds of collaborative interactions to test computer-supported cooperative work systems albeit in an innovative way. Jasper is by far the most contextualist-bound simulation we use. We have evolved NeoCITIES and Jasper in many ways over the last 15 years, and they have been our bread and butter go-to simulations to test theories and hypotheses in socio-cognitive science.

Understanding the challenges that the cybersecurity domain presents is a complicated endeavor. To that end, NeoCITIES has gone through several modifications, each with a specific research agenda. The first of these, CyberCITIES [14], was created to afford the capability to examine the effect that SA has on a Network Administrator's ability to respond to cyberattacks on a computer network. As with NeoCITIES, CyberCITIES continues to use the artificial concept of regret as opposed to modeling actual damage caused during an event. This concept, included in the original design of CITIES [11], is defined as "a measure of a player's opportunity lost in an event through inaction and slow or incorrect response" [15]. The use of regret as a measure allows the various frameworks to have a consistent measure across different scenarios irrespective to their contexts.

A second foray into the cybersecurity domain was with idsNETS, which focused on intrusion detection tasks of a single intrusion detection analyst. The interface of idsNETS differed significantly from previous versions of the NeoCITIES framework in that participants were responsible for not only identification of an effected network device and associated problem, but also for acknowledging the category and priority of the problem. The interface, while simplistic, provided a platform which could be extended to include more realistic tools, complex visualizations, and other such additions for further research.

Finally, teamNETS [16] served as a return to team research for our group. Using teamNETS, teams of three participants were each assigned to one specialty, intrusion detection, malicious software, or policy management. Participants, through monitoring events, take action by either filing a report to mitigate the problem or transfer the event to another player. This research was conducted to assess the impact that team knowledge structures have on team performance and collaboration using the same scoring model as the other NeoCITIES iterations [16].

While NeoCITIES and Jasper have endured, we have co-developed other simulations that vary teamwork, cognitive analytics, and contextual variation in unique ways. Briefly, two simulations have been developed to test intelligent agents-systems architectures within a complex team environment. R-CAST [17] provides intelligent analyst workers with team assistants in an emerging macrocognitive world. This world was very concrete and practical—IRAQI command and control tasks that required timely context switching and attention management. Hence, R-CAST equilibrated information fusion through a visual team interface that afforded cognitive augmentation to team workers. This augmentation was based on the principles of recognition-primed decision-making [18]. This was one of the first examples of testing a human-centered design of intelligent agents assisting teams in multiple tasks that required active switching of attention. This setting was cognitively complex but also grounded in the perturbations of contextual changes within a short timeframe. ABAIS [19] was another type of agent architecture that was specifically designed to assess beliefs and affect and then adapt a graphic user interface within an AWACS team environment. Both of these simulations were designed to test the intersections among interfaces, agents, and teamwork for outcomes that initiated resilience and flexible collaborative interactions. Both also represented human-centered approaches to complex systems where agent architectures were evaluated in highly real-world contexts. While these systems were important for innovation and forward thinking, the simulations behind them were not —for a variety of reasons. In addition to these two simulation systems, we have also worked in other areas of simulation including unique areas such as *design team negotiation*—TRACE—[20], reducing cognitive *conflict among a team of expert systems* [21], *fuzzy cognitive modeling* in emergent AWACS battle management [22]. It is interesting to note that the simulation basis for the AWACS crew utilized an extension to team-based distributed dynamic decision—DDD—simulation that was a descendent of the original dynamic decision model [9] that we began with.

As one examines these multiple simulations, the complex systems they model, and the scaled worlds that allow users to examine issues, problems, and context—grounded within a controlled lab setting—it is important to point out what is studied through the application of a given simulation.

3 Research Foundations in Cognitive Science

Much of the research utilizing the previously outlined simulation capabilities represents cross-sections of cognitive science, human-computer interaction, collaborative technology, and teamwork. This has been a very distinct niche for our research group, going all the way back to the period 1984 1988 when much of this began at the Air Force Aerospace Medical Research Laboratory, where colleagues were all working within the realm of the C^3 Operator Performance Engineering program (COPE) [23]. While this represents the embryonic beginnings, the continuance, expansion, and change through many research angles (theoretical orientation, application direction, measurement specification) and researchers have been rather vast. Yet, the cognitivist-contextualist, positivist-interpretivist, and human-centered/ computation-centered tensions have remained constant, providing the requisite variety that has propelled cognitive science research into new realms.

One way to think about the research areas that have emerged is to cast them into distinct interrelated research contexts: *cognitive functions socio-cognitive interaction socio-technical systems* and *contextual surround.* Most of the experiments undertaken within a given study represent some kind of clustering of specific independent-control-dependent variables within each continua. Table 1 provides examples (representative but not exhaustive) of the type of theories, variables, or focus

Table 1 Continua of cognitive science research areas studied

Cognitive functions	
Time pressure and temporality	Hidden knowledge pro les
Cognition, affect, and mood	Decision making biases/heuristics
Mental models/schema development	Information access/retrieval
Data analytics/integration	Situation/contextual awareness
Analogical problem solving	Storytelling/narratives
Information fusion	Naturalistic decision making
Perceptual anchoring	Information weighting/value
Social-cognitive interaction	
Team/shared situation awareness	Team mental models
Distributed cognition	Information sharing
Common operational picture	Communication patterns
Team-of-teams operations	Cultural identity
Socio-technical systems	
Electronic-mediated communications	Intelligent agents
Geo-spatial visualization technologies	Large group displays
Social networks/social media	Decision aids
Computer supported cooperative work	
Adaptive computing/adaptive interfaces	
Human computer interfaces	Fuzzy cognitive maps
Contextual surround	
Emerging complex situations	Event uncertainty
Information availability/timeframe	Distributed work
Levels of teaming	Collocated work
Scenario event interdependencies	Perceptual pickup
Constrained role-action structure	Information overload

points that we have examined across many studies. While variables represent particular hypotheses, it has been useful to see how a particular simulation with unique simulation parameters and scenario-task structure answers a research question.

3 1 Team Cognition Measurement

While Table 1 examines some of the prominent areas we have explored, it is primarily geared towards research questions with independent variables. One of the most important and often daunting elements of team simulation is collecting and analyzing veridical measures that represent continua processes under investigation. This can often times be highly correlated with the phenomena occurring in the study (e.g., transactive memory evokes certain undeniable measures), but it is also bound to the scaled world simulation itself. Many of the simulations mentioned have been built to automatically collect measurements or easily derive distinct scores from functional components of the embedded task performance. This helps to provide multifold dimensions of dependent variables that can shed light on speci c aspects of individual and team processes.

Within each of the above research areas, speci c operationalization has occurred according to the parameters and demands within a given simulation. As one can see, many directions and research questions may be formulated within the combined continua. Hence research has emerged in unexpected directions at various times. As studies have been completed, much has been considered—much learned. Some of the best learning has transpired through problems that cause failure. Indeed, there are many lessons learned in different areas to contemplate and re ect on. The next section provides a breakdown of some of the major lessons learned that has been discovered while designing, building, and using the simulations discussed in the paper.

4 Salient Considerations Lessons Learned and Insights

This paper examines many of the considerations, complexities and lessons learned in team simulations that the authors have been involved in. This derives from concepts, and full-scale development of many experiments that (1) make use of information that is distributed across individuals, time, place, (2) generate scenarios that involve the use of collaborative technologies, (3) rely on designs of exible client-server architectures and team interfaces, (4) are relevant to novice/expert and interdependent/heterogonous teams, and (5) develop unique team performance measures.

4 1 Lessons Learned and Practical Experience

Experimental Issues and Recommendations. Below, we outline some of the most prevalent challenges to experimentally studying team cognition within the laboratory.

First, requiring multiple people (often 3 or more) to show up to the lab at the same time is a challenge in of itself. Unfortunately, and often, one or more of the scheduled participants fails to show up. If this happens, then the experiment cannot be conducted. Over the years, we have developed mechanisms to anticipate these issues and ensure that the experiment can still be run. Often, we have an on-call participant list, meaning that if someone fails to show up we have a list of willing participants who we can call and ask them to show up in the lab immediately. Clearly this is not optimal, as the other participants have to wait for the new participant to show up, but it does overcome everyone wasting their time to begin with. Another mechanism that we have used in the past is to actually schedule an extra participant for the experiment. By doing this it increases the likelihood that we will have the correct number of team members available to run the experiment.

A topic that is often expounded on within the teamwork literature as a potential concern is the effect that individual differences within the team have on the generalizability of teamwork results. Teams that are typically used in the laboratory are often inexperienced (college students) and diverse in their gender, culture, etc. Because of this, many researchers have pointed out issues relating to statistical analyses being undermined due to the potential influence of inadequately weighted teams. For instance, gender is often a characteristic that is opined as being something that should be accounted for within initial team composition. Some researchers feel that teams should be equally mixed in terms of gender, not having teams that are mainly male or female. Now, the obvious and clear method for overcoming this is to counter-balance the teams before experimentation starts. The problem with counter-balancing is that this requires even more potential participants. Teamwork experiments already require an incredible amount of participants but if one were to counter-balance, even more participants are needed. Another issue related directly to the vast amount of subjects needed for completing teamwork research is that of statistical power. In many research circles, it is believed that the power must reach a certain threshold for the work to be statically relevant and valid. Yet, the problem relating to power and teamwork experiments is that in order to meet a high power, the researchers would then need to run hundreds upon hundreds of subjects through the lab.

In regards to the issues of counter-balancing and power for experimental teamwork studies, we take a logistical standpoint on them. Specifically, although we have counter-balanced in the past, we typically do not. First, as noted before, it is simply often not realistic to counter-balance teamwork characteristics or composition. Also, and more importantly, we feel that counter-balancing for specific characteristics is actually counter-intuitive to real world teamwork. Real teams are often not equally weighted for any specific characteristic, so why should we be promoting inaccurate and unrealistic teamwork in the lab setting? We feel that you should not, and we attempt to create an atmosphere of real world teamwork in our experiments. There are still more than enough statistical variables that can be pulled out and analyzed without the need for counter-balancing. As for power, we believe that power is important to consider but we do not hold firm the belief that it has to be astronomically high for the findings to be valid. We run enough experimental teams to result in what we feel is a respectable power, but we do not feel that power should be the end all be all.

Socio- Technical and Socio Political Considerations. The integration of the human-in-the-loop within the context of simulation environments is necessary and important for understanding the cognitive aspects of teamwork of sociotechnical systems. The affordances of simulation environments in complex sociotechnical environments (such as nuclear power stations, disaster response, crisis management, aviation) allows for the needs of the team to be understood and better designed for in the context. In the case of crisis management, the ingrained complexity of the environment puts significant challenges on responders cognitively and emotionally. Through the use of simulations, security and controllability of the contextual environment can be ensured.

When integrating the human into the team cognitive process, it is important to recognize the inherent biases that accompany them. Political, religious, and social belief systems develop different perspectives and motivations [25]. Differences such as cultural realities can significantly impact how participants react to a situation and share information. The case of the Asiana Flight 214 provides a poignant crisis example as it is presumed that the co-pilot refused to countermand the senior pilot in spite of the latter's obvious errors during approach.

Particularly in team settings, it is important to account for the influence of cultural biases into experimental design, as the inherent cultural perspectives that team members carry with them can dramatically influence interactions and outcomes of team performances. Unfortunately, oftentimes the cultural aspects of cognition are overlooked due to the complexity they add to experimental design. Endsley et al. [26] discuss many of the elements required to generate cultural relevance in the experimental design so that it is relevant to the participants (in this case, university students in the Unites States and in the United Kingdom), and yet also maintains fidelity to both the experiment through cross site parallelism and to the cultural context in which the simulation is being used. In the case of Endsley et al. [24], cultural relevance was obtained by adjusting the events within the scenario so that they were in British English as opposed to American English and that details were rendered salient to British participants, such as the renaming of a role "Hazardous Materials" to "Environmental Services/Army" which was culturally relevant to US participants, but not to British ones.

Performance Measure Considerations.

Quantitative. The determination of how well a team can perform is usually based on multiple dimensions in addressing differing components of what that team is trying to accomplish. Therein for many of the simulations addressed in this paper, quantitative performance generally consists of speed versus accuracy tradeoffs—as influenced by: (a) available time allotments to complete a task, (b) level of workload a task may demand, the degree of uncertainty-certainty associated with different tasks when they appear. There can be built-in variances associated with each of these elements which makes a team's performance easier or much more difficult, and the simulation usually has an architecture designed to flexibly manipulate these parameters according to objectives present in the study's hypotheses. To complicate matters, teamwork consists of individual work along with teamwork wherein individual work leverages different aspects of the above parameters. Yet, this must be successfully orchestrated in the midst of what other team members are doing simultaneously as well as with changes in contextual surround. Lessons learned suggest that dependent measures should be multi-composite wherein these different parameters can be utilized in a given formula (e.g., additive composites representative of a specific layer) that calculates an overall team performance score based on specified variables. The NeoCITIES task is an example of this, as the original composite score came from [11] and utilized a calculation that determined how well resources were applied to a given situation and whether they were able to extinguish the crisis at hand and then subjected this to a summary function. It has been our history to collect multiple dependent variables in addition to a summary team performance score to have a variety of lens to view what is going on.

Qualitative. Team based simulations provide many important things to practitioners in a variety of environments, providing signi cant insight into human behavior and cognition. Not least of these is that they provide a distinct set of shared experiences through which team processes can be explored in rich detail. The integration of qualitative measures into simulations such as these can provide a greater level of detail and insight into team cognitive behaviors and processes (and thus a fuller picture) beyond the quantitative measures alone, and should not be overlooked. Qualitative performances triangulated with other performance measures allow for “a deeper understanding of phenomena within its context, which may be used to inform other contexts” [25]. For example, team communication delivers and effective way to examine team cognition processes in context [26]. Through deliberative assessment and evaluation of content and ow of team communication data, an understanding of team processes and behaviors, successes and failures can emerge. Additionally, aspects of the environment, such as cultural, emotional, social and organizational perspectives can be revealed through qualitative assessment such that a richer integration of factors on teams can occur.

Scenario Development Considerations. When designing for team based simulations, it may be asked: what are the elements that make up a scenario and lend to its utility for both studying aspects of team cognition, and socio technical systems, and for training of users in an environment unencumbered by dangers and risks inherent in the real world? Effective scenario development requires identifying the problem, de ning the scope of the scenario in terms of time frame and activities, recognizing the major stakeholders for which the problem is relevant, and mapping the contextual trends and drivers that establish the decisional environment. The creation of scenarios for a particular context involves the engagement of multiple research methods such as knowledge elicitation and interviews with subject matter experts, content analysis of policies, processes and past events (such as the terrorist events of the Boston bombing, natural disasters such as Hurricane Sandy, and routine emergency response events such as res or chemical spills) which ground the events of the simulation in real world. Using ground truth as an initial context for scenario development improves relevancy and can add to the delity. However, the level of delity in a scenario depends upon the resources and technological applications that are available. The NeoCITIES simulation presents a sound medium delity in that it provides a level of realism such as exhaustion of resources but does not effectively account for human fatigue, which might be considered a characteristic to be included in a high delity operation.

Technical Considerations of Scenario Development. Once all of the elements for the scenarios have been de ned, the technical modi cations to the NeoCITIES framework can begin. This process, typically undertaken by someone that has a familiarity with technical programming, involves modifying the underlying source code for the application. Each of the elements of the scenario events (e.g. event title, event description, correct resource response, dispatch time, etc.) must be entered into the software. Additionally, if the research being performed requires a survey or technical briefing to measure hidden knowledge profiles, these elements must also be included. Upon completion of entering all of the required scenario elements, the software must be compiled and if necessary moved to the appropriate server location.

While the above details the process for scenario creation, there are also other considerations that must be acknowledged. First, depending on the context and measures being assessed, the interface itself may need to be modified. For example, when NeoCITIES was modified for the cybersecurity domain, the interface underwent significant changes related to this new context. Consequently, this process is potentially much more technically involved requiring someone with significant programming experience. Thankfully, the Adobe Flex environment provides a relatively easy mechanism for making interface modifications using drag-and-drop functionality if desired. As with any changes to the NeoCITIES framework, upon completion the software must be recompiled and deployed as necessary.

Cognitive Augmentation. Over the years, we have developed multiple decision aid tools and systems to help enhance both teamwork and more specifically develop team cognition. In sum, creating these cognitively augmented systems is incredibly difficult due to the issues inherently associated with teamwork. Take for instance, the development of a cognitive aid for an individual and consider how challenging the system development for that one product is. The aid must consider the individual's needs, motivations, relevant knowledge and information, trust levels, and awareness levels. This is a lot to account for. Now consider that same individual cognitive aid being then developed at a team level. This new "team level" cognitive aid must account for all of the previously outlined individual attributes, but now also must account for team level needs, motivations, trust levels, awareness levels, and communication and coordination mechanisms.

Developing team based cognitive aids must allow for adequate levels of both individual and team based work. Just because the focus is now on the team level, does not mean that individual work stops. Individual level work continues within the great collective teamwork. If the cognitive aid is focused on aiding the individual or the team too much, it can negatively affect awareness levels of both the individual and team. Too much focus on the team, such as having the aid constantly inform individual team members of team related information and knowledge can distract from individual work and awareness, which is necessary for adequate team level awareness. Likewise, too much focus on the individual's work and awareness will distract from that individual team member's team level awareness. The cognitive aid must understand the correct amount of both individual and team level knowledge and awareness it seeks to create. In order to create this correct balance, we recommend utilizing a human factors approach to first understanding the context, the team's goals, and the team itself. By doing this, a cognitive aid can then be developed that will hopefully assist the team to adequately complete their task. Understanding the context, the team, and the task, are all of paramount importance when developing team level cognitive augmentation.

5 Concluding Remarks

In this paper, we have presented a holistic representation on lessons learned over many years of studying team cognition in simulation. As we continue to use simulation to study team cognition, we must to continue to increase real world delity that is representative of real world tasks and situations.

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