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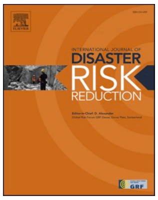

Surprise is inevitable: How do we train and prepare to make our critical infrastructure more resilient?[☆]

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ABSTRACT

While current practices for infrastructure currently follow principles of reliability and risk, these are—by necessity—based on knowledge of *past* events. They are not suited to adapt infrastructure to dramatic change and/or future surprises. In this paper, we propose a research agenda for the development of novel training exercises that complement current approaches by drawing upon a theory of resilience that emphasizes adaptive response to *surprise*. We argue that experience with surprise in 'realistic, yet fictitious' infrastructure systems simulations can improve the capacity of infrastructure managers to sense, anticipate, adapt to, and learn from surprise in virtual crises gaming scenarios when trainees successfully integrate their experiences from simpler to more complex stages of expertise. Virtual platforms that are shareable and extensible to classroom and operational settings might speed this process of integration of experience, and improve success rates among infrastructure managers confronted with surprise.

1. Introduction

Critical Infrastructure (CI) is comprised of lifeline and supporting systems that, when disrupted, can have widespread adverse impacts on human health, the economy, and social well-being [26,78]. Protecting these systems from an increase in the frequency, intensity, and variability of hurricanes [79, 29, 1, 80], floods [16,61], wildfires [34,64,65], extreme heat [67,91], and other environmental phenomena is creating challenges for scientists and policy makers alike. What were previously thought of as 'rare events' in extreme weather now seem commonplace, to the point where scientists now study 'disaster fatigue' in communities who are hit with one event after another [9]. Despite best practices for robust design, CI systems—both civilian and military—remain vulnerable to natural disasters, extreme weather, accidents, and attacks.

Alongside more frequent and disruptive natural disasters seems to be a recurring sense of *surprise*; despite increased warnings on the part of climate scientists and policy-makers, system managers are too often caught unprepared. Given widespread knowledge of natural disasters and their likelihood in specific regions, many surprising weather events–such as Hurricane Katrina in 2005 and Hurricane Harvey in 2017–seem inevitable to experts. Some also argue that if perfect knowledge of these events existed prior to their

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Abbreviations: CI, Critical Infrastructure; TE, Training and Exercises.

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onset, then the catastrophes would not have occurred at the scope and scale that they did. However, this argument is vulnerable to the bias of hindsight [68]—in general, one needs more evidence to commit to a course of action during a live event than it seems looking backwards after the fact. Thus, such events appear avoidable only in retrospect. Moreover, the impacts of extreme events on interdependent CI systems are often overlooked, misunderstood, or never tested prior to the emergency.

The starting point of our work is the inevitability of surprise. Even in information-rich contexts: (1) we will continue to experience things that we have not seen before (i.e., the future is not going to be like the past [58]), (2) surprise will happen, and (3) we need to invest to be better prepared for surprising events.

Recent policies for critical infrastructure protection have focused on improving the *resilience* of these systems to address these concerns [25,75,78]. Despite these efforts, infrastructure resilience has yet to be achieved, in part because there is no single agreed-upon definition of resilience to guide system analysis and design [87]. For example, the National Research Council [59] defines resilience as “The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events.” This definition follows the basic phases of emergency management but conflicts with other definitions across related domains, such as organizational, social, economic, and engineering domains [24,38]. Nonetheless, one of the key commonalities across many resilience definitions is a need for the system to respond or adapt when challenged by unanticipated events. At the heart of the matter is: *how to be better prepared for things that have not happened before?*

Training and Exercises (TEs) serve as one potentially important type of preparatory activity for resilience. For the purposes of this work, we consider training as a learning activity in a controlled environment, often isolated from the operation of real systems to experience fictitious, yet realistic situations that inform how to respond in real settings. Training is often held with experts and non-experts alike for the purposes of learning a new skill or reinforcing previous knowledge, capacities, or capabilities. An exercise is a learning activity conducted in the context of a real system to experience real events.

There exist a number of complicating factors that often make it difficult to develop TEs for CI systems and surprise events. Emergency training is a common activity within CI organizations to prepare for expected challenges, and is often required to hold certain positions involved in system operations and management. However, such training often is limited to experts and the actual operational staff involved in managing CI systems, ignoring users or other stakeholders whose participation during a real event is vital. Moreover, training may be limited when considering surprise events that are hard to predict *a priori*. Real-world exercises are more rare for CI systems even if they may provide more effective capacities to handle surprise events. This is due to several reasons. First, many CI systems cannot be taken offline for an exercise even for short periods due to their lifeline support functions. In fact, many real system operators are hesitant to exercise live backup plans for fear that their failure might cause actual disruptions. Second, the interconnections within and across CI systems are often not known or understood. This lack of understanding makes failure consequences often unpredictable, and it contributes to the reluctance to conduct exercises. Third, the ownership and governance of CI systems is often diverse and involves multiple stakeholders whose agreement and participation for exercises can be difficult to coordinate. Fourth, it is often not clear what should be exercised, and by whom. Infrastructure systems are ultimately socio-technical in their design and operation, and there remain significant knowledge gaps about how to make these systems and organizations more resilient [6,71].

In this work, we consider theory and methods for TEs that help participants understand, study, and learn from *surprise events*. The goal of these TEs is to improve expertise on the resilience of CI systems. The notion of surprise is not just anecdotal; surprise has been studied in a technical way since (at least) the 1980s in the military and the intelligence community [49]. More recently, these same concepts have been applied to events that challenge CI system function [23]. We describe the threat context of CI operation and surprise that must inform TEs for resilience. We differentiate different kinds of surprise based on characteristics and relate them to different methods for TEs. We present one path to develop a platform for TE that supports simulation and gaming activities. We conclude with limitations of this approach for resilience and specify lines of inquiry important for future resilience research.

Throughout this discussion we focus our attention on *military installations* as important systems of study. Military installations are typically a microcosm of a broader community containing environmental (natural) infrastructure, technological (built) infrastructure, and organizational (human) infrastructure. The continued operation of military installations is a national security issue that attracts considerable attention and resources. Many military installations (e.g., naval bases) are particularly vulnerable to climate-driven threats over both the short-term (e.g., hurricanes, typhoons) and long-term (e.g., sea level rise). Military installations are often simpler to study because they have well-defined boundaries (typically, a literal fence-line) as well as explicit ownership, governance, and command structures. Finally, military organization have an inherent TE component to their normal operations readiness activities. Collectively, this makes military installations an important and ideal object of study.

Although we focus here on increasing the resilience of military installations, there is a general recognition that the ability of that installation to operate is intertwined with the operation of the community in which it is embedded. Active duty and civilian personnel are unlikely to be effective if they are concerned with the health and safety of their family and friends. In extreme cases, disruptions in the surrounding community can prevent installation personnel from reporting to work. Thus, the ultimate goal is really operational resilience of a community.

In the remainder of this paper, we argue in favor of the need to explore adaptive response to surprise as a key element of CI system protection and preparedness. Moreover, we argue the need to develop an investigative method and technology platform for vulnerability analysis, simulation, and wargame exercises with “realistic, yet fictitious” infrastructure systems set in a virtual simulation world to assess and improve the capacity of infrastructure systems to adapt to surprise. To be successful, this platform needs to be shareable and extensible to classroom and operational settings. We comment on progress to date, and describe ongoing work that ultimately aims to develop a new theory of resilience.

2. An operational view of infrastructure

Our starting point is a recognition of the need to study the *operation* of CI systems, and not just emergency response in the aftermath of disruptions. We need TEs designed for and practiced by the operators of infrastructure systems. In other words, although emergency management is essential during a crisis, better training of our emergency responders alone is not going to make our CI systems more resilient.

Arguments in favor of an operational view of infrastructure for understanding system resilience have been made in Refs. [3,8]. The key ideas are that: (1) CI system behavior, both during normal circumstances and in the presence of disruptive events, is governed by decisions of its *operators* (both human and automated); and (2) the ability of the system to adjust or adapt its behavior during a disruption depends on the *decision space* (objectives and constraints) available to its operators. Thus, if you want to understand the potential consequences of a disruption (or the vulnerability of a system), you need to explicitly model the adaptive capacity of the system to respond to it. Over the last 15 years, these ideas have been applied to the analysis of a large variety of lifeline infrastructure systems [2,7,12].

2.1. *Operational vulnerabilities*

The performance of every infrastructure system is limited by interactions within and across its technological and organizational systems [52] that dictate its *operational boundary* (or *design envelope*) [72]. More specifically, military installations require technological systems like buildings, roads, water, power, and telecommunications among others to perform missions. Equally, military services are comprised of organizational systems of rules, codes, regulations, governance, and decision-making that dictate how missions are performed [22]. Together, these features of technological and organizational systems give rise to an operational boundary for what an installation is capable of when stressed by a surprise. For example, the total amount of onsite fuel storage often dictates how long mission-critical infrastructure can operate with electricity when running on backup diesel generators. A key issue is identifying where this performance boundary resides relative to the environment in which it must operate. Complicating matters, each of these systems is currently undergoing dramatic change [52].

- Environmental. The frequency and intensity of extreme weather events is increasing beyond what might be expected based on past events [62]. Sea levels are rising, creating direct threats to coastal installations that didn't exist previously [30].
- Technological. There are two distinct elements here:
  - Aging infrastructure. Many of the systems on which we rely are decades old and in many cases have lived beyond their intended functional life. We cannot infer reliability based on past success.
  - System complexity. Existing systems have evolved over decades, often in ways not originally intended and/or ways that are full of hidden interdependencies; this makes is impossible to predict how these systems will really work under novel circumstances.
- Organizational. The diversity of stakeholders on military installations is also different than in the past. Installations now have a more diverse set of missions, and interdependencies. The desire for cost saving and greater efficiency is yielding increased outsourcing of installation facilities and function [77]. This is also true of civilian systems. Although it was previously easy to organize around different systems that could be analyzed independently, this is increasingly no longer the case. There is no single vantage point around which one can see all of the relevant structure and dynamics, and therefore no centralized place that can appropriately manage everything.

2.2. *Operational surprises*

The confluence of factors that dictate the operational boundary of a CI system produce situations that surprise system operators. A *surprise* is something that is commonly understood as an event that contradicts expectation and may result in shock. We refer to extreme events that impact CI system operations broadly as operational surprises, and we treat resilience as a capacity to adapt to surprise.

There is considerable literature on the role of surprise in military history and national security [50] that informs critical infrastructure resilience. For example, surprise attacks on US and Allied forces have overwhelmed military systems and led to significant damages that resulted from the inability to stage an effective response. Recently, Eisenberg et al. [23] were one of the first to draw connections between military history studies of surprise attacks and work by system scientists studying resilience [83, 89] in order to elucidate the characteristics of surprise events in infrastructure operations. One key finding is that there are at least three different types of surprise-related events that challenge infrastructure operations driven from man-made and natural phenomena.

- *Normal variation:* variability in events that fall within the general expectation for normal operation, e.g., hotter, wetter, colder, and otherwise more extreme weather captured in established climate models [41,42,52].
- *Situational surprise:* an event that falls outside of normal expectation (extreme or rare), but is still compatible with previous beliefs, e.g., a major hurricane or flood driven by uncertain climate variability and non-stationarity [15,41]. .
- *Fundamental surprise:* an event that refutes basic beliefs about “how things work” and requires a re-framing on the part of the stakeholders, e.g., Hurricanes Irma and Maria in 2017 [4], Hurricane Dorian in 2019 [43], the Australian Brush Fires in 2020 [60, 73].

If military installation managers had to consider only normal variation in climate-related events, then existing risk-based approaches might be sufficient. However, as climate conditions change, military installations, their supporting infrastructure systems, and the organizations that manage them will experience more situational and fundamental surprises across both acute and chronic temporal scales. As noted by [88], “Responding to surprise requires preparatory investments that provide the potential for future adaptive action.” Thus, *surprise itself is not bad if we are prepared to respond. But surprise in the absence of adaptive capacity can be catastrophic.*

While best practices for military infrastructure planning and operation currently follow principles of reliability and risk, these are—-by necessity—-based on knowledge of past events. Yet, as indicated above we know that the past is not representative of the future, and therefore these tools are not suited to adapt infrastructure to dramatic change and/or future surprising events. Thus, existing management systems are commonly structured to maintain efficiency and reliability, at the expense of adaptability. Moreover, because testing and experimentation at whole system scales is disruptive and expensive, operators, commanders, and users lack knowledge of the sources of adaptive capacity. As a result, military installations are often ill-prepared to handle surprise events.

2.3. *Operational resilience*

Operational resilience is tied to the challenge-response relationship that exists between any system and its environment. The key question is: *how does the system handle challenges that fall outside the design envelope?* When the built capacity is exceeded, there is a need for different elements to come together to extend capability in ways that are novel–this is *adaptive capacity*. For military installations, a lack of adaptive capacity in the presence of surprise can have serious consequences for national security. Being “poised to adapt” is the essence of modern notions of resilience [37, 87, 88]. Therefore, mission assurance for military installations will depend ultimately on their ability to adapt in the presence of these surprising events.

How resilient a system is to surprise relates to the *shock* experienced when extreme events occur. The shock associated with a surprise event stems from misplaced expectations about an installation’s operational boundary. In the context of climate change, environmental surprise would involve misplaced expectations about the ability of an installation to manage acute and chronic climate stressors, either by misunderstanding the capability of known technological and organizational systems to perform in expected climate settings or by misunderstanding the potential shocks that a changing climate can bring. This suggests that surprise is generated by a misunderstanding of the system, the environment, or the interactions between them (i.e., the boundary). As related to known infrastructure vulnerabilities, there is the potential for shock from miscalibrated expectations about each CI system:

- Environmental: the environment is capable of challenging military installations in ways that you didn’t expect or even think was possible;
- Technological: your technological systems don’t work the way you think they work; and
- Organizational: the patterns of interaction within your organization are insufficient to accommodate the first two types of surprises.

All three types of miscalibration result from a similar problem: the working model of the world is *stale,* a situation that is common in the breakdown of adaptive capacity [88].

The key idea is to build upon resilience engineering research [35,36,51,63,76] that identifies the processes that create adaptive capacity and the ways these processes can break down to understand the ways military installations become surprised, what the consequences of these surprises might be, and how surprise events can manifest in uncertain future climates.

3. Training and Exercises for critical infrastructure resilience

The military has long recognized the necessity of experiential training for the purpose of improving response to the volatile, uncertain, high-stakes conditions concomitant to war [74]. Nonetheless, recent experiences with unprecedented natural disasters, hybrid and cyber-attacks [70], and emergent disease now highlight the need for new training paradigms that prepare military systems and personnel to respond to infrastructure challenges that may jeopardize mission readiness when support systems lack the adaptive capacity to respond to surprise across environmental, technological, and organizational dimensions.

Thus there is a need to discover the training techniques, exercises, and experiences that accelerate development of expertise for integration of surprise into adaptive response of infrastructure systems and personnel. Moreover, we need to test the efficacy of new methods for training expertise in surprise applicable to military installations challenged to maintain critical operations under increasing chronic and acute climate stressors. The underlying theory motivating this line of inquiry is that there are extraordinary circumstances create vulnerabilities and opportunities that are only be visible to decision-makers with sufficient experience and expertise in surprise.

3.1. *Recent advances in resilience Training and Exercises*

There have been a number of advances in the use of TE for resilience and/or critical infrastructures that serve as a foundation for the current effort.

For example, Kurapati et al. [46] considers how simulation gaming can facilitate decision-making for resilient intermodal transport operations in a port environment. They focus on the use of simulation games as a training tool as well as a research instrument to observe the behavior of the participants and help them assess different futures, and explore their decision processes. These games consist of multiple rounds of play, with escalating pressures, and involve both professionals and students. By design, the game affords disparate information to players, with explicit communication methods (with costs) for sharing that information. The game records separate individual and organizational scores, to study tensions between selfish and coordinated performance.

Wachs et al.[81] consider scenario based-training for developing resilience skills, using case studies in the electricity sector. They compare physical scenarios and virtual scenarios, and identify the strengths and weaknesses of each, but conclude that both can be effective in developing resilience skills.

Additional efforts have been devoted to identifying key processes supporting resilience. The DARWIN Project, funded by the European Union, has developed its DARWIN Resilience Management Guidelines (DRMG) “to help or advice a certain organization in developing a critical view on its own crisis management activities (management of resources, procedures, training, etc.) based on resilience management concepts” [17,33]. Hermelin et al. [32] consider the development of workshops, table-top exercises, and other training exercises to contextualize these domain-independent guidelines at an operational level for disaster medicine practitioners in the Swedish Regional Medical Command and Control Team.

Improvisation is understood as a key element in adaptive behavior. Mendonça and Fiedrich [56] provide a detailed look at how jazz musicians train to improvise in live performance, with translation to how it could be applied to emergency management. They characterize training needs in terms of (1) knowing *when* to improvise, (2) knowing *how* to improvise, (3) *communication* with decision-makers, and (4) *inference* about what is going on. They enumerate a number of specific techniques used by jazz musicians to develop their improvisation skills. These include: cognitive shadowing, stop and repeat, repetition of others’ solos, individual improvising, practising saves, practising at different tempos, learning a repertoire of behavioral cues, role improvising, and improvising with groups. They also identify several important elements to include any training environment, namely risk, dynamism, tempo, stress, information structure, and feedback.

Work by van Laere et al. [47] identifies four main groups of design choices for simulation-games. In terms of a *learning goal*, is the objective to understand complex system behavior, train the participants, and/or study different forms of collaboration? They also identify a number of *scenario details*, including validity (e.g., as identified by domain experts), fidelity, realism, time scale (e.g., seconds-minutes-hours, days, years, decades), and complexity. They also consider the number and types of *player roles*, their roles, and rules for communications. Finally, they consider a number of *elements of game play*, including action alternatives, ability to re-play, and richness of feedback while playing.

Bergström et al. [11] propose a framework called “Generic Competencies in Management of Escalating Situations” for creating exercises that develop adaptive and flexible competencies that “add up to an organization’s resilience,” based on four processes: Information Management, Communication and Coordination, Decision Making, and Effect Control. They consider a scenario with several specific features: a cascade of effects requiring an increase in cognitive activities among the participants as well as an increase in coordination among the participants, and where escalation is a dynamic process. They developed a simulation exercise for two groups of participants: an experimental group (who receive non-domain specific training and emergency management staff training) and a control group (who received emergency management staff training only). They find that experimental groups demonstrated growth and understanding while control group did not.

On the teamwork front, van der Kleij et al. [44] investigate the utility of a shared leadership training to enhance team resilience. They consider three types of teams: those that receive “transformational” training (involving behaviors believed to create resilience), those that receive “transactional training” (involving behaviors believed to be counter to resilience), and those that receive no training. Teams performed a sequence of naval command-and-control scenarios in which an initial set of cooperative exercises allowed the team to calibrate their activity. After this, a change (in information availability) was introduced, and the teams were evaluated based on their ability to recognize and adapt to the change. Overall, teams receiving transformational training did not perform best overall, but displayed the most resilience in terms of their ability to respond to the change. Teams receiving transactional or no training were observed to be about the same in terms of resilience.

Considerable effort has also gone into studying the role of information technology (IT) to support resilience TE. Mendonça and Fiedrich [56] discuss the types of IT tools necessary to support different training platforms, including seminars and workshops, knowledge databases, drills, tabletop exercises, functional exercises (i.e., “real-time exercises which are based on dynamic models of the event”), and full scale exercises. Di Pietrantonio and Mendonça [18] consider the potential for open-source games as a medium for studying teamwork.

Mendonça et al. [55] considers the development of techniques and technologies to support training in the emergency restoration of infrastructure systems. To study interdependent infrastructure (four real systems from New Hanover County, NC), the researchers developed a synthetic environment in which an interdependent infrastructure network is displayed in an immersive environment, supporting multi-person interaction via laser pointers and includes a simulation engine that manages interaction of participants and databases, providing feedback to actions. This platform was used for a single game involving four participants from emergency management. Players spent their time inspecting different parts of the system and assigning repair crews. They consider different scenarios of increasing complexity and difficulty that affords group interaction to collectively solve a complex task involving interdependent infrastructure repair, Other immersive environments have been used for training on lifeline infrastructure systems. [84].

3.2. A hierarchy of methods for developing expertise on surprise

The scholarship of education and training for expertise emphasizes the role of practice and experience in the development of expertise [21,45]. Several characteristics distinguish experts from novices, including an intuitive understanding of what information is irrelevant, what new questions and activities to prioritize, and the development of effective heuristics for sorting through complex decision challenges [40,82]. Moreover, development of expertise in response to environmental surprise has already been identified as a critical research need in the context of infrastructure resilience [19,57].

Nonetheless, the principal obstacle to research on surprise is creating controlled conditions of surprise. While there is no shortage of real-world environmental surprise, the conditions under which these surprises occur are not conducive to a research agenda, given the urgency of organizing adaptive response. By contrast, advance planning of research, by its nature, precludes surprise. Consequently, study of surprise is dominated by the post-hoc process of narrative reconstruction that participants employ to make sense of their experiences (e.g. Ref. [66]).

Fig. 1 organizes investigative methods for research to advance new TEs for adaptive capacity to surprise. A series of increasingly intensive exercises are plotted relative to two axes: complexity and expense. In the lower left-hand quadrant are found the less expensive, less complex approaches, such as modeling. Certainly, models are capable of revealing surprise [14]. However, the ideal mode of investigation for advancing a theory of surprise will leverage the complexity of games and simulations, without committing the expense of rehearsals and real-world events. The best game platforms will leverage open boundaries, complex and unpredictable human and social interactions, and open-source innovation and expert knowledge to maximize the possibility of capturing emergent phenomena, all without the cost of adverse consequences in the real world [54]. Table 1 provides additional detail.

3.3. *Developing expertise*

Expertise in adaptive response to surprise is developed in stages, and can be trained by methods in Fig. 1 by simulating increasingly complex experiences with surprise. Fig. 2 adapts a classic five-stage model of expertise development from Ref. [21] to consider aspects of surprise. At the lowest level, surprise is simply an unorganized experience. At this level, monitoring and sensing are essential to early detection of surprise that can be represented as new data outside the envelope of expectations. Nonetheless, effective adaptation requires integration of data into more complex meaning-making processes represented at higher levels.

Information is the structuring of new data into revised expectations represented by a change in expected probability distribution functions (p.d.f.), while knowledge is the capacity to apply knowledge of the revised p.d.f. In action. Such knowledge requires more than an improved understanding of the current or possible state of complex systems—it also requires some reliable understanding of how to move from a current to an improved future state. Thus, we use the term *integration of surprise* to emphasize the necessity of making practical sense of new information in the context of understanding larger and connected systems. Finally, knowledge is integrated into a complex, sometimes ambiguous and unstated set of values and heuristics that describe expertise. Participants operating at this stage typically report rapid, unconscious and creative decision-making experiences. Rarely can these experts identify what they were thinking at the time of the crisis. Rather, they report that they adapted effectively without the benefit of calculation or knowing how they knew (e.g. Ref. [28]).

TE for resilience must integrate methods in Fig. 1 with levels of expertise in Fig. 2. With respect to training, there is a need to develop interactive models, simulations, and games to help military and civilian installation mission owners experience climate surprise before it impacts their real-world mission readiness. Training participants to integrate structured observation, formation of probabilistic and possabilistic futures, act upon information, and develop judgement can provide a gateway to new expertise on adaptive capacity and surprise.

Exercises and live events provide more realistic settings to test adaptive capacity *in situ*. However, they may be cost prohibitive in real systems. Planning exercises alone are insufficient to build the experience necessary to build adaptive expertise in surprise. While the best training may be in rehearsals (e.g., drills and exercises) and real events, the additional expense of these potential catastrophes disallows them as routine investigative methods for basic science. One way to confront a greater range of possibilities, is using simulations and games with expert groups on systems similar to their own. The latter adds the additional uncertainty of human action, and the complex interactions between multiple agents or actors. Previous research shows that injection of surprise into training simulations can create a powerful vehicle for demonstrating infrastructure complexity and the conflicts that arise naturally between technological, social, and economic forces [71] and lead to improved adaptive response [48].

3.4. *Processes that produce adaptive capacity*

Building on past work within the resilience engineering community [35,36,51,63], recent work by the authors [71] has made significant strides delineating four required processes for infrastructure operators to respond to known and unknown stressors, namely

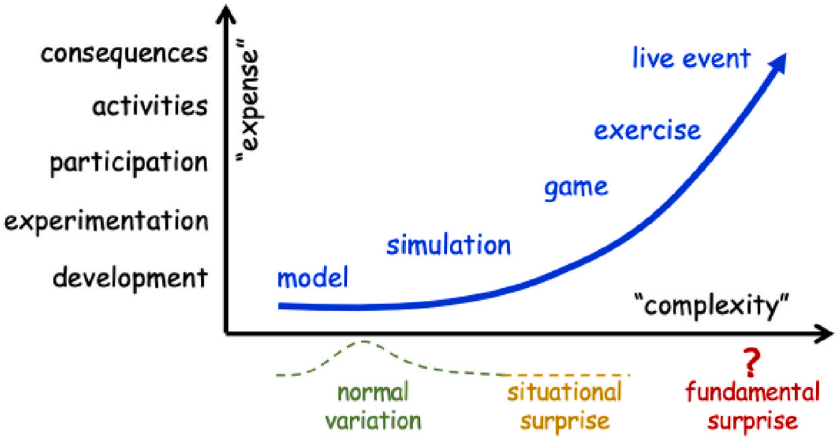

Fig. 1. Progression of Investigative Methods. Models and simulations require relatively little expense, but are unable to explore much beyond the normal variation of events that have been conceived in the model. Games and exercises involving human participants have the potential to experience situational surprise. To date, there is little beyond real events that are of fundamental surprise.

Table 1
Several approaches are available to train for surprise, varying in complexity and expense.

Element	Models	Simulations	Games	Exercises	Live events
Description	focus attention by abstracting away context or distractions. They are simplified representations of reality that allow examination of relationships that otherwise would be obscured by confounding factors.	introduce additional complexity increasing interaction with users. For example, aircraft models describe the lift, drag, and forces on the plane. Flight simulators allow pilots to fly a virtual plane.	create a greater emotional investment from human participants. While simulations allow a dispassionate exploration of the model space, games offer incentives that motivate participants to pursue some outcomes over others [54].	typically take place at full scale, in settings that are temporarily cordoned off from the real world. For example, a school fire drill is conducted in real classrooms, during the real school calendar, albeit without the added excitement of a real fire.	take place in the real world and are rarely structured to facilitate learning or training, although opportunities typically emerge after the crisis of a live event is resolved.
Relative Cost	are less expensive than more complex alternatives.	are more expensive than models, and remain closed to conditions outside the models on which they are built.	are similar in expense and complexity to simulation, but with the additional design burden of creating motivational game mechanics that elicit emotional investment from players.	are more expensive than games, partly because they interrupt normal operations.	are expensive, disruptive, and introduce risk of catastrophe.
Opportunity for Surprise	are effective for exploring **normal variation** (e.g., Monte Carlo simulation) and potentially useful for discovering some **situational surprise** resulting from interaction and feedback loops. are limited with regard to training for fundamental surprise, because everything in the model must first exist in the imagination of the modeler [23].	afford a greater opportunity to investigate and train for **situational surprise** than models do, because human users can be unpredictable, subject to biases and misconceptions, and misinterpret feedback.	punish players who act experimentally to gain an improved understanding of the operational system at the expense of performance. Thus, game incentive structures can obscure **normal variation** and **situational surprise**.	create greater opportunities for **situational surprise**, because some real world conditions that are stripped away from models remain present during exercises. However, the expense of repetition means fewer opportunities for exploring **normal variation** exist during exercises (compared to models).	are often the result of **situational surprise** or **fundamental surprise**. That is, the risk and expense of live events typically precludes them as planning or training exercises. An exception is the Black Start program that tests military installation readiness by intentionally shutting off electric power without prior warning.

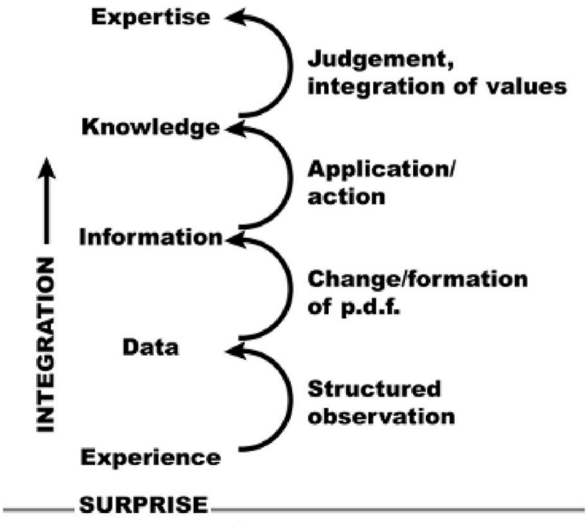

Fig. 2. Integration of the experience with surprise into new expertise requires progressing through five stages of increasingly complex skills that improve understanding and adaptive decision-making.

sensing, anticipating, adapting, and learning (SAAL). As described in Ref. [76]:

- “**Sensing** processes apprehend and interpret information about a system’s operational states relative to known and unknown vulnerabilities and system shocks.”

- "**Anticipating** describes the processes involved with imagining, planning, and preparing for possible system changes, emergency events, and crises scenarios relative to present and future conditions of the system, which includes impacts at boundaries."
- "**Adapting** describes the processes governing system responses to both known and unknown changes in stability and operating performance."
- "**Learning** integrates an open loop cycle of interrelatedness among each subgroup of processes (i.e. sensing, anticipating, and adapting) to inform and adjust system outcomes while retaining knowledge for future access."

These SAAL processes are typically described as proceeding in sequence, but with feedback at all levels; Fig. 3 illustrates.

Collectively, this leads to a few provocative conjectures. First, we argue that how well a military installation can sense, anticipate, adapt, and learn about its operational and environmental systems dictates how well the installation can mitigate the potential consequences of environmental surprise. In addition, we posit how well a military installation can redistribute resources and prepare for new environmental stressors dictates how shocked the installation will become by future surprise. Scientific investigation of these conjectures requires both experiments and exercises.

4. Towards simulation and gaming for resilience Training and Exercises

The approaches to TE that range from modeling to live events are vast. We focus on simulation and gaming because it is an important inflection point among methods for TEs that transitions from fully digital models and analysis to inclusion of human subjects. We present methods that may help establish TE programs for resilience alongside known limitations that can hinder progress. Together, we present a research agenda centered on managing surprise through the analysis and improvement of SAAL processes.

4.1. The need for a platform

To be successful, simulation games and exercises will require context for CI planners and operators to practice SAAL processes, experience their breakdown, and thereby learn how to develop adaptive capacity. For professionals, a cartoon version of an installation is not going to be enough. It has to look real and have sufficiently realistic interactions within the technological and organizational dimensions for them to take it seriously. We need to include details of technological systems (e.g., physics-based models) as well as organizational systems (e.g., command and control) to be more realistic, and more interdependent.

Yet, the context for such games and exercises cannot be *too real* without risking the potential to reveal real vulnerabilities. It is unlikely that we could conduct tabletop exercises or games for disasters on a real military installation for anyone other than the most restricted group of stakeholders. This undermines the potential learning and ability to transfer knowledge from one installation to another.

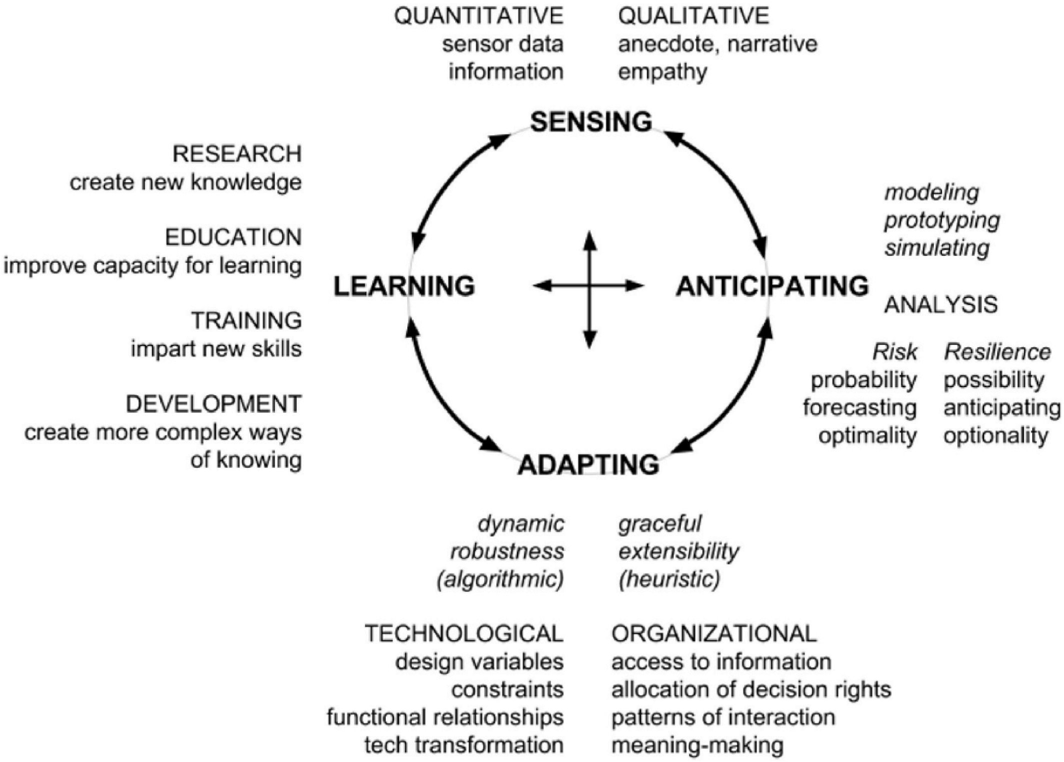

Fig. 3. SAAL processes as a source of adaptive capacity (see Ref. [71] for a detailed discussion).

Our solution to this dilemma is to develop a rich virtual world that is ‘realistic, yet fictitious’ and can serve as an interactive simulation framework, with tools to investigate how infrastructure stakeholders experience surprise and manage its consequences. Specifically, the Dystopia Virtual World (henceforth simply “Dystopia”) was developed previously at the NPS Center for Homeland Defense and Security (CHDS) so that students in homeland security (e.g., police chiefs) could study real-world issues they experience (e.g., active shooter alerts) in contextually rich environments; see Ref. [5]. It was later augmented to include data for critical infrastructure modeling and analysis (e.g., for assessing vulnerability to worst-case attacks; see Refs. [53,69]). In its current form, Dystopia is not a simulation or application in itself but rather a collection of structured data—including geographically realistic terrain, maps, population demographics, and infrastructure systems—to support a wide variety of applications central to this proposed effort. It is an island territory approximately 70 square miles in size (about half the size of Lanai, Hawaii), containing two large urban populations, two military facilities (a fully functional Army base and a National Guard training base), a major international airport, a large port facility, and a variety of public critical infrastructure systems (roads, power, water, oil/gas, etc.) (see Fig. 4). Two key features of Dystopia make it an attractive starting point for use in our work.

- The two notional military installations are embedded within a broader community, making it possible to investigate the relationship between the installation and its surrounding natural, technological, and social environment.
- The Territory can be placed geographically to investigate different environmental conditions. For example, we could place Dystopia in the Caribbean or South Pacific to understand the impact of hurricanes and recurrent flooding, or we could place Dystopia near the Arctic to assess changes in operations from thawing permafrost.

We believe the experience, discovery, and management of surprise through the practice and breakdown of SAAL processes in different climate scenarios requires geographic and infrastructural detail provided by interactive tools like the Dystopia Virtual World. Therefore, the intent is to extend Dystopia to incorporate our framework for understanding surprise and create a platform to investigate how military and civilian practitioners respond to surprising future events driven by climate extremes.

We also propose to integrate climate projections for different regions to generate realistic surprises for different locations and infrastructure systems. This will generate a platform to engage humans and surprise, in at least two ways—(1) allowing experts to recreate their infrastructure in Dystopia and experience surprise for their combined systems; and (2) allowing non-experts to experience surprise with predefined test systems—all in the presence of environmental change. This is not merely a software development exercise to create a realistic virtual world. It is an attempt to create sufficiently realistic context for installation managers, infrastructure planners, and other stakeholders to practice SAAL processes and ultimately participate in learning exercises (as “players”) that will help them to understand environmental surprise and become better prepared to adapt to it.

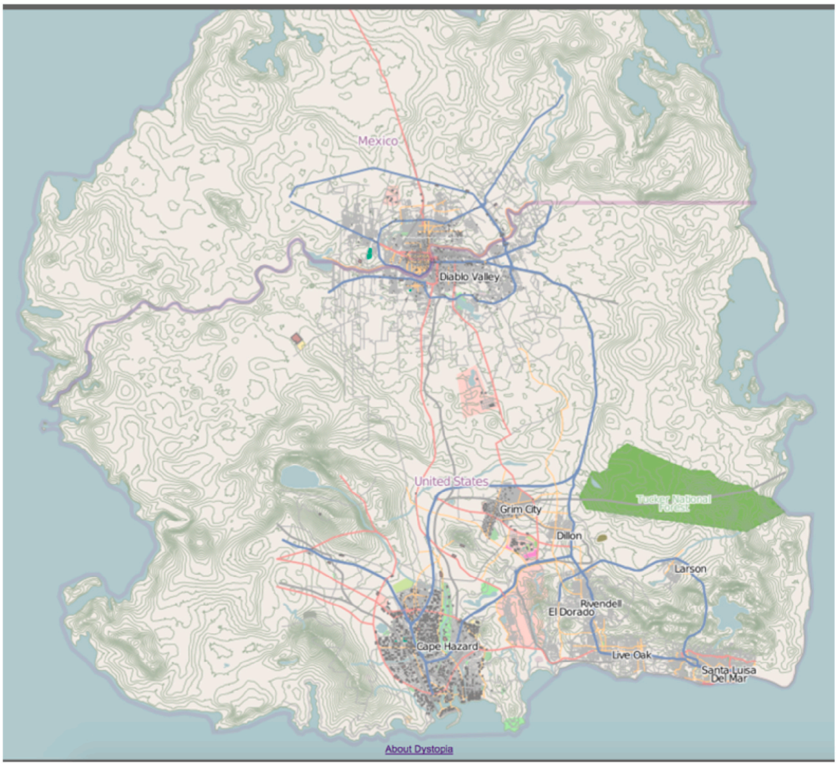

Fig. 4. Map of the current implementation of the Dystopia Virtual World.

4.2. A design space for infrastructure TE

Key questions to be addressed in the design and implementation of these features in Dystopia include:

- *Tempo:* What is the right amount of signal, noise, speed that the players should be operating at to not suffer from fundamental surprise?
- *Tensions:* Players should face the tension between short-term performance and long-term adaptive capacity. For example, will players make experimental investments of reduced productivity that improve their understanding of the changing dynamics of the system, because they do not understand how their systems really work?
- *Adaptive Capacity:* Does the surprise suddenly overwhelm you when it shouldn't?
- *Patterns of Failure:* To what extent will one observe the common patterns in breakdown of complex systems: misalignment of incentives, working at cross-purposes, failure to coordinate [86]?

An effective game-based TE must include, at minimum, three elements:

1. Decision variables for the players to choose (i.e., independent variables),
2. Measures of the state of the game environment (i.e., dependent variables),
3. Goals or "victory" conditions sufficient to motivate players,

A fourth necessary element exists outside the game programming itself–it is the mental model player's have that describes the relationships between the other three elements. That model may be made explicit in notes, sketches, or performance data, or evolve solely in the player's imagination as they gain experience interacting with or decoding elements of the game world. It is in that mental model that player's will formulate expectations about the how decision variable choices will move state variables closer (or further) from their goals.

With the exception of the goal or victory conditions, each of these elements relates to SAAL processes as follows:

- decision variables create adaptive capacity;
- state variables constitute sensing;
- the expectations that exist in each player's mental model constitute anticipation; and
- the process of updating a mental model to form more accurate expectations constitute learning.

To teach surprise, games must challenge mental models by setting and breaking player expectations, without alienating players or destroying their motivation to achieve their goals. Existing literature suggests several effective strategies, including:

- a time lag between decision variable choices and feedback in the form of updated state variables typically obscures relationships, can confuse players, and slow or misdirect learning;
- stochastic elements introduce normal variation and situational surprise, including long-tailed distributions that players may have discounted as outside the realm of possibility;
- non-linear relationships between decision and state variables can confuse the linear extrapolations of past experiences that typically form player expectations; and
- incorporation of interdependent feedback loops between state variables make learning more complex, game relationships more difficult to decode, and introduce the possibility of emergent phenomena.

A design environment using Dystopia could engage each of these mechanisms for challenging player mental models.

Fundamental surprise has a special role in game-based TE. Regardless of the experience of the game designer, surprise is defined by the experience of the game player. That is, the difference between situational and fundamental surprise is defined by the state of expectation that exists in a player's mental model. What is experienced as fundamental surprise when first playing a game, might be downgraded to situational surprise as players gain more experience. Because players will be aware that they are playing a game in a simulated, rather than real, environment, a fundamental surprise that is beyond player disbelief (e.g., flying pink elephants appear) will fail to inspire the reflection and re-imagining that is necessary during the learning phase. In other words, fundamental surprise in game-based TE must seem impossible beforehand, but plausible upon further reflection. Only then will players maintain their motivation to keep learning.

4.3. Designing infrastructure TEs for practical success

The design space for TEs involving critical infrastructure is large. Our investigation is motivated by practical decision problems faced by real stakeholders.

Despite the recent interest in critical infrastructure at the national and international levels, infrastructure in the US has been chronically under-resourced, with routine maintenance often deferred to support new construction supporting economic growth. Decision-makers tend to be under pressure to provide faster, better, and/or cheaper performance, despite growing complexities and emerging threats. In the presence of increasing pressure, the ability to prepare, be ready, or anticipate surprise is degraded [90].

Moreover, the behavior of infrastructure systems tends to be different when the system is far from its performance boundary than when it is under stress and/or near saturation. For example, highway traffic behaves very differently under free-flow conditions than when heavily congested. Nonlinear system dynamics can capture part of this difference, but it is also important to consider the way in which multiple actors effectively collaborate and improvise in the presence of stress or potentially end up working at cross purposes (e.g., [86, 88].

Based on our interest in military installation resilience, we specifically envision two scenarios of immediate interest.

We intend to use dystopia to investigate the ways in which infrastructure operators anticipate and respond to short-term stress events, such as those experienced on a campus or military installation.

For example, during heat waves, power demands increase, while generation and transmission efficiency decline. The physics of power generation is consequently non-linear, while stochasticity exists in the relationship between power demands and temperature. In a game in which players are tasked with building or managing power infrastructure to operate without catastrophic failure during an extreme heat event, they may have decision variables that exist over different time frames, such as building new peak generating capacity, expanding transmission networks, or introducing demand management alternatives. These time frames create the possibility of different lags between decision variable choices and state variable outcomes. Finally, when power systems are modeled in conjunction with water systems, multiple feedback loops exist that may confound player expectations. Thus, a power-water system can provide all the necessary elements to challenge player mental models with surprise during management of a heat wave.

We intend to use dystopia to consider challenges in managing competing infrastructure investment priorities year-over-year.

A common challenge in the study of critical infrastructure systems is identifying the most important elements for protection and/or investment [6]. Infrastructure investment on military installations and many other organizations is driven by annual budget cycles, where the relative importance of different facilities are “racked and stacked” via some institutionally approved scoring system, with the intent to improve overall mission success. Unfortunately, some of the most prominent scoring systems fail to adequately capture interdependencies and their relationship to mission, and they can lead to inconsistent or incorrect prioritization [27]. Separate from the day-to-day operating pressures for infrastructures are the budgetary pressures for reconciling competing objectives when under resourced. Moreover, it is often unclear how to invest in preventative (e.g., hardening) activities versus response, particularly in the face of new challenge events (e.g., extreme weather). At this level of budgeting, a planner could miss what actually makes an installation work and could spend the budget for change on things that are not important (or makes the system worse). Thus, infrastructure planning and response at the level of an installation or community can also provide all the necessary elements to challenge player mental models about the operating environment and how to reconcile competing investment needs.

Both of these examples share some important features. When operating under constant pressure and with limited resources, it becomes difficult to see evidence that things are changing. An important question is how to use elements of the TE to stimulate adaptive capacity on the part of the participants. Specifically, players should be challenged to consider how they can recruit resources to support a needed capability. In environments of ongoing change, this type of adaptation tends to be stale and slow [85].

Although we cannot be certain of the success we will have using Dystopia to create the appropriate learning experiences, the authors have experience developing other interactive experiences and games—e.g., Los Angeles Water Infrastructure Game [54], simulated games for collective dynamics in evacuation modeling [13]—that inform the development of Dystopia as a platform for experimentation.

5. Conclusion

Novel training exercises (TEs) for critical infrastructure operators and stakeholders that strengthen their capacity to adapt to climate-driven surprise are essential for improving crisis outcomes. Building on the latest ideas from resilience engineering, cognitive science, and safety science, we argue that these TEs should explicitly (1) focus on the operation of critical infrastructures, and (2) consider the processes associated with adaptive capacity, namely sensing, anticipating, adaptive, and learning.

A range of exercises is available to trainers. The least expensive are exclusively based on models. However, these are also the least engaging. Real-world exercises have several advantages, including immersion in context and exposure to fundamental surprise, and disadvantages that include high expense of risk of damage to real systems. Between these extremes, games and simulations in a virtual environment offer contact with surprise at less expense and risk. Thus, practice in virtual environments may facilitate integration of expertise from simpler to more complex levels.

The overall framework here presents additional opportunities to create novel learning tools. For example, as argued in Ref. [6], there is a need to create case studies about infrastructure resilience that serve to disseminate results to a broader community. In addition, case studies can potentially become the basis for role play and take advantage of the ‘case study method’ of instruction as championed at Harvard Business School [31] and elsewhere. There is also the possibility to couple case studies with interactive tools like Dystopia so that the student can not only *see* and *experience* new concepts, but also potentially *discover* them [20].

There are a variety of other novel tools now in use for the study of live complex critical infrastructure systems, including *chaos engineering* [10] for cloud-based digital systems and Energy Resilience Readiness Exercises [39] for military installations. Understanding how best to integrate learning about surprise across this spectrum of TEs remains a topic of ongoing investigation.

Declaration of competing interest

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

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