2019

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DeGruyter

Thomas, John E., et al. "A resilience engineering approach to integrating human and socio-technical system capacities and processes for national infrastructure resilience." Journal of Homeland Security and Emergency Management 16.2 (2019).
http://hdl.handle.net/10945/63114

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A resilience engineering approach to integrating human and socio-technical system capacities and processes for national infrastructure resilience

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Abstract:
Despite Federal directives calling for an integrated approach to strengthening the resilience of critical infrastructure systems, little is known about the relationship between human behavior and infrastructure resilience. While it is well recognized that human response can either amplify or mitigate catastrophe, the role of human or psychological resilience when infrastructure systems are confronted with surprise remains an oversight in policy documents and resilience research. Existing research treats human resilience and technological resilience as separate capacities that may create stress conditions that act upon one another. There remains a knowledge gap regarding study of those attributes in each that build infrastructure resilience as an integrated system of humans and technologies. This work draws on concepts found in the resilience engineering and psychology literature to examine the dynamic relationships between human resilience and the resilience of complex, socio-technical critical infrastructure systems. We identify and organize 18 system capacities and 23 human capacities that influence infrastructure resilience. We then correlate individual human and system resilience capacities to determine how each influences four socio-technical processes for resilience: sensing, anticipating, adapting, and learning. Our analysis shows that the human and technical resilience capacities reviewed are interconnected, interrelated, and interdependent. Further, we find current literature is focused more on cognitive and behavioral dimensions of human resilience and we offer ways to better incorporate affective capacities. Together, we present a simple way to link the resilience of technological systems to the cognitive, behavioral, *and* affective dimensions of humans responsible for the system design, operation, and management.

Keywords: critical infrastructure, human resilience, resilience, resilience engineering, socio-technical systems
DOI: 10.1515/jhsem-2017-0019

1 Introduction

Human behavior and decision-making can have a positive or negative influence on the resilience of engineered systems, including infrastructure. For example, the catastrophic system failure at the Fukushima nuclear power plant in 2011 was partly because of inadequate anticipation of key constraints related to risk perception and mitigation during plant design (Hollnagel and Fujita 2013; Park et al. 2013). In subsequent investigations, the flawed design was largely attributed to a working culture that supported false beliefs about safety (IAEA 2015), combined with the inability to deploy key mitigation assets because a complete loss of power was considered *unthinkable* prior to the accident. By contrast, operators at the Oroville Dam during February 2017 narrowly averted a catastrophe with similar cultural root causes by successfully adapting organizational, communication, and decision structures to redirect water releases before complete structural collapse of the reservoir became inevitable (Hollins, Eisenberg, and Seager 2018). Similarly, the successful ditching of US Airways flight No. 1549 in the Hudson River in 2009 demonstrates that the adaptive capacity necessary to respond to surprise can depend on human ability to improvise (Paries 2011). Barely two minutes after takeoff from La Guardia airport in New York City, Captain Sullenberger's plane struck a flock of geese and lost thrust in both engines. In response, the Captain made several critical decisions including turning on the auxiliary power unit without completing other steps on the dual engine failure checklist and ditching the plane in the Hudson River rather than returning to the airport (NTSB 2010). The Captain's capacity to cope with extreme ambiguity while maintaining a psychological locus of control enabled him to rapidly assess conditions and make critical decisions,

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in part, by intuition and felt-experience (Sullenberger, Zaslow, and McConnohie 2009). The above incidents illustrate that human factors such as agency and culture can have a direct impact on the resilience and adaptive capacity of infrastructure.

Both individually and collectively, humans should be considered essential components of infrastructure resilience because built systems are products of human choice and the social, economic, and institutional conditions that enable and constrain that choice (Williams and Edge 1996). Engineering design not only reshapes constraints and provides critical services, it also depends on people for design, operation, and maintenance. Thus, critical infrastructure systems and human stakeholders are interconnected and interdependent (Laugé, Hernantes, and Sarriegi 2015). Although human and technological systems can be impacted individually, a shift in the adaptive capacity of one system can have a direct and cascading impact on the other (Woods and Branlat 2011). Especially for urban areas prone to large-scale disasters, the resilience of engineered systems is dependent on the dynamic processes representing the interactions between people and technology (Masten and Obradovic 2010; Hollnagel 2014). For these reasons, critical infrastructure resilience depends on both proximal and dynamic processes of interaction between people and technology (Hollnagel et al. 2011; Hollnagel 2014; Park et al. 2013).

This interdependence between human and technological aspects of resilient infrastructure systems is not yet fully appreciated in infrastructure policy or practice. In particular, guiding Federal policy directives for US infrastructure security and resilience (DHS 2009, 2013; The White House 2011, 2013) *do not explicitly identify human or social behavior as essential components of critical infrastructure system resilience*. A prominent example of this is the National Infrastructure Protection Plan (NIPP) – a guide to managing national infrastructure risks created by the Department of Homeland Security (DHS) in response to Presidential Policy Directive 21 (DHS 2013). Although NIPP 2013 names 16 sectors of critical infrastructure (including “communication” systems), and acknowledges that threat prevention, recovery, and mitigation requires close coordination of partnerships between public and private interests the document fails to consider how human behavior impacts infrastructure resilience. Further, while the NIPP emphasizes that critical infrastructure security and resilience is essential to national well-being, it makes no reference to how infrastructure designers, operators, maintenance workers, or users might contribute to or undermine infrastructure resilience.

The NIPP and other prominent policy documents (DHS 2009, 2013; The White House 2011, 2013) do not give necessary attention to how human resilience may contribute to or detract from infrastructure resilience nor guidelines for addressing the interdependence of human behavior and infrastructure resilience. Thus, a gap remains regarding the study of human attributes that relate to infrastructure and help build resilience to support national goals. Given that human performance is dynamically coupled with infrastructure performance, a comprehensive approach to resilience must consider this coupling. To address this gap, we review resilience engineering and psychology research to produce four novel outputs that inform an integrated perspective of human and infrastructure resilience not available elsewhere in the literature: (1) a list of resilient system capacities for engineered systems, (2) a list of human psychological resilience capacities for the people embedded in infrastructure systems, (3) a conceptual framework for linking system and human capacities together via socio-technical processes, and (4) a mapping of human and system characteristics using the framework to inform infrastructure resilience policies.

We focus on resilience engineering and psychology research to determine how positive human decision-making and individual cognitive, affective, and behavioral capacities impact infrastructure resilience, and vice versa. The field of resilience engineering presents a positive paradigm for safety in socio-technical systems by focusing on what makes systems *work* in a given operational context, versus the emphasis in risk analysis on what causes them to *fail* (Righi, Saurin, and Wachs 2015). A socio-technical system is characterized by complexity (Wu et al. 2015) and must consider the interdependent role people play in system performance, and how system performance impacts the people managing and using the coupled systems (Schöttl and Lindemann 2015). Resilience engineering theory posits that socio-technical systems like infrastructure work because people can adjust their behavior and modify how they interact with technical systems as conditions change (Hollnagel 2014). Thus, resilience engineering emphasizes both learning from what has happened in the past and engaging human capabilities to anticipate and outmaneuver surprises that may challenge infrastructure in the future. For example, resilience engineering considers the ability for people to cope with disruptions occurring outside of designed performance levels, such as when human operators make innovative changes in the allocation of resources in response to novel stressors (Hollnagel, Woods, and Leveson 2006). Thus, resilience engineering theory and research offers a useful basis for understanding the relationships between human behavior and infrastructure resilience.

Psychology and psychiatry research broadly considers human resilience as the positive capacity of individual people and human systems to rebound and adapt when faced with adverse conditions. Human resilience enables people to navigate and negotiate the physical, psychological, and social resources that make human development possible in a context of adversity (Ungar, Ghazinour, and Richter 2013) like personal loss or the experience of disaster events. When applied to individuals, human resilience describes the capacity to access and maintain physical and psychological resources and to positively adapt to unforeseen conditions and disruptive events (Bonanno 2004; Ungar 2012; Masten 2014b). Equivalent concepts apply to human systems embedded within and dependent on technological systems like infrastructure (Masten and Obradovic 2010). Human resilience also refers to the ability of a person or group to tolerate stress and respond to adverse conditions and events in ways that enhances the possibility of positive adaptation and development (Luthar, Cicchetti, and Becker 2000; Masten 2001; Bonanno 2004). The descriptions of human resilience as positive adaptation and development amid adversity represents a shift that occurred in the psychology literature away from a focus on vulnerability (i.e. what goes wrong) and toward the study of resilience (i.e. what goes right) (Rutter 1987). The shift in perspective is similar to the concepts brought about in resilience engineering as described above. Thus, each body of literature shares a perspective of resilience that emphasizes 'what works' as opposed to 'what failed' in the context of a disruptive event.

Organizing resilience engineering and human resilience literature provides a basis for integrating human and system capacities influencing the resilience of critical infrastructures. National policies lack detailed explanations for how human resilience may appear in engineered systems like infrastructures and little is known about how human resilience may influence outcomes of coupled systems amid unexpected disruption and uncertainty. Resilience engineering research provides a systems perspective on this issue that reveals the capacities for complex socio-technical systems to continue work and remain safe during crises. Likewise, human resilience research provides a perspective on this issue that reveals the individual human capacities to cope and adapt to adverse situations. We integrate both fields via four socio-technical processes – sensing, anticipating, adapting, and learning (SAAL) – as linking mechanisms for how humans and technological systems interact during surprising events. Our analysis suggests that many of the human, technical, and socio-technical resilience capacities reviewed are interconnected, interrelated, and interdependent when applied to the SAAL framework. While reinforcing the important roles of cognitive and behavioral dimensions, our findings further suggests that the affective dimension of human resilience is effectively ignored in the resilience engineering literature. We argue that the resilience of critical infrastructures can be influenced by the cognitive, behavioral, *and* affective dimensions of human resilience that are linked by the SAAL socio-technical processes.

2 Resilience and Infrastructure Systems

The interdependencies of multiple overlapping human and physical infrastructure systems have significant implications for large-scale disaster scenarios (Masten and Obradovic 2010). This is because critical interactions between people and infrastructure can lead to unexpected and uncertain conditions and outcomes that can propagate across operational domains (Woods 2015). That is, disaster events and catastrophic failures can disrupt human interactions with infrastructure and lead to cascading breakdowns among other coupled complex systems like water, power, and transportation (Park et al. 2013). Moreover, the people occupying front-line roles and responsibilities like operators in the control room of a power plant are engaged in proximal interactions with infrastructure that can influence possible adaptive pathways and outcomes (Hollnagel et al. 2011). First responders, individual operators, and working groups interacting with and managing critical technological systems and services are examples of individual people embedded in the operational flow and contributing to infrastructure resilience. To examine the interdependencies of human and infrastructure resilience, it is important to understand how resilience appears in the literature related to technical systems and contrast that with resilience literature in the social sciences.

2.1 Resilience Concepts and Definitions

Although a practical interpretation of resilience can vary by application, complexity, and context, a conceptual definition broad enough to encompass human and technical dimensions is needed. This means a resilience engineering approach must consider multiple interpretations and perspectives of resilience to account for people as dynamic components of socio-technical systems. Furthermore, the definition must provide a meaningful reference to context to support comparing human and technical resilience capacities. Several authors have compiled lists of resilience definitions (Hassler and Kohler 2014; Hosseini, Barker, and Ramirez-Marquez 2015; Righi, Saurin, and Wachs 2015; Woods 2015). Likewise, multiple frameworks have been proposed for resilience analysis (Madni and Jackson 2009; Hollnagel et al. 2011; Hollnagel 2012; Park et al. 2013; Linkov et al. 2018). This points to a lack of common reference to validated terms, concepts, definitions, and frameworks of resilience in the resilience engineering literature. In general, resilience refers to the capacity of a system to absorb a shock or disruption and either return to homeostasis or re-organize to a new state of stable operation (Martin-Breen and

Anderies 2011; Reid and Botterill 2013; Brand and Jax 2007). Reorganization may include adjusting state variables or by changing connections among existing structures. Previous descriptions of "engineering resilience" may be viewed as an efficiency of function that is measured by the time required for the system to return to a steady state (Holling 1996) or as a complex adaptive system with dynamic feedback allowing for continuous adjustment (Pendall, Foster, and Cowell 2009), suggesting an approach to resilience that emphasizes resistance and control. However, resilience may also be viewed as emergent process in response to a system disruption (Park et al. 2013). The emergent processes represent the dynamic relationships between systems and components that effectively adjust parameters and govern interactions to maintain viable performance levels. The concept of resilience as an emergent property holds promise because the interdependent feedback loops that characterize complex socio-technological systems will inevitably defy traditional engineering controls.

Notwithstanding the many definitions of resilience, our socio-technical perspective builds on the definition provided by the National Academy of Sciences (NAS) that describes resilience as the ability to plan for, absorb, recover from, and adapt to actual and possible disruptive events (Cutter et al. 2012). We choose to build upon the NAS definition as it applies to infrastructure for several important reasons. First, the NAS definition provides a reference frame in time that characterizes distinct state transitions prior to, during, and after system shocks, stressors, and catastrophic disruptions. Each reference frame describes a specific capacity of infrastructure systems that requires both technological functioning and human actions to succeed. Second, the NAS definition is consistent with disaster policy and with definitions adapted by US government agencies. Moreover, an important factor in this definition is the ability to anticipate and prepare for unknown disruptions (Hollnagel and Fujita 2013) creating the *presumption* that humans are involved. The capacity to plan and prepare for possible threats and mitigate potential risks also engages learning from prior experiences to develop strategies for resilient pathways. Finally, the NAS definition and framework has proved useful in showing how various resilience concepts are shared among different perspectives and applications including psychology and engineering (Connelly et al. 2017; Wood et al. 2018). Taken together, the NAS definition is both broad for socio-technical context and practical for infrastructure design, operation, and management.

3 Methods

We identify, compile, and organize resilience capacities from resilience engineering and human resilience literature. Resilience capacities are found throughout the literature to conceptualize the characteristics of resilient socio-technical systems (Woods 2006; Madni and Jackson 2009; Dinh et al. 2012) and of human resilience (Luthar, Cicchetti, and Becker 2000; Masten 2001; Lipsitt and Demick 2012). We identify and integrate human and socio-technical resilience capacities with a four-step process:

1. Reviewing the resilience engineering literature to identify a list of system capacities (see Appendix A, which includes summary descriptions and citations);
2. Reviewing of the psychology and psychiatry literature to identify human resilience capacities for an individual person (see Appendix B, which includes summary descriptions and citations);
3. Organizing identified capacities with socio-technical processes that link system resilience to human resilience;
4. Examining the relationships between the human and system domains by comparing the overlap of capacities for each socio-technical process.

Finally, we examine how the human and technical resilience capacities combine to influence the resilience of coupled socio-technical systems and inform national infrastructure policies that lack discussion of human resilience.

4 Resilient System Capacities

4.1 Resilience Engineering

Resilience engineering considers the dynamic interactions among systems that rely on human abilities to learn from prior experiences, and to anticipate possible conditions and outcomes (Hollnagel et al. 2011). The inclusion of human abilities forms the basis of socio-technical systems that acknowledge the role of humans, including designers, operators, managers, and users embedded within, and interacting with, technical systems. Whereas a risk analysis approach to prevention and mitigation requires identification of hazards and characterization of failure probabilities, a resilience approach considers how complex adaptive systems like critical infrastructure may respond to surprise and unknown threats (Park et al. 2013). Thus, in contrast to a traditional approach to risks focusing on the prevention of undesirable outcomes, resilience engineering extends beyond risk management and includes the dynamic processes that characterize how systems behave (Madni and Jackson 2009).

Resilience engineering scholars reference a range of system attributes like adaptive capacity (Madni and Jackson 2009), avoidance (Larkin et al. 2015), flexibility (Paries 2011), tolerance (Woods 2006), and efficacy (Hollnagel et al. 2011) that contribute to the ability of a system to absorb, recover, and adapt system performance amid disruption. Table 1 presents 18 socio-technical system capacities found in a review of resilience engineering and infrastructure systems literature. While not exhaustive, the list represents many of the core concepts associated with system resilience. The range of capacities reflects the multidimensional nature of resilience (Brown and Westaway 2011) applied to infrastructure. The capacities may be viewed as antecedents or latent propensities that influence resilience processes and outcomes in response to system shocks. Appendix A expands on Table 1 by including summary descriptions and references for each capacity. Taken together, the capacities combine with resilience processes to characterize resilience of technical systems.

Table 1: Socio-technical System Resilience Capacities.

Socio-technical system resilience capacities	
– Avoidance	– Adaptive capacity
– Buffering	– Autonomy
– Control	– Cohesion
– Efficiency	– Compensation
– Goals management	– Coping
– Margin	– Diversity
– Pinging	– Efficacy
– Survival	– Flexibility
– Tolerance	– Maneuverability

Appendix A includes descriptions and references for each attribute found in our review of resilience engineering literature.

4.2 Human Resilience Capacities

Human resilience capacities are the qualities (variables, characteristics, protective factors, and personality traits) serving to protect or compensate individuals exposed to risks and adversity (Masten 2001). Table 2 presents the 23 human resilience capacities identified in the psychology and psychiatry literature (Kumpfer 1995; Richardson 2002; Olsson et al. 2003; Connor 2006; Resnick and Inguito 2011; Garcia-Dia et al. 2013) reflecting the multidimensional nature of the resilience of a person (Luthar, Cicchetti, and Becker 2000). Moreover, the resilience capacities in Table 2, which are psychological in nature, represent the internal characteristics known to correlate with resilient outcomes (Kumpfer 1995) amid adverse conditions or events (See Appendix B for further information).

Table 2: Human Resilience Capacities.

Cognitive	**Affective**	**Behavioral/Social**
– Balanced perspective on experience	– Coping	– Ability to adapt to change
– Fortitude, conviction, and resolve	– Faith, religion[1]	– Ability to use past successes to confront current challenge
– Moral reasoning[1]	– Hopefulness[1]	– Action-oriented approach
– Perceive beneficial effect of stress	– Internal locus of control[1]	– Engaging the support of others
– Personal/collective goals	– Optimism[1]	– Secure attachments to others
– Self-esteem[1]	– Patience	– Self-efficacy
– View change/stress as a challenge	– Self-commitment	– Tolerance of negative effect

– Sense of humor[1]
– Meaningfulness and purpose[1]

Adapted and arranged in groups by cognitive, affective, and behavioral dimensions. The list is compiled from a survey of the psychology and psychiatry literature (Connor 2006; Garcia-Dia et al. 2013; Kumpfer 1995; Olsson et al. 2003; Resnick and Inguito 2011; Richardson 2002). The assignment to a group is based on the heuristic approach described in section 3 of this paper. [1]Capacities organized by dimension in literature (Kumpfer 1995).

Cognitive, affective, and behavioral dimensions serve as category organizers representing the resilience capacities of individuals proximal to infrastructure operating environments. The three dimensions are selected because they appear in the psychology (Kumpfer 1995; Mischel and Shoda 1995; Reich, Zautra, and Hall 2010) literature on resilience, and because they provide a meaningful way to group the resilience capacities. These are important because prodigious evidence from prior events suggests that human factors can play a significant role – positive or negative – in the outcomes of catastrophic accidents, complex system failures, and disaster scenarios (Leavitt and Kiefer 2006; Brown and Westaway 2011; Hollnagel et al. 2011; Perrow 2011). Although beyond the scope of this paper, it is worth nothing that sociological factors related to human development can also influence how people interact with technology. For example, societal considerations like poverty, race, or social inequality can give rise to an uneven distribution of risks, vulnerability, and adaptive capacity, which can lead to unanticipated outcomes in response to adversity (Clark, Seager, and Selinger 2015; Thomas, Eisenberg, and Seager 2018).

5 Linking Human and Infrastructure Resilience

The human dimensions of resilience introduce new sources of novelty, innovation, and uncertainty, as well as the capacity to self-organize (Martin-Breen and Anderies 2011). The diversity of coupled systems in a critical infrastructure scenario implies that knowledge from multiple disciplines (e.g. psychology and engineering) must be included to understand the resilience of the composite system (Linkov et al. 2013). Moreover, the dynamic behavior, motivations, and intentional interactions between humans and technological systems contribute to the characterization of the resilience of coupled complex systems (Hollnagel and Fujita 2013; Park et al. 2013). Thus, a resilience engineering approach to infrastructure must incorporate multiple perspectives, methods, and interpretations of resilience to account for embedded human subjects (Thomas, Eisenberg, and Seager 2018).

A better understanding of the relationships between the dimensions of human resilience and the processes influencing socio-technical systems can inform methods and adjustments to improve system performance.

5.1 Resilience Processes

5.1.1 Socio-technical System Processes: Sensing, Anticipating, Adapting, and Learning

The characterization of resilient socio-technical systems with four dynamic processes as introduced by Hollnagel et al. (2011), Hollnagel et al. 2011) is widely adopted in resilience engineering literature (Madni and Jackson 2009; Rankin et al. 2013; Righi, Saurin, and Wachs 2015). These four processes suggest that resilient systems are the result of human factors applied on a system-wide scale, and consist of: monitoring – knowing what to look for; anticipating – knowing what to expect; responding – knowing what to do; and learning – knowing what has happened. Hollnagel (2012, 2013, and 2014) furthermore developed the functional resonance analysis method (FRAM) to show how each of the four resilience processes are dynamically coupled to the other processes and to identify the dependencies among them. Together, Hollnagel and others' work with FRAM (Hollnagel 2012; Cvijetic and Netjasovov Feda 2015; Tian et al. 2016) demonstrate the feasibility of linking human actions and technological system response via processes. The four processes are focused on different ways of knowing and thus emphasize a *cognitive* perspective of how humans can influence system resilience. This important consideration offers valuable insight about how people access information and expert knowledge to interact with infrastructure in response to acute stressors or system shocks. Although a sole focus on cognition precludes the consideration of other influences on individuals and groups interacting with technical systems, the underlying framework can accommodate a range of human perspectives.

An important refinement to the framework by Park et al. (2013) emphasizes the *recursive* nature of four socio-technical processes characterizing the dynamic behavior of resilient systems: sensing, anticipating, adapting, and learning (SAAL). The SAAL processes describe how humans and social systems interact with technological systems like infrastructure to maintain a viable level of operation in both expected and unexpected conditions. Resilience engineering engages the processes to manage operational boundary conditions and sustain adaptive capacity amid external stressors (Rankin et al. 2013). In this way, the SAAL processes mediate the capacity of a system to cope with surprise and adapt to changing conditions.

The four SAAL processes are summarized as follows (Hollnagel et al. 2011; Hollnagel and Fujita 2013; Linkov et al. 2013; Park et al. 2013):

- *Sensing* processes apprehend and interpret information about a system's operational states relative to known and unknown vulnerabilities and system shocks. Learning informs sensing about what to look for based on prior experience. Anticipating informs sensing by providing inputs about what to look for or what system conditions to expect disruption or change. Sensing also includes access to physical and functional indicators and methods for monitoring the environment at the operational boundary for thresholds and threats impacting system performance.

- *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. Anticipating considers known potential failures in addition to unexpected changes in system states. A resilient system aims to anticipate both threats and opportunities that can impact performance. Because anticipating extends to include potential future states – known and unknown – a resilient system is sentient and self-reflective about operating conditions and potential impacts at the boundary. This shows how humans are a vital component of complex socio-technical systems and serves an important role interacting with the resilience processes.

- *Adapting* describes the processes governing system responses to both known and unknown changes in stability and operating performance. A system adapts to changing conditions and either returns to its previous state or shifts to a different operating state while maintaining a viable level of essential functions. The adaptive capacity of a complex socio-technical system determines its ability to compensate for stressors by considering tradeoffs with capacities like efficiency and safe operation at the system boundary.

- *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. Learning becomes possible when information from prior experiences or system disruptions serve to inform and mitigate current experiences. Dynamic feedback from sensing can enable adaptive learning during a disruptive event whereby real-time adjustments follow intentional changes in response to status updates on conditions and system performance.

The SAAL processes offer a mechanism for exploring the relationships between human resilience and socio-technical system resilience. Moreover, the recursive processes can serve as a guide to interrogate a system and to assess its capacity to navigate resources and adjust functioning in response to changes in its environment. The SAAL processes readily accommodate the cognitive and behavioral dimensions although it is less apparent how they may consider the *affective* dimension.

5.1.2 Human Resilience Processes

Unlike a human resilience capacities perspective, a process perspective compares dynamic processes representing adaptive patterns of actions and behaviors by people in differing context and time scales to identify high-risk individuals more susceptible to adversity (Rutter 1987; Luthar, Cicchetti, and Becker 2000; Masten 2001, 2014b). In a context of infrastructure, psychological human resilience capacities combine with dynamic processes to characterize the resilience of people interacting with coupled complex systems. That is, the interactional processes represent a coupling mechanism linking human resilience capacities with a socio-technical system. Moreover, resilience processes link the internal characteristics of a person to the external environment and outcomes. Systems-theoretical perspectives of human resilience that incorporates dynamic processes emerged from the application of general systems theory (Von Bertalanffy, L 1968) to human development (Masten 2007; Ungar, Ghazinour, and Richter 2013). Humans are conceptualized as a myriad of overlapping biological, psychological, neurological, and sociological systems interacting via processes with each other and with other complex systems in their proximal environment. In an infrastructure scenario, a systems perspective considers the resilience and adaptive processes representing the relationships between a person and interdependent technological systems.

5.2 Integrated Socio-technical Framework for Resilient Infrastructure

We apply a ‘person-process-context’ concept from the psychology literature describing how humans interact with their environment (Bronfenbrenner 2005) to develop a novel model linking system and individual human resilience capacities with the SAAL processes. The structure of the model (Figure 1) supports the rationale for relating human and socio-technical resilience capacities by engaging the dynamic processes that characterize the relationships and interactions between humans and infrastructure. There are two key motivations for this approach. First, the person-process-context concept is foundational in the psychology literature influencing a wide stream of human resilience and development research (Masten 2014a; Sameroff 2010; Ungar, Ghazinour, and Richter 2013). Second, the conceptual model in Figure 1 provides a simple and convenient structure for integrating human and technological concepts. We incorporate the person-process-context concept by substituting infrastructure as the contextual environment. We then apply the SAAL processes as a linking mechanism to examine the relationships between the human and socio-technical resilience capacities.

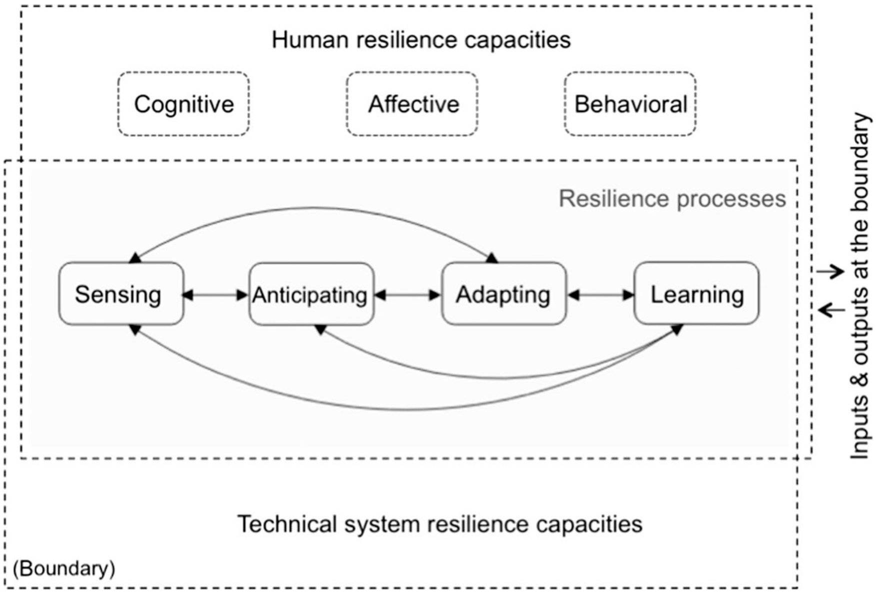

Figure 1: Coupled Human and Technical Resilience Capacities.
Cognitive, affective, and behavioral dimensions organize the human capacities. The resilience processes are the coupling mechanism corresponding to sensing, anticipating, adapting, and learning. The dashed lines represent the boundary conditions and the shaded area represents the domain where human and technical systems overlap. The feedback loops represent the reciprocal properties of the SAAL processes.

Whereas the NAS definition fails to describe how its planning and preparing, absorbing, recovering, and adapting capacities are realized, SAAL identifies the processes that must be undertaken to create these capacities. It is important to note that NAS capacities differ from SAAL processes despite using similar terminology. While adaptation in the NAS sense refers to improvements in system function, adaptation in SAAL refers to socio-technical *actions* that influence system function. In other words, the capacity for an infrastructure system to improve function post disruption (“adapt” in NAS terminology) depends on successful negotiation between human and technological ability to take action (“adapt” in SAAL terminology).

5.3 Linking System and Human Capacities

Table 3 synthesizes and summarizes the results from implementing the steps described in the methods section above for each group of capacities. The cognitive, affective, and behavioral dimensions organize human capacities of an individual.

Table 3: Distribution of 18 Socio-technical System Capacities (see Appendix A) and 23 Human Capacities (see Appendix B) when Compared with the SAAL Resilience Processes.

	Sensing	Anticipating	Adapting	Learning
System	– Avoidance – Cohesion	– Compensation – Goals	– Adaptive capacity – Autonomy	– Buffering – Efficiency

	– Flexibility – Margin – Pinging – Tolerance	– Maneuverability	– Control – Coping – Diversity – Efficacy – Survival	
Human				
Cognitive	– Perceive benefits of stress – Moral reasoning – Self-esteem	– Personal, and collective goals	– Fortitude, conviction and resolve – View change/stress as a challenge	– Balanced perspective on experience
Affective	– Optimism – Meaningfulness and purpose	– Hopefulness – Patience	– Coping – Faith, religion – Internal locus of control	– Self-commitment – Sense of humor
Behavioral	– Engaging the support of others	–	– Adapt to change – Action-oriented approach – Secure attachments to others – Self-efficacy	– Use past success w/current challenges – Tolerance of negative effect

5.3.1 Technical System Capacities

The heuristic for relating the socio-technical capacities to the SAAL processes includes comparing the descriptions of each process provided in section 5.1.1 and the descriptions of the capacities provided in Appendix A. Seven of the 18 system capacities are assigned to adapting processes and six to sensing with anticipating and learning receiving three and two, respectively. As a result, adapting is the most influential, which aligns well with other research investigating the relationship between the SAAL processes and infrastructure resilience (Mathias et al. 2018). Although each of the SAAL processes are represented, the minimal distribution of system capacities for anticipating and learning suggest those processes are less emphasized among the 18 capacities reviewed in this group.

5.3.2 Human Capacities

The heuristic for relating the human capacities to the SAAL processes includes comparing the descriptions of each process provided in section 5.1.1 and the descriptions of the capacities provided in Appendix B. The human capacities in Table 3 are organized by cognitive, affective, and behavioral dimensions described in section 4.2 and distributed among the SAAL processes. Sensing dominates the cognitive dimension while adapting dominates both the affective and behavioral dimensions. None of the capacities are assigned to the behavioral dimension of anticipating, which suggests that these processes rely more on the capacities assigned to the cognitive and affective dimensions among the 23 considered. The affective dimension is largest with a total of nine capacities while cognitive and behavioral both have seven. Among the SAAL processes, adapting is largest with nine capacities followed by six with sensing, five with learning, and 3 with anticipating when cognitive, affective, and behavioral dimensions are combined.

6 Discussion

The results suggests that the SAAL processes can serve as a linking mechanism that shows how the cognitive, behavioral, and affective dimensions of human resilience capacities are interconnected with, interrelated to, and interdependent on system resilience capacities.

6.1 Human and Socio-technical Resilience Capacities are Interconnected

The relationships between human and socio-technical resilience capacities shown in Figure 1 and Table 3 point to the interconnectedness of these capacities within coupled human and socio-technical systems. That is, certain psychological capacities that correlate with the resilience of an individual human also correlate with certain resilience capacities of a socio-technical system.

The cognitive, behavioral, and affective dimensions reflect the interconnectedness of the human and infrastructure resilience capacities by their mutual relationship to the SAAL processes. The relationship between the cognitive dimension and SAAL extends from Hollnagel et al. (2011) four abilities of resilient socio-technical systems to know what to look for, what to expect, what to do, and what has happened. From a psychological perspective cognitive capacities engage mental faculties of knowledge, judgment, and reasoning in influencing resilient behavior (Friborg et al. 2005). These capacities (e.g. moral reasoning, goals, and balanced perspective on experience) reflect individual abilities to access relevant information and expert knowledge to influence infrastructure resilience by enabling the four abilities of knowing. The work by Park et al. (2013) points to the relationship between the behavioral dimension of resilience capacities and the SAAL processes. Behavioral capacities influence resilient behavior and interactions between an individual person or group and their proximal environment (Kumpfer 1995), which refers to infrastructure for the applications considered in this paper. These capacities (e.g. engaging the support of others, action-oriented approach, and tolerance of negative effect) characterize individual abilities to physically interact with systems and manage operational boundary conditions. In this way, the behavioral capacities reflect how human agency can impact infrastructure resilience by enacting the SAAL processes – sensing, anticipating, adapting, and learning.

Prior work in resilience engineering effectively ignores the relationship between the affective dimension of human resilience and the socio-technical processes that describe a resilient infrastructure system. According to the psychology literature, affective resilience capacities engage the experience of emotions to influence resilient behavior (Ong, Bergeman, and Chow 2010). Moreover, affective resilience capacities (e.g. hopefulness, optimism, and internal locus of control) can influence both cognitive and behavioral dispositions (Reich, Zautra, and Hall 2010) that determine how people may or may not respond to disruptive conditions. Thus, affective capacities are interconnected to system capacities because each can influence the SAAL processes that determine infrastructure resilience. Taken together, the cognitive, behavioral, and affective dimensions elucidate the interconnection between individual psychological resilience capacities and system capacities.

6.2 Human and Socio-technical Resilience Capacities are Interrelated

A comparison between individual human capacities and socio-technical systems shows the interrelated nature of coupled systems. For example, the human capacity 'internal locus of control' found in the psychology literature has a conceptual correlate in the resilience engineering literature with the capacity 'control'. The concept of 'control' is particularly important in both human and technical contexts. In psychology, an internal locus of control describes perspectives of self-regulation over one's internal resources that enable abilities such as making decisions and taking action. The human resilience capacity 'internal locus of control' inspires a belief in one's own effectiveness in relation to extreme adversity (Olsson et al. 2003; Noltemeyer and Bush 2013; Werner 2014). Moreover, a sense of control impacts the ability to cope and to function (Garcia-Dia et al. 2013) and helps guide self-efficacy and a sense of personal integrity (Kaminsky et al. 2007). Compared to psychological concepts of control, resilience engineering considers the control of a resilient system as the ability to manage adaptive capacities amid surprise (Woods 2015) or unanticipated disruptive events. In other words, a controlled system is able to achieve specified or desirable states of operation while avoiding undesirable states (Dinh et al. 2012). Thus, the control of a resilient system effectively enables the system to adapt to surprise events. In applications such as infrastructure, control refers to the ability of a system to regulate brittleness at its operational boundary by making specific performance adjustments in response to surprise (Woods 2015). This is a dynamic form of adapting. An essential condition for maintaining control of a system is the ability to acknowledge when a situation exceeds the performance level anticipated by the operators (Hollnagel et al. 2011). This points to a possible relationship between anticipating and adapting to surprise, and suggests that operator training and experience, which support anticipating, are important factors in establishing and maintaining system control (cf. Hollnagel et al. 2011 for possible "negative" interference between anticipation and serendipity).

The relationship between the system capacity of control and the sense of control that support individual human adaptive capacities supports our rationale for ascribing 'control' to the SAAL process, adapting, as shown in Table 3. Likewise, there are other human and socio-technical system capacities (e.g. coping, efficacy, and goals) that share similar terms, descriptions, and processes with one another although the meaning of these terms in technological and psycho-social contexts has not to our knowledge been compared. Moreover, these capacities and others are interrelated because each capacity contributes to the same basic phenomenon (i.e. infrastructure resilience) via a common relationship with the SAAL processes similar to the description above for control.

6.3 Human and Socio-technical Resilience Capacities are Interdependent

In the psychology literature coping is often described as a resilience characteristic (Connor 2006; Kaminsky et al. 2007; Garcia-Dia et al. 2013), an outcome (Garcia-Dia et al. 2013), or a part of the resilience process (Masten, Best, and Garmezy 1990). Although coping can include cognitive, emotional, and behavioral dimensions (Skodol 2010), the emotional dimension of coping is associated with higher levels of distress and supports feelings of control (Folkman and Moskowitz 2004). By comparison, a resilient socio-technical system must be able to cope with unexpected perturbations that extend beyond design expectation (Hollnagel and Fujita 2013). Resilience engineering describes failure as the inability of a system to cope with increasing complexity (Hollnagel, Woods, and Leveson 2006) and to maintain control over operational performance amid adversity (Madni and Jackson 2009). In coupled systems, the human capacity to cope with adversity is therefore dependent on the socio-technical systems' capacity to cope and vice versa. Coping and control are examples of interdependent resilience capacities because they have a mutual influence on one another. Likewise, other resilience capacities are interdependent because coupled systems rely upon the human ability to accommodate unknown changes and disruptions.

7 Conclusion

Despite the scholarly basis for viewing human individuals – including those responsible for the design, operation, and management of infrastructure – as dynamic components of the built environment that can impact system resilience and outcomes, Federal directives seeking an integrated approach to strengthening the resilience of critical infrastructure fail to consider how human resilience may contribute to technological resilience. The SAAL resilience processes serve as a linking mechanism between human and technological domains. The diversity of capacities and processes identified reflects the multidimensional nature of infrastructure resilience by effectively integrating definitions and concepts from the psychology, infrastructure, and resilience engineering literatures. Our findings suggest that human and technological resilience capacities are interconnected, interrelated, and interdependent to one another. Moreover, they suggest that the affective dimension of human resilience may be more critical than tends to be acknowledged in resilience engineering literature. Thus, we argue that cognitive, behavioral, *and* affective dimensions of human resilience contribute to the resilience of infrastructure essential to public health, safety, and well-being.

Funding

National Science Foundation, Funder Id: http://dx.doi.org/10.13039/100000001, Grant Number: 1441352.

Appendix

Appendix A

Technical resilience capacities

Resilience capacity	Description, findings	Authors
1. Adaptive capacity	Ability to recover stability and performance and survive a disruptive event or threat	(Madni and Jackson 2009; Jackson and Ferris 2012)
2. Autonomy (local)	Loose coupling (H-p220) Independence among options and solutions	(Fiksel 2003; MacAskill and Guthrie 2015)
3. Avoidance, early detection	Foresee, detect, prevent drift toward brittleness; maintain state during disruption	(Hollnagel, Woods, and Leveson 2006; Larkin et al. 2015; Dinh et al. 2012)

4. Buffering	Kind/size of perturbations that can be absorbed/adapted to, without compromising performance	(Woods 2006)
5. Cohesion	Strong forces that unify or bring together; the capacity of a system to function as a whole unit amid threats and disruption	(Fiksel 2003; Larkin et al. 2015; Mu et al. 2011; Jackson and Ferris 2012)
6. Compensation	Engaging additional resources like buffering and reserve margin to maintain stability within a viable operating region during adaptive system failure. Adapting performance to cope with increased demand	(Rankin et al. 2013)
7. Control	Adaptive capacity management in relation to tradeoffs among multiple dimensions, dynamic access to a preferred system state	(Woods 2015; Alderson, Gerald Brown, and Matthew Carlyle 2014; Dinh et al. 2012)
8. Coping	Capacity to sustain unexpected surprise and complexity, local and spontaneous	(Hollnagel, Woods, and Leveson 2006; Madni and Jackson 2009; Labaka, Hernantes, and Sarriegi 2016)
9. Diversity	Variety of system operational/functional behavior and performance; multiple products and services; alternative plant location	(Fiksel 2003; Larkin et al. 2015; Mu et al. 2011)
10. Efficacy	Effectiveness of system to identify and mitigate hazards, System response to specific inputs and risks	(Hollnagel, Woods, and Leveson 2006; Haimes 2009)
11. Efficiency	Tradeoff with brittleness at boundary conditions; maintain a viable operating level with minimal resource consumption	(Fiksel 2003; Hollnagel et al. 2011)
12. Flexibility	Capacity to adjust performance in response to external changes, threats, boundary conditions, and viable operating region; lack of flexibility contributes to brittleness; exploit resilience principle	(Woods 2006; Paries 2011; Dinh et al. 2012; Jackson and Ferris 2012)
13. Goals management	Tradeoff between acute and chronic goals; conflicting goals pit safety against efficiency; dynamic balancing	(Woods 2006)
14. Maneuverability	Ability to regulate the risk of brittleness; ability to manage variability; continuous adjustment to conditions	(Madni and Jackson 2009)
15. Margin	Ability to manage boundary conditions; how close is the system operation to boundary; successful compensation	(Woods 2006)
16. Pinging, early detection	Proactive probing for changes in risk profile, rapid and accurate access to changes in system states	(Hollnagel, Woods, and Leveson 2006; Dinh et al. 2012)
17. Survival	Ability of system to persevere and survive while providing a viable level of service	(Hollnagel, Woods, and Leveson 2006)
18. Tolerance	How a system behaves at the boundary; graceful or abrupt degradation	(Woods 2006; Jackson and Ferris 2012)

Appendix B

Human Resilience Capacities

Cognitive Dimension

Human resilience	Description, findings	Authors
Cognitive		

1. Balanced perspective on experience	Personal beliefs that promote a sense of meaning and purpose; ability to sustain effort over time; help overcome negative effect of personal, social, and economic risks; a sense of equanimity about one's life conditions	(Olsson et al. 2003; Sinclair and Wallston 2004; Skodol 2010; Dyer and Mcguinness 1996)
2. Fortitude, conviction, tenacity, and resolve	Perseverance to tasks and goals; sustained by a deeply held belief that life has meaning; beliefs that sustain motivation and effort to adapt/survive; mastery motivation; agency	(Masten and Wright 2010; Olsson et al. 2003; Masten 2014a; Dyer and Mcguinness 1996)
3. Moral reasoning	Informed conscience, capacity to judge right from wrong; valuing compassion, fairness and decency; internal standards for the way things should be; based on ethical grounds; moral perception associated with faith	(Kumpfer 1995; Stokols, Lejano, and Hipp 2013)
4. Perceive beneficial/strengthening effect of stress	Viewing stress as an opportunity for growth; positive perception of stress; enhanced optimism, patience, and perceived value of interpersonal communications; posttraumatic growth; learning from crises	(Connor and Davidson 2003; Connor 2006; Rutter 1985; Lyons 1991; Tedeschi and Calhoun 2004; Kobasa 1979)
5. Personal/collective goals	Ability to set desirable objectives and obtain a sense of mastery when life events threaten beliefs; contribute to a sense of coherence and meaning; self regulation	(Connor and Davidson 2003; Connor 2006; Rutter 1985; Mayer and Faber 2010)
6. Self-esteem	Having a value, acceptance, and respect of oneself; sense of self-worth; positive self-appraisal of personal strengths and capabilities; enhanced by creativity	(Connor and Davidson 2003; Connor 2006; Skodol 2010; Campbell, Chew, and Scratchley 1991; Rutter 1987; Kumpfer 1995)
7. View change/stress as a challenge/opportunity	Perceive stress as a vehicle of positive change; experiences of awakening to responsibility, validation and acceptance from others; able to be self-nurturing to recognize and seek-out individual needs	(Connor and Davidson 2003; Connor 2006; Kobasa 1979; Skodol 2010; Lyons 1991)

Affective Dimension

Human resilience	Description, findings	Authors
Affective		
8. Coping	The emotional dimension of coping involves adopting new perspectives of adverse events to benefit one's values and beliefs thereby supporting feelings of control; An emotional approach to adaptation involving the expression of emotions as a means of actively moving toward acceptance and positive re-appraisal of stressful encounters; Buffer effects of stress on psychological outcomes; Availability of responses to endure stress	(Luthar, Cicchetti, and Becker 2000; Folkman and Moskowitz 2004; Stanton, Parsa, and Austenfeld 2002; Sinclair and Wallston 2004; Kobasa 1979; Skodol 2010)
9. Faith, religion	Helps integrate meaning of both individual and social disruptive life events; Religious beliefs help stabilize emotions and emotional behavior and can help promote emotional resilience; Positively influences an individual's ability to cope with life stressors and impacts subjective well-being	(Park and Folkman 1997; Murphy, Johnson, and Lohan 2003; Freud 2012; Krause 2003; Pargament and Cummings 2010)
10. Hopefulness	Positive motivation/outlook based on successful agency; associated with positive adaptation to stress	(Kumpfer 1995; Olsson et al. 2003; Ong, Edwards, and Bergeman 2006)

11. Internal locus of control	Believing that life's challenges are related more to an individual's behavior rather than bad luck or some other person; contributes to effective coping; belief that one is an active participant and determinant of outcomes	(Skodol 2010; Kobasa 1979; Connor and Davidson 2003; Connor 2006; Kumpfer 1995)
12. Optimism	Positive appraisal/outlook of stressful events or adverse conditions; belief that one can influence the outcome of a stressful situation; associated with coping, positive reinterpretation, and seeking support	(Connor and Davidson 2003; Connor 2006; Kumpfer 1995; Skodol 2010)
13. Patience	Capacity to accept/tolerate delay, accepting of conditions without undue stress	(Connor and Davidson 2003; Connor 2006; Lyons 1991)
14. Self-commitment	Pledge to self; adherence and persevere with of intention, direction, and responsibility; ability to feel deeply involved; belief system minimizes perceived threat; vital to health under stress	(Kobasa 1979; Kumpfer 1995; Connor and Davidson 2003; Connor 2006)
15. Sense of humor	Able to view the ironic and amusing aspects of stress and conflict; cognitive reappraisal to adjust perspective and reference frame of experience to evoke positive emotion/meaning; emotional regulation; defense mechanism to ameliorate stress	(Connor and Davidson 2003; Connor 2006; Rutter 1985; Fraser, Galinsky, and Richman 1999; Feder et al. 2010; Skodol 2010)
16. Sense of meaningfulness, purpose	Self-perception of values, goals, capabilities; cognitive control	(Connor and Davidson 2003; Connor 2006; Kobasa 1979)

Behavioral Dimension

Human resilience	Description	References
Behavioral		
17. Ability to adapt to change	Adjust behavior to accommodate environmental conditions, stressors, and negative effects; ability to anticipate and plan and take reflective actions, related to agency	(Connor and Davidson 2003; Connor 2006; Rutter 1985; Kumpfer 1995; Brown and Westaway 2011)
18. Ability to use past successes to confront current challenge	Capacity to engage cognitive reappraisal to find benefit from stressors; accepting of life conditions and imperfections	(Connor and Davidson 2003; Connor 2006; Pargament and Cummings 2010)
19. Agency, action-oriented approach	Mastery motivation system, self-perception of positive and effective action, enact adaptive pathways, capacity to self-direct, builds confidence	(Connor and Davidson 2003; Connor 2006; Rutter 1985; Masten and Wright 2010; Brown and Westaway 2011)
20. Engaging the support of others (a.k.a. social support)	Social resources (friends and relatives) promote positive adaptation; mentors and role models can alleviate stress; acts as a stress buffer; outlet for expression of feelings and assist navigating life conditions; facilitates adjustment to trauma	(Connor and Davidson 2003; Connor 2006; Rutter 1985; Skodol 2010; Friborg and Hjemdal 2003; Garcia-Dia et al. 2013)
21. Secure attachments to others	Close bonding relationships; universal process in human development that begins in infancy with caregivers, parents, and family; also involves close relationships with friends and romantic partners; threats trigger behaviors seeking contact and reassurance; provides secure base for exploring the world; supports the process of agency and mastery motivation	(Connor and Davidson 2003; Connor 2006; Olsson et al. 2003; Masten and Wright 2010; Ungar 2006; Friborg and Hjemdal 2003)
22. Self-efficacy	Belief and confidence in one's ability to achieve a goal and overcome adversity and disruptive events; self-confidence; belief in one's ability to navigate and manage difficulties effectively	(Garcia-Dia et al. 2013; Rutter 1993, 1987; Olsson et al. 2003; Skodol 2010)

23. Tolerance of negative effect	Sufficient internal coping mechanisms to manage stressors; strategies for dealing with traumatic conditions	(Connor and Davidson 2003; Connor 2006; Olsson et al. 2003; Smith 1999)

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