SYNESIS
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Neurotechnology and operational medicine

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Abstract

Effective approaches to achieve and maintain situation awareness are a fundamental underpinning of effective management of operational medical or other assets in national security and homeland security. A neuroscience-based approach to achieving situation awareness is described and contrasted with the approach proposed originally by Endsley. This neurotechnology approach regards situation assessment as analogous to interoception. It is amenable to implementation by hybrid agent-based and continuous time simulation methods for decision support applications. Both developing and potential application areas for this approach in operational medicine, disaster response planning and cybersecurity are discussed. Finally, it is noted that a neurotechnology approach reproduces key features associated with humans showing positive adaptations to adverse events: (1) the recognition of and ability to operate under conditions of uncertainty, (2) the development of a sense of connected detachment ('integration of affect and cognition') and (3) the recognition and acceptance of human limitations. As a result, tools based upon this approach have the potential to inculcate the wisdom that lies at the heart of resilience in the face of adversity.

Key words: Situation awareness, interoception, neuroscience, decision support, resilience, wisdom

Overview

From an operations research perspective, operational medicine is the projection of societal medical and public health resources into the realms of homeland security medical operations, disaster relief and humanitarian assistance. The effective management of these assets requires a system with the resilience and flexibility to respond to a changing threat landscape, particularly within the confines of an event. An event scenario evolves as a function of actions (and reactions) of response personnel, victims and bystanders, each acting from different frames of reference that determine situation awareness. This communication presents elements of a neurotechnology approach to formalizing situation awareness for different roles in operational medicine contexts.

Operational medicine in the civil defense, public health and medical intelligence domains is governed by the principles that achieve situational awareness in the face of natural events and/or deliberate actions of foes. A first principle is to "know your foe(s)", whether an environmental or human (viz. – man-made as well as the actual nature of a human enemy). In operational medicine, one's foe is, first and foremost, the developing scenario, including its potential direct consequences and its potential collateral consequences. Awareness is achieved by engaging procedures that identify the evolving natural and/or man-made scenario, yet work prudently and safely to minimize its impact. These procedures are embedded in a process of situation assessment that yields a sufficiently clear hypothesis for current operational safety and efficacy. A second principle is to know the strengths and weakness of the operational medical system – and those of allied forces that are collaborating. This principle is implemented by developing facile working knowledge of our resources, capabilities and vulnerabilities, by understanding how they can be projected onto evolving scenarios, and by having an intuitive ability to detect when unexpected or unusual behavioral conditions are emerging. A third principle is to know what adversities can achieve – whether such adversity represents natural environmental or human factors. One primary goal of adversaries is to demonstrate the ineffectiveness of the extant operational medicine infrastructure, which contributes to creating a sense of anxiety, panic and hopelessness in the population.

Neurotechnology and formal representations of situational awareness

Situational awareness is a concept that is invoked often without explicit definition in operational contexts. This contribution explores applications of neurotechnology to the issue of adaptively establishing and maintaining situation awareness in different frames of reference, ranging from the relative macrocosm of operational command and control to the relative microcosm of the perception of personal health: This issue is viewed as analogous to an interaction of sensorimotor, interoceptive and cognitive neural networks in the expression of co-morbid features (including emotion and affect) of balance disorders, migraine and anxiety disorders in conditions that include mild traumatic brain injury. This analogy can be rendered operational by implementing hybrid agent-based and discrete simulation tools that can be parameterized for each frame of reference and used for real-time decision support.

The applications of this approach also will raise significant issues for security and intelligence communities. For example, this approach can generate families of trajectories for an individual patient's behavior in terms of latent (underlying) neural/neurochemical mechanisms, which can be compared to the current status to guide further treatment by improving the situational awareness of both the health providers and the patient. The same argument holds for a decision maker in an application of the approach to a command and control center. In either case, the individual models become a meta-data representation of the patient that can constitute a form of protected personal information and, for key personnel, a matter of potential high security and intelligence value.

Neurotechnology and formal operational representations of situation awareness

The March 1995 issue of the journal *Human Factors* was truly a watershed event in the formalization of the concept of situation awareness as a cognitive construct. The definitions of situation awareness included "adaptive, externally directed consciousness" toward an environmental [external] goal (1), "up to the minute cognizance required to operate or maintain a system" (2) and "…just a label for a variety of cognitive processing activities that are critical to dynamic, event-driven, and multitask fields of practice…"(3). The general conceptual consensus was that situation awareness is the product of processes that map the knowledge, capacities, beliefs and extrinsically directed goals (and criteria) of an agent onto the dynamic behavior of the environment.

Endsley (4) provided a comprehensive framework for viewing situation awareness from a cognitive approach. The term situation awareness was defined as a state of knowledge that is the result of an adaptive, dynamic neurocognitive process that has been termed *situation assessment*. Situation assessment was represented as the product of purely cognitive processes, envisioned as rational agents (Figure 1A). A decision is produced by interactions among three different levels of rational processes (or agents), progressing from perception of the elements of a current situation (level 1) to comprehension of the elements in a context (level 2) to the projection or prediction of the future status (level 3) of a complex system, result in a decision. The decision then affects the instantaneous state of the evolving environment, which, in turn, influences the continuing situation assessment process. The holistic state of knowledge represented by the three levels of agents is termed situation awareness.

This modular approach is attractive because it extends inductively to the situation awareness of a group of interactive decision makers. For example, Endsley (4) also defined Team Situation Awareness as the degree to which each member of a team possesses the situation awareness that is necessary for their responsibilities. Since the situation awareness of each team member can be envisioned as collection of three simple, smaller autonomous processes for situation assessment, the net construct parallels Marvin Minsky's (5) metaphorical description of an artificial intelligence "society of mind". The quality of team coordination can be assessed by examining the quality of the situation awareness of team members with shared responsibilities. Conversely, potential vulnerabilities or weak links are produced by a team member lacking situation awareness for one element of a responsibility area. In this sense, the cognitive architecture in Figure 1A is one of a rational agent as the basic building block of individual and group situation awareness.

Much thought and effort has been directed at developing operational situation assessment and intelligent data fusion processes that can approach an ideal of omniscience for command and control applications However, public health and medical operations during high consequence events are necessarily undertaken in an uncertain environment where it is unrealistic to expect global situation awareness. Stated simply, the agents (e.g., the victims, the worried well, the public and the response community) all act in the absence of a complete forensic picture (6). Therefore, one is left with a default approach: we regard an operational scenario pragmatically as a collection of quasi-independent agents, with each agent acting upon situation assessments that reflect a personal frame of reference. As a result, the fidelity of predictive modeling of the processes and consequences of situation assessment by the agents becomes an essential factor in effective operational medicine.

Figure 1B shows a prototype for a neurotechnology-based representation of an agent that performs situation assessment of its internal state of health. It is an extension of a framework that is being developed to understand the bases for co-morbid aspects of balance disorders, migraine and anxiety disorders. This heuristic schema distinguishes three basic underlying brain process classes: sensorimotor processing, interoception and cognitive processing. It is important to note that each component is a "black box" that represents more complex computations and interrelationships. Sensorimotor processing includes afferent activity from the externally and internally directed neuronal sensors (e.g., peripheral mechanoreceptors, chemoreceptors and photoreceptors) and circuitry that mediates their conversion into perception and action (somatic, endocrine and autonomic responses). The interoception and cognitive processing components are modified from schemata that have been proposed in the area of functional somatic syndromes and medically unexplained physical symptoms (7-10). Interoception is used here in the broad sense proposed by Cameron (11) as any effect of internal sensations on molar organic activity, even in the absence of awareness. In the case of disease perception, intero-

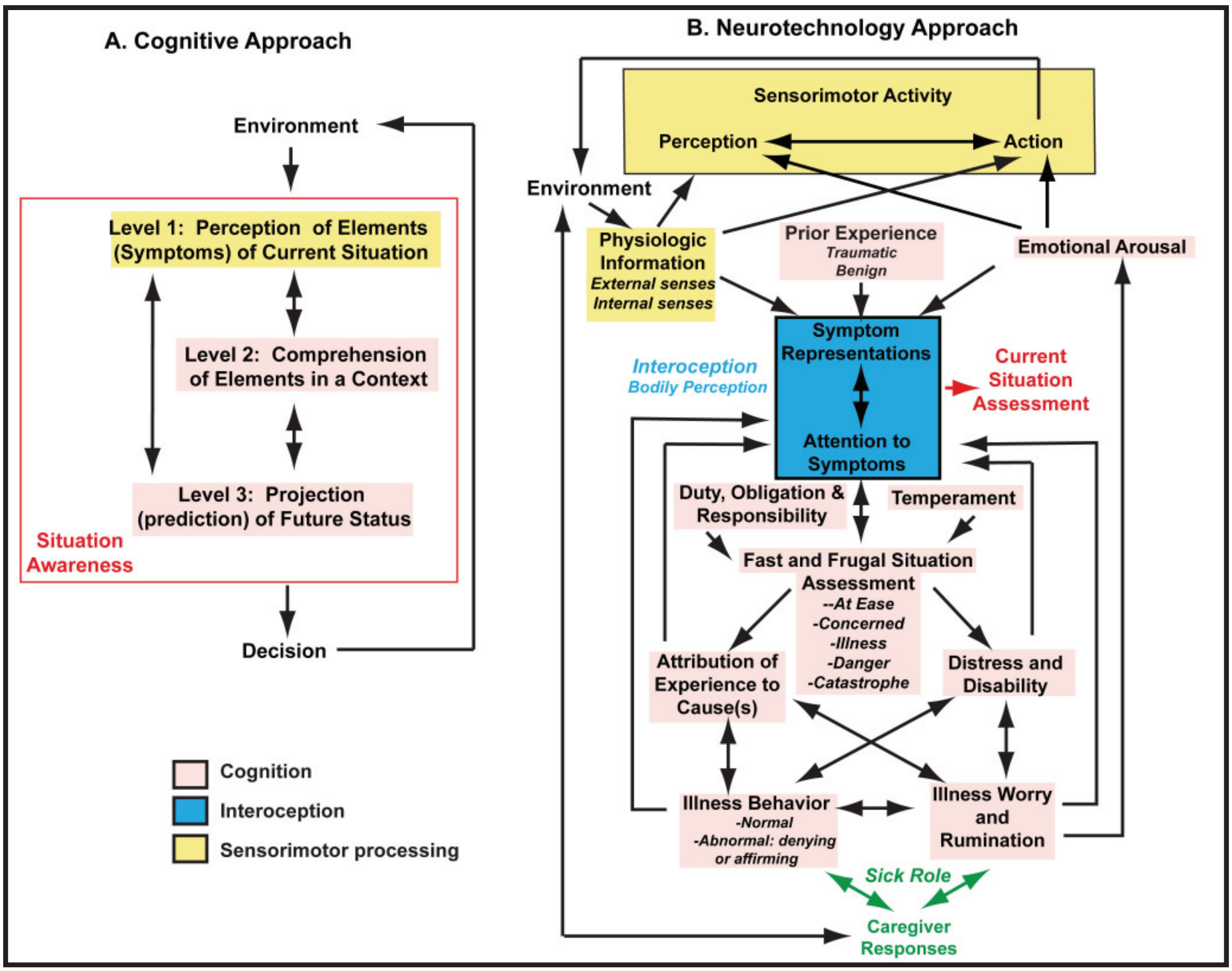

Figure 1. Approaches to achieving situation awareness

ception can be envisioned as a process that maps physiological information onto symptom representations and modulates attention to those symptoms. In a more general decision making sense, it can be envisioned as forming a "gut feeling" of subjective state along a continuum from well-being to discomfort to danger to panic. Craig (12) has recently reviewed evidence for an important role of the insular cortex and amygdala in interoception. It is also modulated by prior experience (both conscious memory and classical conditioning) and is updated on the basis of results of upstream cognitive processes.

The selection of higher order cognitive processing components for the schema recognizes that human decision making displays bounded rationality (13), which is a necessary consequence of limits imposed by the structure of the environment, the structure of the perceived solution space (mental models), and human cognitive capabilities (14). The schema itself performs a form of "satisficing" (13) that concludes a search of limited options as soon as a "good enough" criterion is reached. The instantaneous interoceptive status is subjected to initial situation assessment estimate of context, which is influenced by the individual's temperament and, in many contexts, sense of duty, obligation and responsibility. In cognitive terms, this initial estimate is based upon a fast and frugal heuristic (15,16) or "rule of thumb" (17) assessment of the current situation within the context of their knowledge base and roles. Further analysis of this rapid estimate is used to attribute the status to a cause (e.g., "It must have been something I ate.") and to generate distress/disability, illness worry/rumination, and illness behaviors (18) The outcomes of these cognitive processes can influence interoception directly; alternatively, effects on emotional arousal can affect both interception and sensorimotor activity. From a neuroscientific perspective, these cognitive processes likely engage both 1) mechanisms for setting affective state (that are associated with the ventrolateral prefrontal, orbitofrontal and ventral anterior cingulate cortex) and 2) mechanisms for regulation of the affective state (that involve at least the dorsal (lateral and medial) prefrontal and dorsal anterior cingulate cortex (13, 19)). Social interactions with caregivers and others, which is influenced by self-labeling adoption of a *sick role* (8), can intervene in the environment in parallel to influences of one's own actions.

There are two approaches to scale this architecture to include local or global aspects of scenarios. First, the model of a patient can be generalized to encompass any response personnel, victim or bystander in an operational medicine scenario by simply changing the term "symptom" to an analogous concept, "unusual aspects of the current environment or unfolding scenario". The task of the agent, then, is to develop the analog of the (patient's) interoceptive situation assessment relative to the current responsibility domain of concern, which is analogous to the (patient's) "body". For example, let us consider a basic dyad of first responder who is treating a victim. The responder 1) functions as a caregiver to the victim and 2) includes information about the patient with their own physiologic responses. Conversely, the caregiver actions influence the behavior of the patient and the environment.

The second scaling approach proceeds from the microcosm of the body of the individual to the macrocosm of larger frames of reference within the scenario, which parallels classical Platonic microcosm-macrocosm relationships (20). Hence, a neurotechnology approach provides a scalable common framework for viewing situational assessment on two different levels: 1) the domains of individual health (versus disease) status, behavior and community interactions and 2) in domains of mechanistic interconnections between sensorimotor, interoceptive, cognitive and social (interpersonal interaction) subsystems. Each agent's "*situational awareness"* can then be operationally defined as the set of causes in the agent's experience base that are hypothesized to be consistent with the current symptoms or analogous conditions.

Hybrid modeling and simulation approaches to enhancing situation awareness

Hybrid agent-based and continuous time simulation methods provide a flexible architecture for implementing *systems of systems* models of situation assessment for decision support. Time domain simulation methods, such as classical linear and non-linear systems approaches, are now used commonly in the neurosciences for modeling instantaneous neuronal signal processing and plasticity on the basis of underlying cellular phenomena (including enzyme and ion channel kinetics). Even the simplest linear systems approaches can provide heuristic insight into the dynamic aspects of judgments of the intensity of exteroceptive and interoceptive perceptual phenomena (21). As such, they are appropriate for simulating the sensorimotor processing components for the neurotechnology approach

(Figure 1B) as a specific systems model with parametric operations.

Agent-based models provide a far more flexible approach for simulating (and understanding) emergent properties of systems that can be characterized by complex rule-based behavior (22,23). These methods have been employed widely in the social sciences (24-28) and have been applied to defense and intelligence medical issues such as pandemic and biowarfare scenarios (29-31). Agent-based methods are appropriate for simulating the cognitive and interoceptive components for the neurotechnology approach (Figure 1B), as well as caregiver interactions.

Models that are hybrids of agent-based and continuous time components are becoming increasingly common for parsimonious simulation of complex and large problems. One of these hybrid systems is the Dynamic Discrete *Disaster Decision Simulation System* (D^4S^2). The D^4S^2 platform has developed by the Center for National Preparedness at the University of Pittsburgh for planning and decision support in one area of operational medicine, casualty clearance from an disaster scene (32-36). This hybrid simulation architecture integrates an operations research simulation engine, a rules-based agent simulation, geographical information system (GIS) infrastructure data, graphical interfaces and disaster information databases. In addition to standard simulations, the architecture has been used for evolutionary decision making and frugal multi-criterion optimization by constraining the heuristic search with a meta-modeling approach, non-linear mixed integer programming (36). A key feature of this architecture is the explicit definition of "*situation awareness" as the set of active hypotheses that is consistent with both the history of implemented rules (plans) and contextual information from the data base*. This definition allows us to track the convergence of situation awareness to a small set of cause(s) and optimize the performance of agents to preserve options and improve resilience. These results can easily be extended to implement a neurotechnology approach to situation awareness in a hybrid simulation platform.

Neurotechnology platform for situation awareness: implicit human-machine interfaces

Because the simulation components are linked to findings and models related to brain activity, the neurotechnology approach to situation awareness is amenable to both experimental validation and to the future integration of validated real-time physiological measurements into a human-computer system. For example, the neuroscientific literature on interoception and emotional control (12,19) provides a theoretical basis for using methods such as near infrared spectroscopy to identify vascular perfusion changes that are related to interoceptive brain network activity that produces affective state and effortful regulation of affective state during the situational assessment process. Sensorimotor components, on the other hand, can be monitored by actions. The process of integrating these measures with simulation provides a roadmap for intermeshing physiological sensor, human response and simulation features in the development of human-computer systems that achieve high fidelity representations of individual's situational assessment processes.

Some operational applications for civil defense, public health and medical intelligence

The previous sections have presented an academic background for using a neurotechnology-based hybrid simulation approach for modeling the instantaneous situation awareness of individuals and groups of individuals in an operational medicine response scenario. This section will discuss several examples of its applications to specific problem domains. It is not meant to be exhaustive; rather, it is designed to encourage inductive thinking about the broad scope of potential applications for the civil defense and medical intelligence communities.

Predicting help-seeking behavior

The help-seeking behavior of victims, the public at-large and the response community is an important consideration during an unfolding medical response scenario (6). Help-seeking behavior is determined by the current situation assessment, which maps onto the process termed interoception in the neurotechnology approach (Figure 1B). Inappropriate help-seeking manifests as the *worried well* phenomenon; it is an interoceptive hypervigilance-driven form of panic that creates bottlenecks in resource delivery by demanding assessment and treatment. Conversely, others may delay reporting symptoms, with negative implications for outcomes. Literature from both public health and social science domains provides ample evidence for predictable effects of factors such as personality, age, ethnicity, race, career role, socioeconomic status and gender on the perception of illness and the likelihood of reporting potential illness to a response facility (37-44). Specifically, the behavior of individual agents can reflect distinct clusters of "Big 5" personality characteristics that impact the threshold for emergence of help-seeking behaviors (37,38,40,41), the style of self-presentation (44) and the likelihood of seeking help from different resources (e.g., self-help books, religious institutions (43), internet resources, nurse practitioner hotlines, pharmacist, clinical facilities or emergency responders). A hybrid simulation, neurotechnology approach is thus envisioned as a common platform for generating predictions from a formalization of the relationship between individual situation assessments and mass civilian and military mass responses to perceived threats and significant events (45-48).

The ability to predict help-seeking behavior in context can be an asset of particularly high value for responses to pandemics, bioterrorism, biological warfare, unsuspected chemical toxin exposure or unsuspected radiological exposure. These scenarios are examples of latent events, which are detected only as the victims develop symptoms and conclude that they need to seek help. A special case is an "announced attack" scenario, where information about an impending or developing attack is released by terrorists to elicit panic responses in the public. The detection phase, defined as the period encompassing release (or infection), appearance of symptoms, illness and first deaths, is a period when public responses to perceived symptoms and the societal milieu (including information, misinformation and disinformation) can have a profound impact on both 1) the ability to detect a significant latent event and 2) the resulting demands for response assets. When they are neither understood nor predictable, these individual variations become a significant component of noise (or "fog of war") that can impede the process of detection and the initiation of an effective response. However, a situation assessment simulation approach can be used to help identify sentinel populations (or features of multiple populations) to improve the speed and accuracy of detection of a latent event.

Decision support for diagnosis and treatment

The neurotechnology-based approach is designed to provide a mechanistically based, integrated overview of the progression of neurological and psychological signs of symptoms from the perspectives of both the patient's self-report and the clinical objective and subjective observations by medical and paramedical staff. This statement is hardly surprising because the approach is generalized from research directed at elucidating scientific bases for the co-morbidity of balance disorders, anxiety disorders and migraine and the clinical responses of the signs and symptoms to different therapeutic regimens (49-55). The agent-based representation of the patient is intended to be a mechanistic, neurological and psychological hybrid model that explains the history and current clinical status. It can also be projected into the future to generate prognostic trajectories for the signs and symptoms on the basis of different sets of assumptions. On one hand, these prognostic hypotheses can assist the physician in outcome-oriented case management by providing templates for the clinical course that indicate a good outcome or the need to correct treatment to account for other likely underlying factors. On the other hand, this approach may prove particularly useful as a research tool for untangling the interplay between neurological and psychological factors in the development of co-morbid aspects of mild traumatic brain injury and post-traumatic stress disorder during acute, sub-acute and chronic presentations (56). This approach is also being adapted to create analogous forms of network interoception for cybersecurity applications (57).

Impact of competing of duties, obligations and responsibilities

It is well-known that a sense of duty, obligation and responsibility can over-ride considerations of personal well-being in difficult situations, sometimes to the benefit and sometimes to the detriment of the outcomes. The Milgram experiments (58) and the Stanford Prison Experiment (59) are prominent examples in the social psychology literature of sinister effects that can emerge in experimental social settings. They are counterbalanced by myriad cases of altruism and heroism in operational settings, including willful suppression of help-seeking behavior for others deemed more deserving. Serious consideration of these effects has been restricted to the anecdotal and forensic domains, with the purpose of generating ethical lessons and building a culture of *esprit-de-corps*.

More complex dilemmas arise in other operational medicine scenarios. The expected absenteeism of personnel in CBRN mass casualty scenarios likely reflects resolution of conflicting demands from multiple sets of duties, obligations and responsibilities (immediate family versus community concerns). Because agent-based simulation methods can test the effects of rules for resolving these competing interests, the approach has the potential to build and validate structures for predicting implications of these competing interests in individual cases. These models can then be used to investigate the impact of difficult decisions by individuals on the outcome of an operational medicine response. Finally, the model predictions can be used prospectively to detect the effects of potentially deleterious individual decisions during a response so that prompt corrective actions can be taken. In particular, it allows us to improve situational awareness by identifying situations when acts of altruism / heroism can be beneficial or deleterious to a scenario outcome.

Personal and network simulation agents as private information and intelligence assets

High fidelity hybrid simulation representations of both individual patients and operational medicine response systems have the potential to be 1) a form of protected medical personal information and 2) a highly valued intelligence target for others. Let us assume that a neurotechnology-based hybrid simulation with individualized parameters (or data) is sufficient to predict the help-seeking behavior and the clinical courses of individual patients for a class of medical care scenarios. Within the context of the model, the parameters are a predictive metadata representation of the behavior and, hence, a parsimonious representation of the patient's medical status in electronic personal records. This raises many questions. Does model representation (either parameters alone or parameters plus model) qualify as personal data that are subject to the privacy rule under the Health Insurance Portability and Accountability Act of 1996 (HIPAA)? Does a set of parameters (or parameters plus model), linking treatments with individual outcomes of many patients with a particular condition, qualify as a Patient Safety Work Product under Patient Safety and Quality Improvement Act of 2005? Could the models and data be used for biometric identification or profiling? Do the parameters for key decision makers have intelligence value, either for actions directed against the individuals, for sabotaging response capabilities or for revealing vulnerabilities to further a foe's operational goals? It is likely that the answers to these (and related) questions will depend upon the results obtained with neurotechnology-based simulation systems.

Building resilience into operational medicine

Neurotechnology-based computational hybrid models have the capability to facilitate the design of psychologically resilient operational networks. This goal can be realized by a direct application of research from the area termed "psycho-traumatology", which examines factors that enhance psychological resilience the face of traumatic experiences. *Growth through adversity* is a term that describes the positive adaptations and adjustments that can emerge in the process of living through traumatic and threatening situations (59). Linley (60) has made the interesting assertion that three dimensions of wisdom contribute to these positive adaptations to adverse events: 1) the recognition of and ability to operate under conditions of uncertainty, 2) the development of a sense of connected detachment ('integration of affect and cognition') and 3) the recognition and acceptance of human limitations. It is significant to note that these aspects of wisdom can emerge from the operations of the schema in Figure 1B. The first two dimensions represent interactions between interoceptive and cognitive components. The third dimension is equivalent to the cognizance of bounded rationality and the recognition that all human decisions are merely satisficing. Our challenge is to design interfaces to convey this view to operational medicine responders and managers such that psychological resilience is embedded in the daily practices of operational medicine. If executed correctly, such a simulation platform has the potential to serve as an inductive teaching tool to inculcate the wisdom that lies at the heart of resilience in the face of adversity.

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Competing interests

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