Human Resilience and Development in Coupled Socio-technical Systems: A Holistic Approach to Critical Infrastructure Resilience

by

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ABSTRACT

The resilience of infrastructure essential to public health, safety, and well-being remains a priority among Federal agencies and institutions. National policies and guidelines enacted by these entities call for a holistic approach to resilience and effectively acknowledge the complex, multi-organizational, and socio-technical integration of critical infrastructure. However, the concept of holism is seldom discussed in literature. As a result, resilience knowledge among disciplines resides in near isolation, inhibiting opportunities for collaboration and offering partial solutions to complex problems. Furthermore, there is limited knowledge about how human resilience and the capacity to develop and comprehend increasing levels of complexity can influence, or be influenced by, the resilience of complex systems like infrastructure. The above gaps are addressed in this thesis by 1) applying an Integral map as a holistic framework for organizing resilience knowledge across disciplines and applications, 2) examining the relationships between human and technical system resilience capacities via four socio-technical processes: sensing, anticipating, adapting, and learning (SAAL), and 3) identifying an ontological framework for anticipating human resilience and adaptive capacity by applying a developmental perspective to the dynamic relationships between humans interacting with infrastructure. The results of applying an Integral heuristic suggest the importance of factors representing the social interior like organizational values and group intentionality may be under appreciated in the resilience literature from a holistic perspective. The analysis indicates that many of the human and technical resilience capacities reviewed are interconnected, interrelated, and interdependent in relation to the SAAL socio-technical processes. This work contributes a socio-technical perspective that incorporates the affective dimension of human resilience. This work presents an ontological approach to critical infrastructure resilience that draws upon the

human resilience, human psychological development, and resilience engineering literatures with an integrated model to guide future research. Human mean-making offers a dimensional perspective of resilient socio-technical systems by identifying how and why the SAAL processes may change across stages of development. This research suggest that knowledge of resilient human development can improve technical system resilience by aligning roles and responsibilities with the developmental capacities of individuals and groups responsible for the design, operation and management of critical infrastructures.

DEDICATION

To Ashley, Sean, and Shayna for their love, inspiration, and support for *our* continued growth and development.

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CHAPTER 1

INTRODUCTION

Federal directives call for a *holistic* approach to critical infrastructure resilience that considers the interrelatedness and interconnectedness among systems essential to national health, security, and well-being such as energy, water, transportation, and cybersecurity (The White House 2013). The directive seeks to strengthen and enhance the security and resilience of critical infrastructure on a national level for all types of natural and man-made hazards, threats, and vulnerabilities (The White House 2013). Presidential Policy Directive - 21 (PPD-21) is clear to acknowledge the complexity, multi-organizational, and socio-technical integration of critical infrastructure, and identifies the strategic imperatives, roles, responsibilities, and implementation plans for Federal agencies. However, there is no definition of the term holistic and no reference in the directive to identifying or maintaining the resilience of the people involved with any part of the design or operation of critical infrastructure systems. Thus, in failing to clarify that holistic includes people, PPD-21 excluded an important factor in their understanding of 'holistic'—the human interior. In doing so, the directive fails to acknowledge important lessons learned over decades of research involving people and complex systems suggesting that the adaptive capacity of organizations resides within its people (Hollnagel et al. 2011). Moreover, because humans are agents possessing individual and collective agency, intensions, and motivations embedded in, and dynamically influencing, other systems (Brown and Westaway 2011; Nelson, Adger, and Brown 2007), the people interacting with the design, operation, and management must be included in a holistic approach to critical infrastructure.

However, little is known about how the interrelatedness of human resilience and development may influence the resilience of technical systems such as critical infrastructure. In this work I address the scarcity of research—theoretical, conceptual, and *operational*—linking resilience and human development in a context of social ecologies embedded in complex systems (Masten & Obradovic, 2010). The social ecologies include people—children and adults, and the systems considered include critical infrastructures, which can be impacted by natural and man-made disasters. Child development research emphasizes the interactions of individuals concerning different environments such as risk and adversity (Masten 2001), social ecology (Bronfenbrenner 1999; Ungar, Ghazinour, and Richter 2013), and culture (Ungar 2006). Adult resilience research is scarce compared to children. However, although resilience represents a fundamental component of human development in children (Luthar, Cicchetti, and Becker 2000), research is modest about how the construct functions over a lifespan (Campbell-Sills, Cohan, and Stein 2006). Nonetheless, critical infrastructure systems are designed, maintained, managed, and governed by adults with individual and group capacities, intentions, and motivations. Moreover, the people embedded in infrastructure are influenced by laws, values, culture, and worldviews. Thus, there are a myriad of human factors that can impact how people interact with complex systems like infrastructure.

Linking human and technical system complexity

Given the interconnected, interrelated, and interdependent nature of infrastructure systems, certain critical roles require individuals to make sense of systems in complex ways that can involve high degrees of ambiguity and uncertainty. However, there is limited knowledge about how the human capacity to develop and comprehend increasing levels of complexity can influence, or be influenced by, the resilience of complex systems like infrastructure. Evidence suggest that factors such as complex systems thinking, capacity for multiple perspectives, and other adaptive capacities emerge in later stages of human development (Cook-Greuter 2004; Vincent 2015). Moreover, research by Cook-Greuter (1999) indicates capacities for factors like complex systems thinking are less common, and are only accessible after passing through an invariant sequence of stages of development. Evidence from other studies suggest that environments found among many educational institutions and traditional management structures often discourage individual development by reinforcing early stage patterns and by limiting transformational growth opportunities (Torbert et al. 2004). This means certain catastrophic infrastructure breakdowns may exceed the capacity of some individuals with front-line role responsibilities to effectively function and cope with high degrees of complexity and uncertainty. In the present work, I address the research gap linking human and technical system complexity to support a holistic understanding of human resilience, psychological development, and infrastructure resilience.

Evidence for the justification that this problem is meaningful

Disaster events such as the Three Mile Island accident in 1979, the Challenger explosion in 1986, and the New Orleans Levee breakdowns in 2005 illustrate how human failures can amplify technical failures (Perrow 2011). These events and others including the Fukushima disaster in 2011 (Hollnagel and Fujita 2013) and U.S Airways Flight 1549 in 2009 (NTSB 2010) justify a need to know about the relationships between human resilience, development, and critical infrastructure resilience. From a resilience engineering perspective human failure can be viewed as a lack of resources and adaptive capacities (Hollnagel, Woods, and Leveson 2006). By comparison, in human development a lack of psychological resources and adaptive capacities corresponds to underrepresented stages of potential growth and developmental maturity. Moreover, a need to understand the relationship between human resilience and development is compounded in disaster scenarios involving multiple overlapping domains (Masten and Obradovic 2010). These domains include individual humans and social systems embedded in dynamically coupled systems including technological systems like power generation, water treatment, and transportation. Impacts from disasters in one domain can cascade and amplify across domains in addition to spatial and temporal scales. The debacle surrounding the Flint Michigan water supply, for example, showed how breakdowns in human behavior and decision making propagated across social and technical domains causing widespread damage among community members (CNN 2017). The damage was amplified over a two year time period before the problems were identified and corrective measures were taken. Likewise, the human ability to adapt to climate change is an example of a long time scale event with broad impacts linking complex relationships reflecting values, ethics, and world views (Adger et al. 2009), human development (O'Brien and Hochachka 2010), and built infrastructure. Both short and long time scale events can have lasting impacts across large spatial regions involving multiple social, environmental, and technical domains of influence involving humans and infrastructure. Thus, new knowledge of human resilience and development in people could help align roles and responsibilities with capacities of individuals and groups embedded in infrastructure systems thereby improving system resilience.

The frameworks, tools, and models constructed in this work are used to examine the complex relationships between human resilience, psychological development, and critical infrastructure resilience. Finally, the new knowledge and resources derived from this research can be adapted for the design and support of other resilience research initiatives seeking a holistic approach to resilience. A potential positive social impact of this study is to underpin national health, safety, and well-being with enhanced critical infrastructure resilience.

Chapter-wise Summary

Table 1 Chapter 2 summary

Chapter 2: A Holistic Approach to Resilience Research Using an Integral Map	
Research questions	What is holism? What is a holistic approach to resilience research and why is it needed? How can an Integral Map guide holistic resilience research? How can a holistic approach to resilience research reveal knowledge gaps while contributing to a more comprehensive understanding of resilience?
Approach	Identify and analyze 20 highly cited resilience research articles; adapt and apply an Integral heuristic to organize the articles by their dominant epistemological orientation. Analyze differences in resilience concepts, definitions, and perspectives, and identify resilience research areas of focus in addition to those that are underrepresented.
Deliverable	Journal article in Environment Systems and Decisions , under review
Intellectual Merit	This study examines holism and demonstrates how to apply a holistic methodology to analyze existing resilience research by epistemology and to guide new research initiatives. The dominant areas of focus in resilience research among the articles reviewed are identified as ecology, psychology, neuroscience, socio-ecological systems, and technology. The study suggests less attention is given to factors related to the social interior that contributes to human resilience including social vulnerability, ethics, values, culture, and worldviews.

Key figure

Perspective—Individual Interior *Subjective (1st-person, 'I', 'me')* Focus on individual interior experience, resources, and phenomena. Examples • Cognitive capacity, • Affect (emotional intelligence) • Moral capacity • Psychological development • Individual beliefs and attitudes • Individual knowledge & skills Resilience: self-esteem, locus of control, stress response, emotional adaptation. **Experience**	**Perspective—Individual Exterior** *Objective (3rd-person singular, 'it')* Focus on individual exterior behavior, structure, functions, and phenomena. Examples • Individual characteristics and measures (person/technology/environment) • Individual actions & behaviors • Individual structures & functions • Individual interacting with environment • Characteristics of individuals/components Resilience: sensing, anticipating, adapting, and learning, individual capacity to absorb & recover. **Behavior**
Culture **Perspective—Collective Interior** *The inter-subjective (2nd-person, you, we)* Focus on group interior culture, organizational & political ideology, resources, and phenomena. Examples • Shared values & beliefs • Culture, customs, & lifestyle • Interpersonal communication • Ethics & worldviews • Religious views Resilience: social cohesion, community ability to cope, self-organize, & community efficacy.	**Systems** **Perspective—Collective Exterior** *The inter-objective (3rd-person plural, 'Its')* Focus on group exterior systems, dynamic interactions, structures, functions, and phenomena. Examples • Interactions within and among systems • Systems functions and structures • Economic & geopolitical structures • Social, ecological, and technological systems • Socio-ecological & socio-technical systems Resilience: sensing, anticipating, adapting, and learning, robust, capacity to absorb & recover.

Figure 1 A heuristic representing each quadrant of the Integral Map.
The heuristic is a synthesis of multiple works (Esbjörn-Hargens and Zimmerman 2009; Wilber 2000b; Cook-Greuter 2005) and applied to include different ways of knowing in addition to example resilience indicators for each quadrant.

Table 2 Chapter 3 summary

Chapter 3: A resilience engineering approach to integrating human and technical resilience capacities with socio-technical resilience processes in coupled infrastructure systems	
Research questions	What are the relationships between human resilience and infrastructure resilience? How can human resilience influence infrastructure resilience and vice versa? How do human resilience and technical system resilience capacities relate to the SAAL processes?
Approach	This study examines the resilience of humans and infrastructure interacting with one another via four socio-technical processes: sensing, anticipating, adapting, and learning. A group of psychological constructs—cognitive, affective, and behavioral capacities—representing human resilience are correlated with technological capacities found in the resilience engineering and infrastructure literature.
Deliverable	Journal article in *Journal of Homeland Security and Emergency Management* (under review)
Intellectual Merit	This study contributes an integrated perspective of infrastructure resilience linking human and technical capacities to resilience processes. Human and technical resilience capacities are interconnected, interrelated, and interdependent. This work suggests that human affect contributes to infrastructure resilience in addition to cognitive and behavioral dimensions.

Key figure

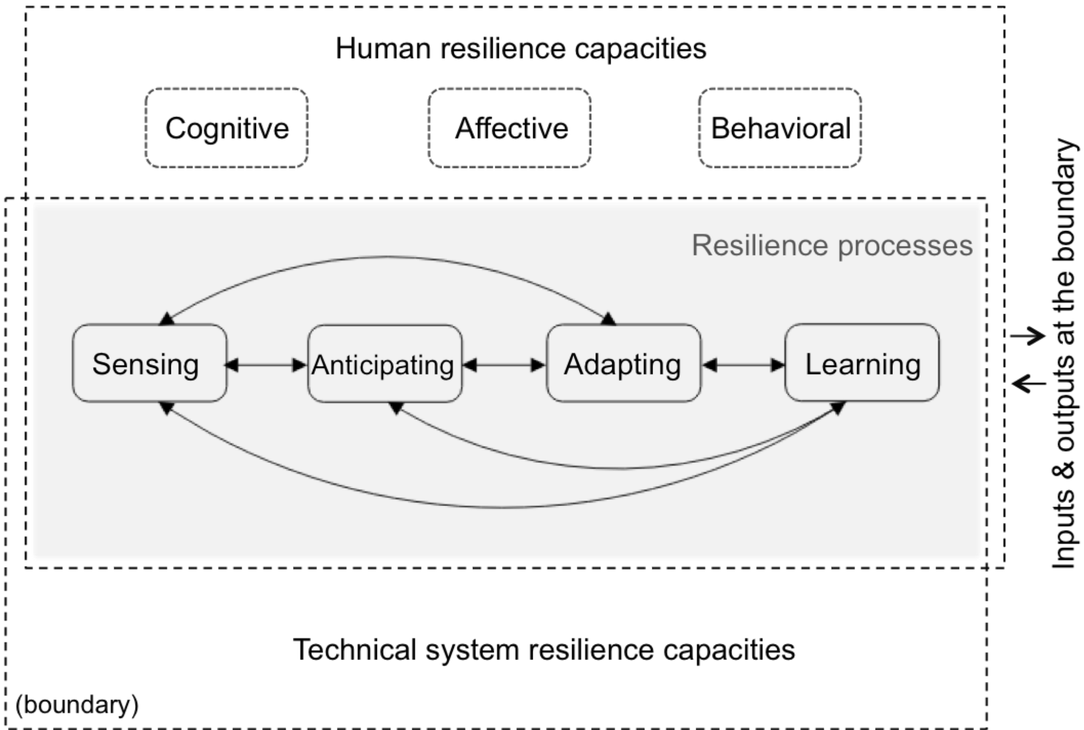

Figure 2 Coupled human and technical resilience capacities and SAAL processes. Cognitive, affective, and behavioral dimensions organize the human capacities. The resilience processes are the coupling mechanism corresponding to sensing, anticipating, adapting, and learning. The dashed lines represent the boundary conditions and the shaded area represents the domain where human and technical systems overlap.

Table 3 Chapter 4 summary

Chapter 4: An ontological framework integrating human development and technological resilience in socio-technical systems	
Research questions	What are the relationships between human development and infrastructure resilience? How can knowledge of human development influence infrastructure resilience?
Approach	This research examines the dynamic relationships between psychological human development and critical infrastructure resilience. An ontological approach synthesizes human resilience, development, and resilience engineering literatures to construct an integrated model. A stage theory of human development is conceptually correlated with an effectiveness scale corresponding to the socio-technical resilience processes—sensing, anticipating, adapting, and learning (SAAL).
Deliverable	Publication in a peer-review journal pending journal selection and submission.
Intellectual Merit	This research contributes new knowledge about the relationships between human psychological development and critical infrastructure resilience. The analysis suggest that the SAAL processes are progressively more differentiated, enhanced, and effective amid higher degrees of complexity and uncertainty in later stages of development compared to earlier stages. An ontological model is derived that relates infrastructure resilience to four human developmental stages by linking assessments with the SAAL processes.

Key figure

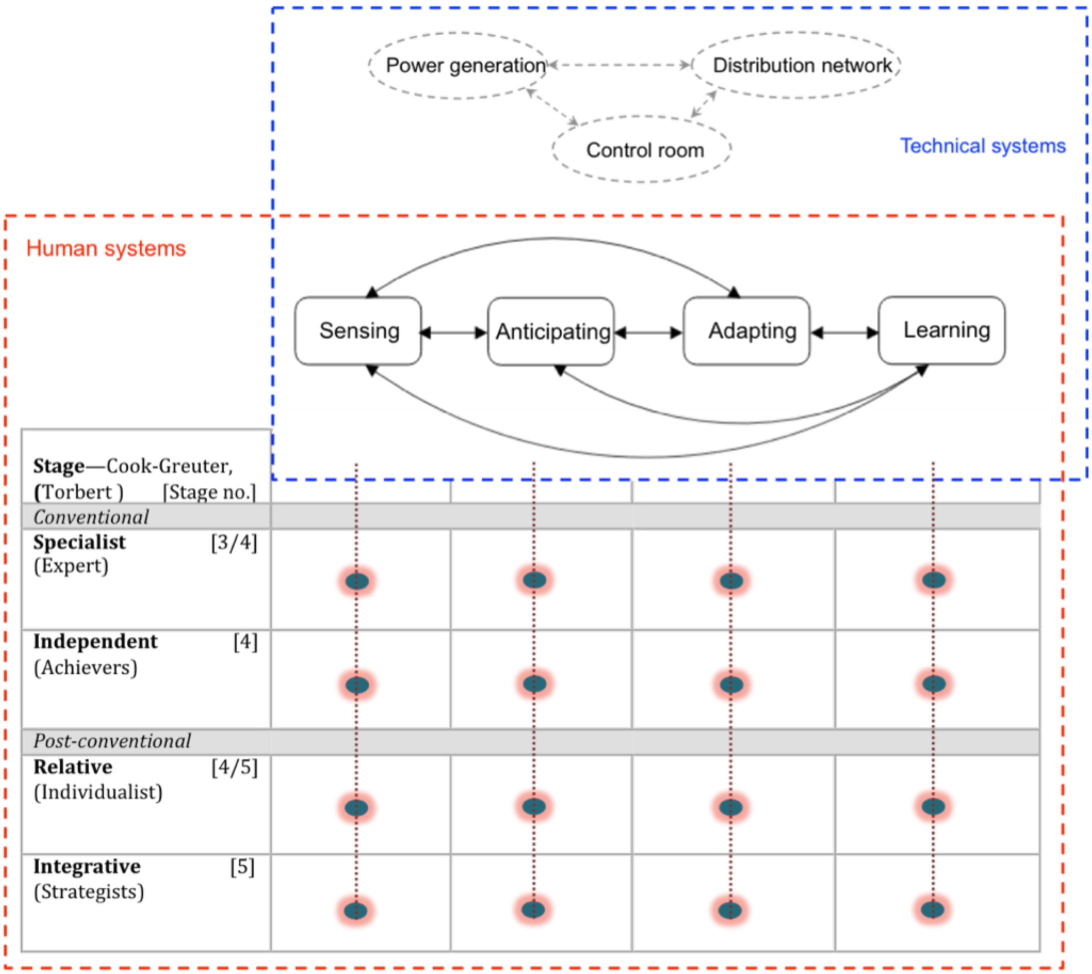

Figure 3 An ontological framework integrating infrastructure with development. Each cell may be characterized by a combination of endogenous and exogenous, properties and processes corresponding to sensing, anticipating, adapting, and learning (Cook-Greuter 1999; Torbert et al. 2004; Park et al. 2013).

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CHAPTER 2

A HOLISTIC APPROACH TO RESILIENCE RESEARCH USING AN INTEGRAL MAP

Introduction

The growing interest in resilience research reflects a diverse landscape of definitions, concepts, and applications across broad range of academic disciplines. Resilience concepts both predate and have expanded since the mid-1800's, when "resilience" was first used to describe the engineering properties of materials (Alexander 2013). For example, psychology and psychiatry began using 'resilience' in the 1950's to describe children's health and social adaptation in response to loss or adversity. Now, resilience is used in many fields to describe the ability to respond to unpredicted interruptions or shocks. In particular, academic interest in resilience is often attributed to research by Holling (1973) that extended resilience concepts from physics and engineering to ecological systems theory. Now the body of resilience research has grown to include child development (Masten 2001), systems engineering (Madni and Jackson 2009; Hollnagel et al. 2011), cybersecurity (Linkov et al. 2013), ecology (Nelson, Adger, and Brown 2007), neuroscience (Feder, Nestler, and Charney 2009), operations research (Alderson, Brown, and Carlyle 2015), psychiatry (Connor 2006), psychology (Bonanno 2004), sociology (Keck and Sakdapolrak 2013), and sustainability (Sweet et al. 2014; Redman 2014). In addition, resilience is now a common term in the public realm among federal and international agencies, particularly those focused on managing major crises caused by natural disasters and terrorist attacks (The White House 2013; Cutter et al. 2012; DHS 2013; UNISDR 2005; Larkin et al. 2015) and emerging long-term threats such as climate change (IPCC 2014a). Moreover, private funding organizations like the

Rockefeller Foundation (2016) are already implementing multinational programs to improve physical, social, and economic resilience of cities.

Resilience research has widespread implications for social, ecological, and technological systems and applications. Resilience in psychology demonstrates ways to improve how individuals and groups respond to catastrophe in their lives, (Bonanno 2004) mental and physical disabilities, (Hauser 1999) and normal physiological processes such as aging (Resnick and Inguito 2011). Ecological resilience describes how ecological cycles of growth and collapse can influence environmental states (Holling 1978; Gunderson 2000; Folke et al. 2004; Hughes et al. 2003; Peterson, Allen, and Holling 1998). Socio-ecological resilience extends these concepts to include interactions between humans and environments in support of ecosystem management strategies (Adger 2000; Folke 2006; Folke et al. 2004; Carpenter et al. 2001). Resilience in engineering systems orient designers, operators, and crisis managers to better plan and prepare, absorb, recover, and adapt to unforeseen threats (Hollnagel, Woods, and Leveson 2006; Park et al. 2013). Although some researchers suggest that the resilience of a system can be indexed and measured, (Petit et al. 2012) others argue that because resilience is emergent from the states of a system it cannot be empirically assessed (Haimes 2009). The diversity of disciplines and research areas offer different perspectives (i.e., different ways of knowing and interpreting resilience) that contribute knowledge in accordance with their given areas of expertise. However, differences in vocabulary, boundaries, methods, and epistemologies, across these disciplines make it difficult to compare findings, translate knowledge among researchers, or support collaboration.

In applications like infrastructure, which include multiple interrelated and interconnected social, ecological, and technological systems, the need for integration of diverse concepts, definitions, and perspectives of people and coupled systems is particularly acute. Critical infrastructure is a good example because it presents an ensemble of interdependent complex systems such as power, water, transportation, and cyber-security (Alderson, Brown, and Carlyle 2014). These coupled systems interact with one another on multiple levels to deliver products and services deemed essential to public health, safety, and well-being (DHS 2013). For example, power requires water for cooling and water needs power to operate pumps and filtration systems (Bartos and Chester 2014). Both systems rely upon complex security and communication networks across heterogeneous spatial and temporal scales. However, direct contact between systems at an operational level is limited, and protocols for communication across operational boundaries are typically absent (Chang et al. 2014; Derrible 2016). Moreover, in addition to the complex physical and functional connections among systems, *people* are involved with every part of the power, water, and cyber-network systems from theory and conceptual development to design, operation and management.

The difficulties in comparing findings among complex systems may explain, in part, why the surge of resilience work across disciplines reveals that researchers and practitioners alike recommend taking a *holistic* approach to theoretical and applied resilience research (IPCC 2014b; Labaka, Hernantes, and Sarriegi 2016). However, research enacting a holistic approach to resilience is limited, and concepts of holism can vary among researchers, applications, and disciplines. A holistic approach to infrastructure resilience, for example, must incorporate a diversity of coupled complex systems while reconciling different research methods and perspectives. As such, a holistic framework of resilience research must accommodate the dynamic interactions between people, systems, and environmental contexts. This is difficult even within a single discipline such as psychology, where different researchers offer contrasting concepts of resilience focusing on individual internal capacities, (Connor 2006) external behavior, (Masten 2014b) embedded cultures, (Ungar 2006) and social systems in which people interact with one another like families (Walsh 2003) and communities (Zautra, Hall, and Murray 2008). Therefore, holistic approaches to psychological resilience research must be able to incorporate knowledge from each of these perspectives (Lipsitt and Demick 2012).

Applied to infrastructure, researchers describe a holistic perspective as a comprehensive consideration of systems—local and nonlocal—interdependent upon the system, or systems, under investigation, (Labaka, Hernantes, and Sarriegi 2015; Laugé, Hernantes, and Sarriegi 2015) which is true, but partial. The inclusion of multiple systems, for example, like power generation and water treatment in addition to exo-systems like institutions and policy regulations arguably does contribute to a more comprehensive understanding of resilient infrastructure. However, whereas holism includes both interior and exterior perspectives of people interacting with environments, (Esbjörn-Hargens and Zimmerman 2009) the inclusion of more system objects cannot account for the interior human perspectives like shared values, ethics, cultural beliefs, and worldviews (Wilber 2000a). Taken further, we argue that a holistic approach requires recognition of irreducible knowledge perspectives such as psychosocial versus behavioral capacities of people, and a holistic resilience research agenda will incorporate and compare these different ways of interpreting resilience.

In this work, we examine a holistic approach to resilience research and adapt the "Integral Map" (Esbjörn-Hargens 2010) as a framework for organizing resilience knowledge across disciplines and incorporating multiple perspectives. We use the Integral Map to organize a set of 20 highly cited resilience research articles to identify commonalities, differences, and potential gaps among perspectives. Given that incorporating multiple ways of knowing can contribute to a greater understanding of complex problems, (Miller et al. 2008; Martin 2008) we argue that a holistic approach to resilience research provides a logical and coherent way to incorporate diverse concepts, methods, and perspectives from diverse academic disciplines.

A holistic approach to resilience research

While policy documents such as Presidential Policy Directive 21 call for a "holistic" approach to building resilient infrastructure (The White House 2013) there is little policy guidance on the breadth of boundaries necessary to constitute holism. Although holism is an important consideration for complex systems like infrastructure, it is seldom discussed in the literature, and models of holistic research are rare. As a result, researchers have little to guide their holistic intensions, and references to the term *holistic* or *holism* often lack sufficient definition, context, or specificity to clarify a common meaning that can be recognized across disciplines. Thus, to understand a holistic approach to resilience research, we must first clarify how we interpret holism.

What is holism?

There are multiple definitions and concepts of holism in the literature. Overton (2013) describes holism as the inclusion of all subjects, objects, and events in addition to the relationships among them. That is, holism includes the interconnectedness and interrelatedness among people, systems, and the environmental contexts within which they are embedded. Although this description lacks detail about the nature of the relationships, others are more specific. Cardona (2003) argues that a holistic understanding of risk and vulnerability in relation to disaster events includes multiple interrelated subjective and objective factors among social, economic, and environmental impacts. In contrast to

Overton, Cardona argues a holistic perspective must also include internal (i.e., human interior) properties, capacities, and vulnerabilities (e.g., values, ethics, and worldviews) to increase the effectiveness of risk management (Cardona 2003). Thus, a holistic understanding elucidates how risks and vulnerability can be unevenly distributed over a region or a population according to factors related to the individual and group interiors of people.

Koestler (1970) suggests that holism considers how each part of a system exist in relation to other parts, both as a whole, and as a part of a larger whole. Koestler used the term 'holon' as a unit of holistic analysis characterized by its relationships among other parts. The metaphor of Russian dolls nested one inside of the other and forming hierarchal structures of increasing complexity is sometimes used to describe the concept of holons (Koestler 1970). In other words, holons may be viewed as nested structures of complexity representing distinct "wholes" that are made up of equally whole parts (Esbjörn-Hargens and Zimmerman 2009). As a unit of analysis, a holon can be an object such as a power plant, a person such as an operator, or research topic such as critical infrastructure resilience that includes people and technology. Moreover, there are social holons (e.g., families, communities, region, state, and nation), organismic holons (e.g., atoms, molecules, cells, organisms), ecological holons (e.g., soil, foliage, insects, birds), and technical holons (e.g., microprocessors, circuit boards, computers, and networks). Although the above definitions and concepts of holism are helpful, there is no apparent method or operational guidance in Koestler's definitions for enacting a holistic approach to research that includes both people and systems.

Applications of holistic research

There are limited examples of applied holistic research in the literature. Labaka (2016) argues that a holistic approach to critical infrastructure is one that includes technical, organizational, economic, and social domains, in addition to external agents influencing them. These four domains help clarify boundary conditions of the units or systems of consideration and determine what variables are included. The holistic framework proposed by Labaka offers a thorough and comprehensive consideration of the exterior properties, processes, and systems impacting critical infrastructure in addition to a wide range of stakeholders. However, the social domain is focused on operating policy, and there is no consideration for the impact and influence of the interior properties or processes of human dynamics such as value systems, group adaptive capacity, culture, or political ideology.

Lauge (2015) presents a holistic approach to understanding critical infrastructure dependencies, by collecting comprehensive surveys representing 11 system operators (e.g., energy, water, and transport) across Europe, North America, and Asia. The holistic approach described in the study considers the impacts on each system in response to potential impacts on the other systems. However, none of the 11 infrastructures represented people or social systems. Yet people are embedded in each, and differences among responses reflect the complex dynamics of individuals and social systems interacting with technological systems.

Anti-holism

Redman & Miller (2015) consider a comprehensive inclusion of social, ecological, and technological systems sufficient to explain resilience, without endeavoring to broaden the boundaries of analysis to be holistic. That is, a systems perspective of the dynamic interactions that describe how resilience and vulnerability cascades across social, ecological, and technological systems are considered adequate for applications like infrastructure. Others reject holism outright as "technocrat's dreams" (Sarewitz 2010) that will never be achieved. This argument claims we need only to know about a few specific things, rather than everything, thus reducing information requirements to practical levels. However, these parochial arguments are inadequate or inapplicable to infrastructure resilience. It should be clear that human factors such as individual agency and subjective well-being can influence human resilience to environmental change (Brown and Westaway 2011; Nelson, Adger, and Brown 2007). Moreover, resilience and adaptive capacity contrast with risk-based perspectives focused on empirical objectivism (Park et al. 2013). Thus, both interior and exterior properties and processes of resilience contribute toward a holistic perspective of people and systems. Without consideration for a range of human dynamics such as culture, ethics, and values, even a systems perspective to understanding resilience is partial and reductionist. That is, people and infrastructure are interrelated and interconnected complex systems, so they must be incorporated.

Another approach to holism

Integral theory presents a comprehensive holistic framework for organizing a diversity of knowledge in a meaningful and coherent manner (Wilber 2000b). The theory posits that there are four fundamental perspectives that are always present, and cannot be reduced any further (Esbjörn-Hargens 2010). These perspectives, which may be combined to form a holistic approach, embody two epistemological distinctions of how knowledge may be considered. The first distinction is between interior and exterior, and the second distinction is between singular and plural. The four perspectives are individual interior (I), group interior (we), individual exterior (it), and group exterior (its). The interior refers to the intangible properties and processes that cannot be identified by the physical senses(O'Brien and

Hochachka 2010) like psychological and emotional capacities. The exterior refers to the objective, physical properties, processes, and interactions that can be observed and measured like social structures, technical systems, and the natural environment. The four perspectives appear in linguistic structures, which are used to construct, communicate, and interpret meaning, knowledge, and experience. Thus, Integral theory suggests that the four perspectives correspond to four pronouns in the English language:

- Subjective: 'I' (individual interior)
- Intersubjective: 'we' (group interior)
- Objective: 'it' (individual exterior),
- Interobjective: 'its' (group exterior).

Moreover, Integral theory argues that the four irreducible perspectives, summarized as 'I', 'we,' 'it,' and 'its,' are fundamental to any inquiry,(Esbjörn-Hargens 2010) and a holistic understanding must include representative knowledge from each perspective without favoring one over another (Wilber 2000b). Therefore, an Integral approach to research seeks to identify what perspectives are included, or not, in a given research investigation by organizing knowledge, epistemologies, and methods (Cook-Greuter 2005). Numerous researchers have applied Integral theory to other holistic research programs. Examples include developmental psychology, (Cook-Greuter 2005) ecology, (Esbjörn-Hargens and Zimmerman 2009) education, (Crittendon 2007) and sustainability (Floyd and Zubevich 2010). Although holistic approach to research includes both epistemological and ontological diversity in each of the four quadrants of the Integral Map, this work is focused on epistemological perspectives of resilience representing different ways of knowing.

The characteristic method for a holistic organization of knowledge with an Integral approach is through use an Integral Map as shown in Figure 4. The quadrants represent the interior and exterior of individual and collective human perspectives (Wilber 2000c). An Integral Map can be applied to any phenomena or unit of investigation (e.g., resilience research) whereby related knowledge is assembled in a structure of four perspectives corresponding to experience ('I'), culture ('we'), behavior ('it'), and systems ('its') (Esbjörn-Hargens 2010). The framework provides a holistic structure for research by incorporating different ways of knowing, methods, and tools from each of the four perspectives. This means an Integral Map can help differentiate among research perspectives, (Martin 2008) and provides a clear and systematic method of determining what knowledge is present in a given investigation (Cook-Greuter 2005). Thus, an Integral approach can be helpful in identifying gaps among diverse perspectives in existing research. Moreover, the Integral Map is content-free, i.e., it does not add any new information to the research question or initiative in consideration. Instead, it distinguishes among perspectives and identifies which ones are represented or not. Taken together, the four quadrants of the Integral Map combine to support a mixed-methods approach to research (Esbjörn-Hargens 2006) by incorporating multiple ways of knowing to interrogate a research question or investigation. A holistic approach to research will include perspectives from all quadrants, thereby representing each of the four fundamental perspectives corresponding to different ways of knowing. With an Integral approach to holism, no research knowledge or method is given preference over another, and all perspectives are allowed equal consideration.

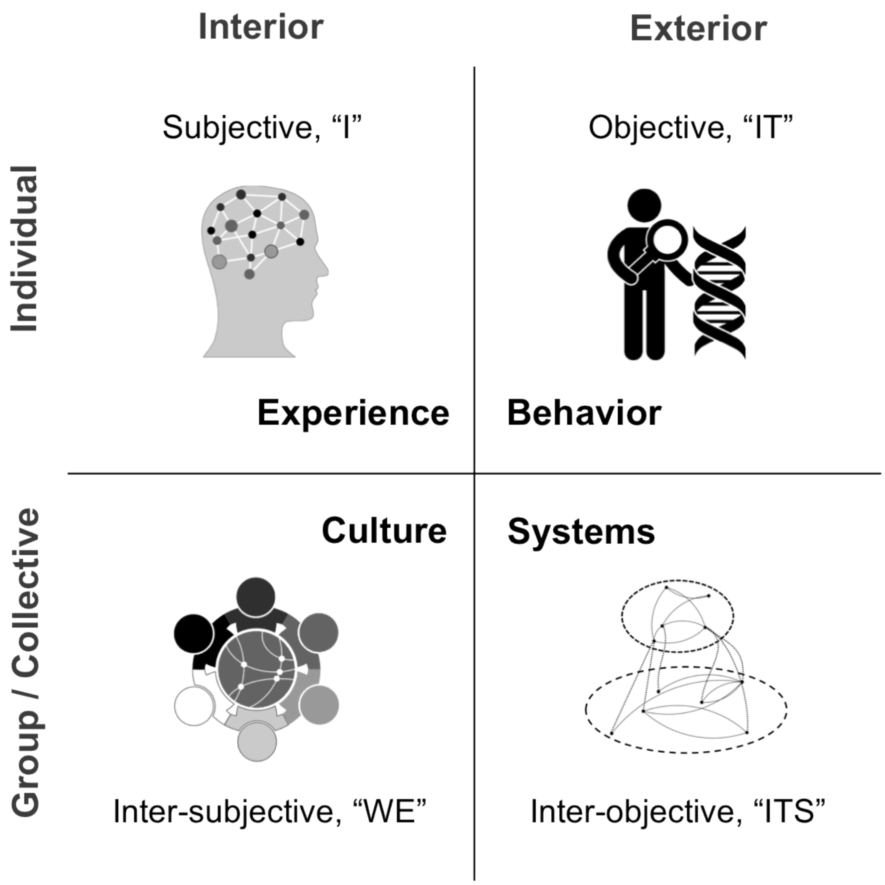

Figure 4 Integral map of human perspectives
The four quadrants represent four fundamental ways of knowing: 1) individual 1st person subjective experience; 2) group 2nd person shared culture; 3) individual objective 3rd person behavior; 4) interobjective 3rd person (plural) social, ecological, and technological systems. The four quadrants are concomitant, and represent distinct epistemological orientations or ways of knowing. Adapted (Wilber 2000b; Esbjörn-Hargens 2010).

An Integral Map may be used, for example, to assess an individual's different ways of knowing, interacting with, and experiencing a given phenomena. The *experience* quadrant in Figure 4 (upper left) identifies interior awareness represented by a subjective 'I' perspective. Knowledge in the experience quadrant includes factors such as cognition, affect, and psychological maturity. The *behavior* quadrant (upper right) identifies exterior awareness represented by an objective 'it' perspective. In the behavior quadrant, knowledge includes individual actions, physical properties, and artifacts. The *culture* quadrant (lower left) is a collective interior of shared human awareness represented by the intersubjective 'we' perspective. Knowledge in the culture quadrant includes factors such as shared values, ethics, and worldviews. The *systems* quadrant (lower right) identifies a collective exterior awareness. Sample knowledge in the systems quadrant includes dynamic interactions between and among complex social, ecological, and technological systems. Thus, an Integral Map offers a structure and process to organize a holistic approach to research.

Why holism?

There are two key reasons why a holistic approach to research is needed. First, in addition to a comprehensive consideration of physical properties and interactions, a holistic approach also includes the human interiors influencing and impacting relationships among coupled systems. The interior may be viewed as subjective in nature and can include factors such as ethics and culture (Cardona 2003). The term subjective is used here to refer to individual's personal experience that cannot be directly observed or measured (Diener 2000) and can influence adaptive capacity (Adger et al. 2009). In contrast, the exterior is objective in nature and can include factors such as operating policies and system attributes (Madni and Jackson 2009) that can be observed and measured. Second, current methods that rely on systems theory to examine the interactions of people and technological systems are not only insufficient, but they are not capable of incorporating the interior characteristics of people. This is because a systems-only approach considers human subjects as objects, (Wilber 2000a) and therefore excludes any form of interiority, which is a form of reductionism. Although a systems perspective contributes valuable insights about how infrastructures function and interact in complex ways, (Alderson, Brown, and Carlyle 2015) holism incorporates the interiority of people (Esbjörn-Hargens and Zimmerman 2009) included in coupled complex systems.

The ability to respond to disruptions affecting communications and mitigation efforts during the critical early stages of disasters offers contrasting examples of the potential impacts of human interiors on coupled complex systems. On the one hand, disasters like the Fukushima power plant show how basic assumptions about safety (e.g. tacit cultural beliefs, attitudes, and perceptions) held by workers and government officials can impact disaster recovery (Hollnagel and Fujita 2013). The safety culture before the disaster, which was based on inaccurate assumptions, led to diminished authority and poor decision making that delayed critical disclosures and compromised safety and recovery efforts (IAEA 2015). On the other hand, disasters like the Christchurch earthquake exemplify how community members experiencing shared vulnerabilities responded (i.e. exterior actions) with a collective capacity to rapidly innovate and self-organize (Hayward 2013). A group of college students used social media to quickly form a large volunteer force, which grew from hundreds to thousands, to support and coordinate resources amid multiple infrastructure failures (Hayward 2013). Thus, a holistic approach to understanding a given whole unit of consideration (i.e. a holon) such as the resilience of a power plant in response to a natural disaster will incorporate both interior and exterior perspectives linking the dynamic relationships between people and complex systems.

A key factor emphasized in the holistic approach described by Overton (2013) is that individual parts of systems (e.g., subjects, objects, components, or subsystems) must be considered within the functional (i.e., relational) and environmental context of the whole system, or systems, to which they belong. The significance here is that systems information is only meaningful in relation to functional and environmental context. More importantly for the work herein, systems theory cannot account for functional or relational interiority of people as parts of systems. As a result, important information related to a holistic approach to the resilience of complex systems like infrastructure could be excluded. This means a holistic approach to resilience research must include the interior and exterior dynamics of people embedded as systems, system components, and end-users. Thus, complex systems involving people and infrastructure require a holistic framework capable of accommodating multiple definitions, disciplines, functions, and perspectives of resilience.

Why a holistic approach with an Integral map?

Despite the Integral framework's separation between quadrants, a holistic approach can combine different perspectives or ways of knowing by incorporating multiple epistemologies in relation to a common research question or unit of investigation. This is because the quadrants on the Integral Map representing *experience*, *culture*, *behavior*, and *systems* are concomitant perspectives, which means they occur together in mutuality. Thus, the framework provides a means of investigating the interrelatedness among perspectives, which can support comparison, correlation, and potential linking of knowledge claims investigating the same or similar resilience phenomena. The ability to incorporate multiple perspectives in a single framework means resilience concepts once considered as conflicting may be complimentary or even mutually informing when viewed with a holistic approach through an Integral lens. Moreover, conflicts may be better understood when different concepts and definitions are considered with regard to the interior and exterior of individual and collective perspectives corresponding to the quadrants of an Integral Map. For example, whereas child psychology describes resilience as observable processes representing positive adaptation amid adversity, (Masten 2001) some researchers view human resilience in terms of interior characteristics or properties such as self-esteem or the ability to cope (Bonanno 2004; Connor 2006). The distinction between interior qualitative and exterior quantitative properties and processes has been the subject of debate in the psychology resilience literature for many years (Alexander 2013; Masten 2001). With a holistic approach, both perspectives contribute valuable information about individual human resilience and indicate how interior properties of individual experience or group culture may relate to or influence exterior behavior and dynamic interactions among coupled complex systems.

The recognition that each quadrant of the Integral Map contributes irreducible information to holism (Esbjörn-Hargens and Zimmerman 2009) may help resolve differences between perspectives arguing one view over another. This is because each of the four perspectives co-exist in mutuality within a holistic framework without a need to reduce or marginalize other perspectives to establish its claims. Although a holistic approach incorporates perspectives from all four quadrants, it does not mean that all research articles or investigations should consider all four quadrants. Research in each quadrant offers a distinct way of knowing and interpreting resilience that can contribute valuable knowledge toward a holistic view. However, with regard to holism, it is important to understand how resilience concepts, definitions, and paradigms align within a holistic framework like the Integral Map. This approach can guide researchers to ascertain what perspectives are included or excluded with a given investigation while offering new research questions about potential relationships between otherwise differing resilience perspectives. Thus, a holistic approach with the Integral Map helps ensure multiple ways of knowing are considered to provide the most complete, comprehensive, and holistic understanding of resilience possible. This could inform resilience research initiatives seeking a comprehensive approach to integrating perspectives from multiple disciplines.

Holistic resilience research assessment

The absence of a common interdisciplinary framework for organizing and linking resilience research inhibits opportunities to extend learning beyond isolated academic boundaries. As a result, disparate disciplines like engineering and psychology lack a structure or means of informing one another's concepts and findings by incorporating multiple perspectives. This, in turn, precludes a larger, more holistic, transdisciplinary understanding of resilience by privileging some perspectives while marginalizing others. To address this gap, we apply a holistic approach to resilience research and use an Integral Map to organize research literature according to perspectives corresponding with the quadrants. We then demonstrate how an Integral Map can serve as a guide for assessing holism, and designing a holistic approach to resilience research.

Method

To apply the Integral Map and organize resilience research perspectives, we identified the most cited publications that resulted from a Web of Science literature search for the terms "resilient," "resilience," *or* "resiliency" in the title. A total of 15,574 publications resulted, spanning 115 years (1900 – 2015). No other search terms or field limitations were applied to capture publications from a wide range of subjects—technology to natural and social sciences—and a variety of sources including peer-reviewed journal publications and conference proceedings. We selected the top 20 articles from the search with the largest number of citations as a representation of those that have been most influential. The 20 articles were grouped into six research areas as judged by title, abstract, and publication journal: adult psychology, child psychology, ecology, neuroscience, socio-ecological systems, and technology. We reviewed each article to assess how it aligned with knowledge perspectives and examples associated with the four quadrants of the Integral Map. To accomplish this we adapted the heuristic shown in Figure 5 and modified it to include example ways of knowing and properties of resilience corresponding to experience, culture, behavior, and systems.

Perspective—Individual Interior *Subjective (1st-person, 'I', 'me')* Focus on individual interior experience, resources, and phenomena. Examples • Cognitive capacity, • Affect (emotional intelligence) • Moral capacity • Psychological development • Individual beliefs and attitudes • Individual knowledge & skills Resilience: self-esteem, locus of control, stress response, emotional adaptation. **Experience**	**Perspective—Individual Exterior** *Objective (3rd-person singular, 'it')* Focus on individual exterior behavior, structure, functions, and phenomena. Examples • Individual characteristics and measures (person/technology/environment) • Individual actions & behaviors • Individual structures & functions • Individual interacting with environment • Characteristics of individuals/components Resilience: sensing, anticipating, adapting, and learning, individual capacity to absorb & recover. **Behavior**
Culture **Perspective—Collective Interior** *The inter-subjective (2nd-person, you, we)* Focus on group interior culture, organizational & political ideology, resources, and phenomena. Examples • Shared values & beliefs • Culture, customs, & lifestyle • Interpersonal communication • Ethics & worldviews • Religious views Resilience: social cohesion, community ability to cope, self-organize, & community efficacy.	**Systems** **Perspective—Collective Exterior** *The inter-objective (3rd-person plural, 'Its')* Focus on group exterior systems, dynamic interactions, structures, functions, and phenomena. Examples • Interactions within and among systems • Systems functions and structures • Economic & geopolitical structures • Social, ecological, and technological systems • Socio-ecological & socio-technical systems Resilience: sensing, anticipating, adapting, and learning, robust, capacity to absorb & recover.

Figure 5 An Integral heuristic representing human perspectives and resilience concepts.
The heuristic is a synthesis of multiple works (Esbjörn-Hargens and Zimmerman 2009; Wilber 2000b; Cook-Greuter 2005) and modified for this exercise to include example resilience indicators for each quadrant.

Results

We applied the heuristic (Figure 5) to each article to identify perspectives, arguments, research methods, and claims that align with the items listed in the experience, behavior, culture, and systems quadrants. The process of reviewing the articles and assessing the dominant perspectives of each was based on the opinion of the three co-authors. Although other readers may disagree with our assignments, the results (Table 4) will nevertheless reveal that intersubjectivity is underrepresented in the highly cited resilience literature.

Experience

Articles assigned to the experience quadrant of the Integral Map are focused on the interior characteristics of individual people. Thus, in the experience quadrant, the holon is an individual human being. Perspectives in this quadrant align with factors such as cognitive capacity, affect, moral maturity, psychological development, and individual beliefs and attitudes. The interior factors related to human resilience including constructs like self-esteem, locus of control, stress response, and emotional adaptation represent perspectives characterized by the experience quadrant of the Integral Map. Articles from two research areas were assigned to this quadrant as shown in Table 4. In the area of adult psychology, four articles represent perspectives associated with the experience quadrant (Connor and Davidson 2003; M. Tugade and Fredrickson 2004; Fredrickson et al. 2003; Bonanno 2004). These articles identify qualitative properties of constructs such as hardiness and self-enhancement that correlate with resilience of people faced with adversity. Likewise, three child psychology articles (Rutter 1987; Luthar, Cicchetti, and Becker 2000; Rutter 1985) represent perspectives of individual properties—a.k.a. variables or characteristics—related to human resilience like self-esteem and self-efficacy. A total of seven articles were assigned to the experience quadrant.

Behavior

The articles that we assess to align with the behavior quadrant represent perspectives that emphasize physical and empirical concepts. The holon in this quadrant could be a person (if examined exclusively as an object, like an economic agent), a technical device, or an element of the environment. Other characteristics of this quadrant include actions, behaviors, structures, and functions of individual holons. Articles from three research areas were assigned to the behavior quadrant. First, we assessed one article in adult psychology (M.

Tugade and Fredrickson 2004) to align with both the experience *and* behavior quadrants of the Integral Map as shown in Table 4. This could include, for example, psychological characteristics corresponding to the experience quadrant and individual actions related to the behavior quadrant. Likewise, three articles in child psychology are assigned to both the experience and behavior quadrants. Luthar et al. (2000) and Rutter (1985; 1987) each describe variations of behavioral processes (mechanisms) such as age-salient tasks completion or positive adaptation to social and environmental conditions such as the early loss of parents. The fourth child psychology article (Masten 2001) represents a perspective focused on objective properties and behavioral processes that align with the behavior quadrant. A single article in the physical sciences presents the detailed study of neurological networks (Achard 2006) that aligns with the behavior quadrant.

Table 4 The Integral heuristic applied to 20 highly cited resilience journal articles. Articles are grouped by research area and listed by author name and year of publication. Articles representing multiple perspectives (e.g., experience and behavior) are listed in the corresponding quadrants and identified with an * symbol.

Experience **Adult Psychology** (Bonanno 2004) (Connor and Davidson 2003) * (Tugade, 2004) (Fredrickson et al. 2003) **Child Psychology** * (Luthar, Cicchetti, and Becker 2000) * (Rutter 1987) * (Rutter 1985)	**Behavior** **Adult Psychology** * (Tugade, 2004) **Neuroscience** (Achard 2006) **Child Psychology** * (Luthar, Cicchetti, and Becker 2000) (Masten 2001) * (Rutter 1987) * (Rutter 1985)
Culture *No articles were assigned to this quadrant.*	**Systems** **Ecology** (Hughes et al. 2003) (Folke et al. 2004) (Gunderson 2000) (Peterson, Allen, and Holling 1998)

Culture	**Systems**
The authors recommend the following articles: (Adger et al. 2009) (Brown and Westaway 2011) (O. Cardona 2003) (Cutter and Emrich 2006) (Masten 2014a) (Norris et al. 2008)	**Socio-ecological Systems** (Folke 2006) (Walker et al., 2004) (Carpenter et al. 2001) (Adger 2000) (Olsson, Folke, and Berkes 2004) **Technology** (Cohen et al. 2000) (Zhao et al. 2004)

Systems

Articles assigned to the systems quadrant of the Integral Map align with perspectives related to physical and functional interactions among two or more of the holons identified in the *behavior* quadrant. Example perspectives include social, ecological, and technological system functions, interactions, and structures in addition to economic and geo-political systems. Perspectives in this quadrant describe the properties and processes of coupled systems that enhance their capacity to adapt to unexpected changes by adjusting performance. Eleven of the 20 articles reviewed represent the properties and processes corresponding to systems perspectives found in the systems quadrant. Here, there are four articles in the area of ecology, (Peterson, Allen, and Holling 1998; Gunderson 2000; Hughes et al. 2003; Folke et al. 2004) five articles in the area of social-ecological systems, (Adger 2000; Carpenter et al. 2001; Folke 2006; Walker et al. 2004; Olsson, Folke, and Berkes 2004) and two articles in the area of technology (Cohen et al. 2000; Zhao et al. 2004). Thus, in contrast to child and adult psychology, which includes articles representing both interior and exterior individual perspectives, resilience research focused on systems does not include perspectives corresponding to the culture quadrants among the top cited articles.

Culture

There were no articles assigned to the culture quadrant. Perspectives that align with this quadrant describe a group or collective interior. These are the intersubjective experiences of groups such as working teams and families, organizations that operate and manage infrastructure, and institutions that set policy and oversee regulations. Perspectives assigned to the culture quadrant correspond to factors such as shared values, beliefs, cultural norms, ethics, religious views, and worldviews. Together these properties represent the collective interior that shapes intentionality and motivation influencing collective exterior actions and behavior in the systems quadrant. However, the absence of a single article in the culture quadrant indicates papers addressing group interior perspectives of resilience are cited less often. Thus, although research suggest a linkage between collective interior factors influencing resilience (e.g., values, ethics, and culture) and ecological, (Nelson, Adger, and Brown 2007) social-ecological, (Adger et al. 2009) and technological (Madni and Jackson 2009) systems, resilience perspectives related to cultural factors are not represented among the top 20 search articles. Nonetheless, factors related to a collective interior of a group, community, or urban region may inform perspectives on resilience and adaptive capacity (Cardona et al. 2012; Brown and Westaway 2011) in response to large-scale disasters such as Hurricane Katrina or the Fukushima power plant disaster.

Discussion

A holistic approach to resilience research will benefit from including both individual and group interior perspectives in addition to exterior perspectives focused on behavior and physical systems. Individual interior perspectives corresponding to experience are well represented among the top cited articles that we reviewed. Critical infrastructure literature (Hollnagel et al. 2011; Hollnagel 2014; Woods 2015; Righi, Saurin, and Wachs 2015) provides examples that align with the systems quadrant. However, resilience engineering knowledge corresponding to perspectives aligning with the culture quadrant is scarce. The multidimensional nature of resilience in complex socio-ecological (Brown and Westaway 2011) and socio-technical (Smith and Stirling 2008) systems includes irreducible knowledge representing both subjective *and* objective human perspectives. Thus, without consideration for the interior perspectives of individuals, working groups, communities, and organizations, important information that could impact critical infrastructure resilience could be missed. Examples of group interior perspectives that may contribute toward a holistic perspective of infrastructure resilience include research areas such as *community resilience* and *social vulnerability* in response to natural or man-made disasters.

Community resilience

Norris and Stevens (2007) consider hope and shared subjective interpretations of health and safety as important factors related to community resilience in a disaster scenario. These factors can influence infrastructure resilience because the people involved with the design, operation, and management of critical infrastructure are members of working groups, communities, and organizations. Whereas the built environment contributes to public health, safety, and well-being, (DHS 2013) community resilience and infrastructure are interrelated (Berkes and Ross 2013). Norris et al.(2008) argues that community resilience emerges from linking the adaptive capacities of community members and resources, and includes factors such as collective efficacy and empowerment. A sense of connectedness among family members, partners, and close attachment groups can also influence social responses like positive collective action and community restoration in response to mass-trama (Norris and Stevens 2007). In addition, concepts of community resilience are relevant to system shocks on both short and long-term time scales. Masten (2014a) and Ungar (2013) suggest understanding psychological resilience in a cultural context may help explain differences in adaptive capacity among diverse populations that could have important implications for short-term events like disaster management and recovery. Adger et al. (2009) considers the potential limitations of a society's ability to adapt to long-term events like climate change are due to factors related to the social interior such as ethics, beliefs, attitudes, and culture. Moreover, the limits are viewed as fundamentally subjective in nature that can change with location, time, and context. This means cultural assets may have unique place in shaping attitudes and values inside of social systems and may thereby influence how shocks like climate change are experienced among diverse populations (Adger et al. 2009). How people interpret and assign meaning to experience of disaster events will partially determine how risks and vulnerability are distributed among populations embedded within, and interdependent upon, critical infrastructure.

Social vulnerability

Numerous researchers refer to the subjective properties of risks, vulnerability, and resilience of people in relation to factors such as climate change (Adger et al. 2009; Brown and Westaway 2011) and disaster risk management (Cutter, Burton, and Emrich 2010; Cardona 2003). Adger (2009) argues that the underlying social values, ethics, and cultural interpretations about risks and vulnerability among populations impact how people respond to climate change. This means the actions and behaviors of individuals, groups, and even whole societies are influenced by factors such as beliefs, perceptions, and shared meanings. Although the capacity to adapt to uncertain conditions is partly dependent on technological systems and human behaviors, the ethics of how vulnerable people are impacted and influenced by social structures responsible for decision-making sets limits to adaptation. Thus, vulnerability and adaptive capacity are determined in part by the subjective characteristics of the social systems they belong to (Adger et al. 2009). Additionally, Adger, Brown & Westway (2011) argue that understanding how people impact and respond to environmental change requires consideration of the subjective human characteristics that influence behavior. These factors include the psychosocial properties affecting human agency, resilience, and the ability to cope with uncertainty amid disruptive change. The variation of societal factors among populations means risks, vulnerability, and adaptive capacity are often unevenly distributed across regions and social groups. Cutter and Emrich (2006) suggest social vulnerability is based on the characteristics of the people embedded within a given region or population, which may vary according a variety of indicators such as poverty, race, and social inequality. This means applications like critical infrastructure resilience can be influenced by factors such as social coherence and cultural interpretations of risks and vulnerability, which can lead to different experiences by different social groups. Hurricane Katrina was a vivid example of how social vulnerability to hazards can be unevenly distributed among population groups and across spatial regions, and how inequalities can amplify impacts (Cutter and Emrich 2006). This was evident in that many individuals with access to resources were able to mitigate losses and evacuate the region before the hurricane hit. Others, with no option to leave and minimal resources faced dire circumstances. Many of the differences in exposure, impact, and recovery pathways were directly related to social inequalities (Cutter and Emrich 2006).

Cardona (2003) proposes a holistic perspective of risks and vulnerability, which he defines as 'internal' risk factors that are partly determined by the subjective characteristics of people and social groups. By this definition, vulnerability can vary according to the collective understanding and interpretation of risks by different people and organizations that could either enhance or diminish potential mitigation efforts and disaster management strategies.

Thus, similar to perspectives described above on climate change, the capacity of a person or group to adapt to a sudden or unexpected change in their environment represents a subjective context that can influence how disaster events are experienced and managed (Cardona 2003). This means the interior characteristics of people can impact how they interact with technology, and therefore influence the resilience of coupled complex systems like infrastructure. Finally, Cardona (2003) emphasizes that risk management is dependent on how risks and vulnerability are perceived and interpreted by society and by social groups. That is, how people define their worldview and make meaning of experience and environmental conditions could be an important consideration in disaster management scenarios. In addition to the above, research in other areas including psychology (Masten 2014a; Ungar 2012), ecology (Esbjörn-Hargens and Zimmerman 2009), socio-ecological systems (Stokols, Lejano, and Hipp 2013), and socio-technical systems (Smith and Stirling 2008) provide examples of why cultural perspectives representing the collective interior of people and environments are relevant to a holistic approach to resilience research.

Conclusion

Resilience is relevant to a wide variety of applications ranging from psychological health and well-being (Bonanno 2004) to regime shifts in ecological systems (Folke et al. 2004) and critical infrastructure operations (Alderson, Brown, and Carlyle 2014). However, the heterogeneous nature of resilience knowledge among academic disciplines means definitions and concepts are often incongruent with one another, which can lead to partial solutions of complex resilience problems. Moreover, without a framework for integrating disparate resilience perspectives, a holistic understanding of resilience will remain elusive. In this work we examined holism and applied the Integral Map as a holistic framework for organizing 20 resilience research articles with the largest number of citations. Our results indicate that articles reflecting collective interior perspectives of resilience are not represented in the top cited publications. These results suggests that research including factors such as cultural beliefs, shared values, and ethics will contribute to a more holistic understanding of the resilience of complex systems like infrastructure. Thus, we argue that a holistic approach to organizing resilience research by epistemological perspective with tools like the Integral Map offer a simple, logical, and coherent way to include multiple perspectives. With a clear distinction among perspectives, disparate resilience concepts can be examined to determine how they may be interrelated and mutually informing. In sum, a holistic approach to resilience research must include both objective *and* subjective perspectives of the properties and processes that enable people and coupled complex systems to cope with unanticipated disruptions and adapt to change.

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CHAPTER 3

INTEGRATING HUMAN AND TECHNICAL RESILIENCE CAPACITIES WITH SOCIO-TECHNICAL PROCESSES

Introduction

Humans can have either a positive or negative influence on the resilience of engineered systems like infrastructure. The catastrophic system failure at the Fukushima nuclear power plant in 2011 was partly because of the inability of people to accurately anticipate key design constraints related to risk perception and mitigation (Hollnagel and Fujita 2013). In subsequent investigations, the flawed design was largely attributed to a working culture that supported false shared assumptions about safety (IAEA 2015). These concerns combined with the inability to deploy key mitigation assets due a complete loss of power considered *unthinkable* prior to the accident (Hollnagel and Fujita 2013) show how humans can negatively impact technical system resilience. In contrast to the Fukushima disaster, the successful ditching of U.S. Airways flight No. 1549 in the Hudson River in 2009 demonstrates how humans can have positive influence on catastrophic system failures (Paries 2011). After losing thrust in both engines at an altitude of 2,800 feet barely two minutes after takeoff from La Guardia, the captain's decisions 1) not to return to the airport, 2) to turn on the auxiliary power unit, and 3) to abandon the dual engine checklist were critical actions that contributed to the successful outcome without a single fatality (NTSB 2010). Moreover, the captain's capacity to *cope* with extreme ambiguity while maintaining a psychological locus of *control* enabled him to rapidly assess the conditions and make critical decisions, in part, by intuition and felt-experience (Sullenberger and Zaslow 2009). In the psychology literature, coping involves adopting new perspectives of adverse events to benefit one's values and beliefs thereby supporting feelings of control (Folkman and Moskowitz 2004); A locus of control affords access to the ability to make decisions and take action amid adversity by governing internal psychological and emotional resources (Bonanno, Papa, and O'Neill 2001). Each of these capacities—coping and control—reflect aspects of human intention, imagination, and motivation representing the ability to anticipate possible adaptive pathways. Thus, in the two failures described above humans had a direct impact on the resilience and adaptive capacity of infrastructure that cannot be conceived of, or reproduced in engineered systems alone.

Engineered systems are dependent on human society for their design, operation, and maintenance, and human society is dependent on engineered systems to provide vital public services. Engineered systems include physical and functional infrastructures such as water treatment, energy production, and cybersecurity that are critical to public health, safety, and well-being (DHS 2013). Infrastructures like these are designed, maintained, and operated by people that determine the meaning and value of the products and services provided (Holling and Gunderson 2002), which means critical infrastructures and human stakeholders are interconnected and interdependent on one another (Laugé, Hernantes, and Sarriegi 2015). Moreover, the duality between human actions to operate and maintain technology, and the functional integrity of engineered systems to sustain a quality of living for people, reveals a reciprocal relationship between human and infrastructure systems. Although each system can be impacted by disruptive events, a shift in adaptive capacity of one system can have a direct or cascading impact on the adaptive capacity of the other (Woods and Branlat 2011). That is, each system can potentially impact and influence the resilience of the other. This explains, in part, why it is important to consider the interdependencies between people and critical infrastructures, especially for urban areas prone to large-scale disaster events (Masten and

Obradovic 2010) like hurricanes and earthquakes. The reason is because infrastructure systems are products of human intention (Park et al. 2013). The resilience of engineered systems is therefore dependent on the dynamic processes representing the interactions between people and technology (Hollnagel 2014). These processes involve the capacity of humans to interact in complex and unpredictable ways with engineered systems.

Aiming to learn from prior disaster events like 9/11 and Hurricane Katrina, and intent on improving the ability to plan, prepare, and respond to ongoing natural and man-made threats, the Federal government enacted numerous policy directives toward U.S. infrastructure security and resilience (DHS 2009; DHS 2013; The White House 2013). Although the directives are explicit about an integrated approach that incorporates interdependent systems, people are not identified as components of infrastructure. Presidential Policy Directive 21 (PPD-21) addresses the dependency of national security and well-being on critical infrastructure that underpins American society (The White House 2013). While the document makes strong arguments for certain vital benefits of infrastructure, there is no attention to how the resilience of people may contribute to the resilience of coupled interdependent systems. Moreover, PPD-21 directs national policy on critical infrastructure security and resilience across Federal, state, and local entities including public and private infrastructure owners and operators, the directive does not provide a guideline to follow or a mechanism to address the interdependencies of human and infrastructure resilience.

In response to PPD-21, the Department of Homeland Security created the National Infrastructure Protection Plan (NIPP) 2013 as a guide to managing risks with plan implementation left to regional and private owners and operators on a volunteer basis (DHS 2013). NIPP 2013 names 16 sectors of critical infrastructure (e.g. communications, energy, government facilities, and transportation systems) that group products and services representing multiple systems and components according to their dominant structural and functional properties. Each sector is assigned to a government agency tasked with coordinating partnerships with the industry stakeholders to enhance the effectiveness of critical infrastructure risk management. However, while the NIPP acknowledges that threat prevention, recovery, and mitigation requires close coordination of collaborative partnerships between public and private interests (DHS 2013), the document fails to consider how humans can impact infrastructure resilience. Although the NIPP emphasizes that critical infrastructure security and resilience is essential to national well-being, there is no reference or description explaining what that means, or how it may be applied to people. In particular, how it may apply to the people in direct interaction with infrastructure like designers, operators, and maintenance workers. Furthermore, although the document identifies humans as a key element of a risk framework, there is no consideration for integrating people as dynamic components of infrastructure systems capable of influencing resilience processes and outcomes. Given that humans are dynamically coupled with infrastructure, a comprehensive approach to risk management must consider how knowledge of human resilience may inform knowledge and perspectives of infrastructure resilience. While NIPP 2013 goes to great length to specify critical infrastructure risk factors, policy guidelines, and operating environments and outlines specific calls to action, there is no mention of the roles or impact that the resilience of people may have in the process. To address this gap, we apply concepts from resilience engineering and psychology to relate the resilience capacities of a person to the resilience capacities of a technical system.

Resilience engineering presents an alternative paradigm for managing safety in socio-technical systems by focusing on what makes such systems work in a given operational context versus what causes them fail (Righi, Saurin, and Wachs 2015). This means that in addition to learning from what has happened in the past, resilience engineering engages human imagination to consider what may happen in the future. When applied to applications like the built environment, resilience engineering posits that socio-technical systems work because people can adjust their behavior and modify how they interact with technical systems as conditions change (Hollnagel 2014). For example, an operator can make real-time changes to a system performance by increasing or decreasing critical resources as service demand or supply varies. A socio-technical system is characterized by social and technical system complexity coupled by the dynamic processes governing the interactions between the systems (Wu et al. 2015). Thus, human interactions with technological systems introduce added layers of complexity and uncertainty corresponding to factors like human intention and anticipation that are unaccounted for in a traditional systems engineering approach. This means socio-technical systems must consider how to integrate the roles of humans while managing the complexity of coupled systems (Schöttl and Lindemann 2015) like critical infrastructure. In contrast to a more traditional systems engineering approach based on a reactive response to failure, resilience engineering takes a proactive approach to risk management (Hollnagel 2014). This means resilience engineering views failure as the inability to cope with complexity, especially with regard to disruptions occurring outside of designed performance levels (Hollnagel, Woods, and Leveson 2006). Thus, resilience engineering is a useful tool for understanding the relationships between human resilience and the resilience of complex socio-technical systems like infrastructure.

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. Broadly, human resilience refers to the capacity of individual people and human systems to rebound and adapt when faced with adverse conditions. 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). Human systems include individual people, groups, organizations, and institutions that are embedded within and dependent upon other systems like socio-cultural, ecological, and engineered systems (Masten and Obradovic 2010). Human resilience 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; George 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. However, research is scarce on how adult human resilience may appear in engineered systems like infrastructures. As a result, little is known about how the resilience of people may influence outcomes of coupled systems amid unexpected disruption and uncertainty.

In this work, we address a gap in the resilience literature relevant to the integration of human and technical resilience capacities influencing the resilience of critical infrastructures. We apply a holistic approach to resilience research (Thomas, Eisenberg, and Seager 2017) that draws on the resilience engineering and psychology literature to investigate the nature of the dynamic relationships between human and infrastructure resilience. In response to policy directive assumptions and gaps regarding the interdependencies of coupled human and infrastructure systems, frameworks are combined from each body of literature to form an integrated perspective of infrastructure resilience. To accomplish this we use four socio-technical processes—sensing, anticipating, adapting, and learning (SAAL)—as linking mechanisms between resilience engineering system capacities and human resilience capacities. We compile a list of 18 resilient system capacities and show how they are distributed among the SAAL processes. The distribution is compared to a similar analysis of 23 human (individual) psychological resilience capacities organized by cognitive, affective, and behavioral dimensions. Our analysis suggests that many of the human and 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. Thus, our conceptual model offers an integrated approach to relating the resilience of humans with the resilience of socio-technical systems like infrastructure. 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.

Resilience engineering and socio-technical systems

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 people, including designers, operators, and managers embedded within, and interacting with, technical systems like infrastructure.

Whereas a risk analysis approach to prevention and mitigation is based on known or expected hazards and system failures, 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). Moreover, resilience engineering aims to incorporate deterministic design methods for managing and reducing risks together with resilience methods for enhancing the ability of a system to respond to unexpected changes (Hollnagel et al. 2011; Righi, Saurin, and Wachs 2015).

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 humans 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. Among the many definitions to consider, some are more relevant to engineered systems while others can include people, making them well suited for socio-technical systems. However, there is no common agreement or reference among scholars regarding terms and descriptions or how they are used in 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 (Brand and Jax 2007; Reid and Botterill 2013; Martin-Breen and Anderies 2011b). Reorganization may include adjusting state variables or by changing connections among existing structures. This description can be applied to a socio-technical system involving people although the lack of specificity limits its utility for practical applications. 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 equilibrium (Holling 1996) or as a complex adaptive system with dynamic feedback allowing for continuous adjustment (Pendall, Foster, and Cowell 2009). Again, while offering useful insight about the concept of resilience in technical systems, the descriptions are narrow in scope making it hard to consider how to integrate people in a socio-technical system. Resilience may also be viewed as emergent process in response to a system disruption (Park et al. 2013). The emergent processes represents 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 process holds promise because the processes provide context and the emergent nature applicable to a socio-technical system like infrastructure. In addition to the above, several authors have compiled lists of resilience definitions (Righi, Saurin, and Wachs 2015; Weinstein 2013; Hassler and Kohler 2014). This points to a lack of common reference to validated terms, concepts, and definitions of resilience in the resilience engineering literature.

Notwithstanding the many definitions of resilience in literature, the one provided by the National Academy of Sciences that describes resilience as the ability to plan for, absorb, recover from, and adapt to actual and possible disruptive events (Cutter et al. 2012). This definition provides a reference frame in time that characterizes distinct state transitions prior to, during, and after system shocks, stressors, and catastrophic disruptions (Figure 6). Each reference frame *in time* describes a specific context with a corresponding interpretation of resilience. The concept of resilience as an emergent process in coupled infrastructure systems compliments this definition by providing an added dimension of context. Moreover, an important factor in the above definition is the ability to anticipate and prepare for unknown disruptions (Hollnagel and Fujita 2013). This distinction presumes that humans are involved, which means they are dynamically interconnected with infrastructure. 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. Taken together, the hybrid definition can be applied to coupled socio-technical systems like infrastructure.

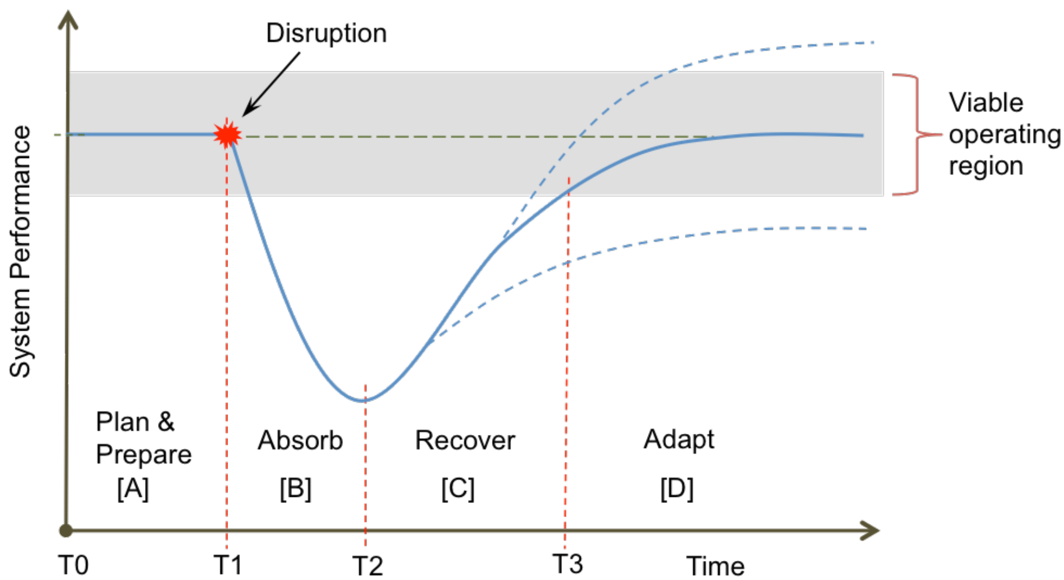

Figure 6 Resilience time sequence of system performance
The time sequence corresponds to a general definition of resilience as the ability to plan & prepare, absorb, recover, and adapt to known and unknown potential threats. (Cutter et al. 2012; Bruneau et al. 2003; McDaniels et al. 2008).

Time and timing are important concepts in infrastructure resilience. Figure 6 illustrates the definition of resilience introduced above with four time blocks reflecting a pattern of resilience concepts that may be applied to an infrastructure environment (Cutter et al. 2012; McDaniels et al. 2008). Each time block contributes to a particular resilience perspective or frame of reference that can be investigated and examined. Planning and preparation, which can include learning from prior events, occurs in the first time block ‘A’ in Figure 6. During this time, there is opportunity to influence infrastructure resilience by increasing protective factors or decreasing vulnerability factors. The second is time block 'B', which represents the impact and absorption time of the event. The resilience of the system is dependent on the ability to absorb shock during this block without catastrophic collapse or dysfunction. Third is time block 'C', which represents a system recovery period whereby functionality, may be restored. This means the system would be able to maintain a stable state or identify a new state of operation. The fourth time block is 'D', which represents the period adaptation in response to the disruptive event. This is the time frame that will determine a system's new baseline of operation and may involve reorganizing or restructuring to remain functioning.

Resilience engineering emphasizes how interconnected complex systems maintain function in both expected and unexpected conditions rather than how they maintain structure (Hollnagel 2014). This important distinction allows for the consideration of open, adaptive systems that can self-organize and respond to intentional interactions with their environments, which includes human systems like individual people, organizations, and institutions. Thus, risk analysis of known system threats compliments resilience analysis of unknown threats (Park et al. 2013), which includes proactive approach to risk management capable of adjusting system performance in response to unforeseen disruptions (Righi, Saurin, and Wachs 2015).

System capacities, processes, and perspectives offer different interpretations on how to consider the resilience of coupled complex systems like humans and infrastructure. Each interpretation applies to socio-technical systems like infrastructure that involve people and technology as shown in the following sections.

Resilient system capacities

Resilience engineering and socio-technical capacities

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. Although many of the attributes are referenced by similar names and descriptions in literature, there little work compiling them with definitive descriptions as resilient system capacities that can be validated with empirical measures. Likewise, there is little research linking the attributes to resilience processes or the properties of other coupled complex systems.

Table 5 Socio-technical system capacities supporting resilience. Appendix B includes descriptions and references for each attribute found in our review of resilience engineering literature.

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

Table 5 presents 18 system attributes found in a review of resilience engineering and infrastructure systems literature. While not exhaustive, the list represents many of the core concepts associated with resilience. The range of attributes reflects the multidimensional nature of resilience (Brown and Westaway 2011) applied to infrastructure. The capacities may be viewed as an antecedents or latent propensities prior that manifests as resilience processes and outcomes in response to system shocks. Appendix B expands on Table 5 by including summary descriptions and references for each attribute. Taken together, the system capacities combine with resilience processes to characterize the resilience of a technical system.

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 (Park et al. 2013) like water, power, and transportation. 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 psychology and psychiatry literature.

Resilience capacities, processes, and systems are three ways to conceptualize human resilience (Masten 2001; Lipsitt and Demick 2012; Luthar, Cicchetti, and Becker 2000). The three conceptualizations are described below. We then relate the concepts to an established model referenced in resilience research describing the relational dynamics of a person interacting with their environment. The model is applied to our application by specifying the criteria of the 'environment' to include complex systems like infrastructure.

Human resilience capacities

A capacity perspective of human resilience considers inherent properties or qualities (a.k.a. variables, characteristics, protective factors, and personality traits) serving to protect or compensate individuals exposed to risks and adversity (Masten 2001). Table 6 presents a group of human resilience capacities found in the psychology and psychiatry literature (Connor 2006; Kumpfer 1995; Olsson et al. 2003; Garcia-dia et al. 2013; Resnick and Inguito 2011; Richardson 2002) reflecting the multidimensional nature of the resilience of a person (Luthar, Cicchetti, and Becker 2000). Moreover, the capacities in Table 6, which are psychological capacities, representing subjective characteristics of people known to correlate with resilient outcomes (Kumpfer 1995) amid adverse conditions or events. Appendix B expands on Table 6 by including summary descriptions and references for each attribute.

Table 6 Human resilience capacities
The list is compiled from a survey of the psychology and psychiatry literature. The assignment to cognitive, emotional, and behavioral dimensions is based on a combination of literature and the assessment of the authors. Appendix B includes descriptions and references for each attribute.

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

Cognitive, affective, and behavioral dimensions are category organizers representing the resilience capacities of individuals proximal to infrastructure operating environments. The three dimensions are selected because they appear in the psychology (Mischel & Shoda, 1995) and human development (Cook-Greuter, 2004) literature, and provide a convenient way to group the resilient capacities. Cognitive capacities engage mental faculties of knowledge, judgment, and reasoning in influencing resilient behavior (Friborg, Barlaug, Martinussen, & Rosenvinge, 2005). Affective resilience capacities engage the experience of emotions to influence resilient behavior (Ong, Bergeman, & Chow, 2010). Behavioral capacities influence resilient behavior and interactions between an individual and their proximal environment (Kumpfer, 1995). Taken together, including the three dimensions provide a meaningful way to group and compare the internal resilience capacities of a person that underpin resilience processes and systems.

Linking human and infrastructure resilience

Organizing resilience research perspectives

The concept of resilience relating human capacities in organizational processes to engineering processes illustrates the complexity and multidimensional nature of resilience engineering (Madni and Jackson 2009). People may be viewed as complex adaptive systems because the human dimension adds novelty, uncertainty, and the capacity to self-organize (Martin-Breen and Anderies 2011a) in an infrastructure environment. 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 (Park et al. 2013; Hollnagel and Fujita 2013). Thus, a resilience engineering approach to infrastructure must incorporate multiple perspectives, methods, and interpretations of resilience to account for embedded human subjects.

Thomas et al. (2017) describe how a holistic approach to resilience research includes individual and group representations of internal subjectivity and external objectivity. This approach suggests there are at least four irreducible perspectives from which scholars might advance a holistic understanding of resilience of complex socio-technical systems (Thomas, Eisenberg, and Seager 2017). First, the individual interior perspective includes the cognitive, emotional, and psychological properties that constitute the *experience* of a person. Capacities known to correlate with human resilience such as the ability to cope and locus of control (Connor 2006) are examples of interior perspectives of individual experience. Second, the individual exterior perspective is characterized by *behavior* and includes the actions, behaviors, and physical characteristics of a person or a physical unit of investigation like a piece of technical equipment, an individual component, or a power plant. The abilities of an individual person to adapt their behavior and to interact with their environment in response to adverse conditions are examples of observable processes that contribute to the resilience of a person (Masten 2001). Likewise, the resilience of a piece of infrastructure may be observed as its ability to maintain function within a viable operating level of performance (Hollnagel, Woods, and Leveson 2006). *Culture* describes the collective interior perspective of groups like family, community, organizations, and institutions. The collective interior includes factors like ethics, shared values, cultural beliefs, and worldviews. The capacity to cope with uncertainty and social coherence amid adversity (Norris et al. 2008) are examples of cultural perspectives of resilience. Finally, *systems* characterize a collective exterior perspective of social, technological, and ecological physical structures like power generation, water treatment, and operations. The collective exterior describes the physical and functional interactions between and among complex adaptive *systems* like humans operating infrastructure or coupled infrastructures like power and water. Rebound, robustness, graceful extensibility, and sustained adaptability are examples of resilience concepts (Woods 2015) corresponding to *systems* characterized by the collective exterior.

Together, the four resilience perspectives—experience, behavior, culture, and systems—represent different epistemological orientations, methods, and techniques that contribute to a more integrated and holistic understanding resilience (Thomas, Eisenberg, and Seager 2017). Thus, a holistic approach to resilience research incorporates both the interior and exterior perspectives of human systems coupled with interdependent technological systems like critical infrastructure. The linking mechanisms between the human and technological dimensions are the SAAL processes reflecting the dynamic interactions.

Resilience processes

Socio-technical system processes: sensing, anticipating, adapting, and learning

The characterization of resilient socio-technical systems introduced by Hollnagel et al. (2011; 2006) is widely adopted in the resilience engineering literature (Righi, Saurin, and Wachs 2015; Madni and Jackson 2009; Rankin et al. 2013). The processes suggest resilient engineering systems must be able to monitor—know what to look for, anticipate—know what to expect, respond—know what to do, and learn—know what has happened. Hollnagel (2012; 2013; 2014) applied the functional resonance analysis method to show how each of the resilience processes are dynamically coupled to the other processes and to identify the dependencies among them. The four abilities are focused on different ways of knowing and thus emphasize a cognitive perspective of how humans influence system resilience

(Hollnagel et al. 2011). This important consideration offers valuable insight to how people access expert knowledge to interact with infrastructure in response to acute stressors or system shocks. However, the focus on cognition precludes the consideration of other human characteristics like psychological, emotional, or behavioral influences on individuals and groups interacting with technical systems. Nonetheless, the underlying framework can accommodate a range of human perspectives.

An important refinement of the four abilities by Park et al. (2013) emphasizes the *recursive* nature of four socio-technical processes characterizing the dynamic *behavior* of resilient systems including sensing, anticipating, adapting, and learning (SAAL processes). 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 (Park et al. 2013). 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 processes mediate the capacity of a system to cope with surprise and adapt to changing conditions.

Figure 7 illustrates the recursive and reciprocal nature that describes how the processes interact and how feedback informs and influences resilient outcomes. The diagram also shows the dependencies among the processes whereby each can influence and be influenced by the others. Although a given scenario may emphasize the influence of one or more processes over others, all of them must be present in a resilient socio-technical system (Hollnagel 2014; Hollnagel et al. 2011). Thus, the diagram also reflects the interdependencies among the processes.

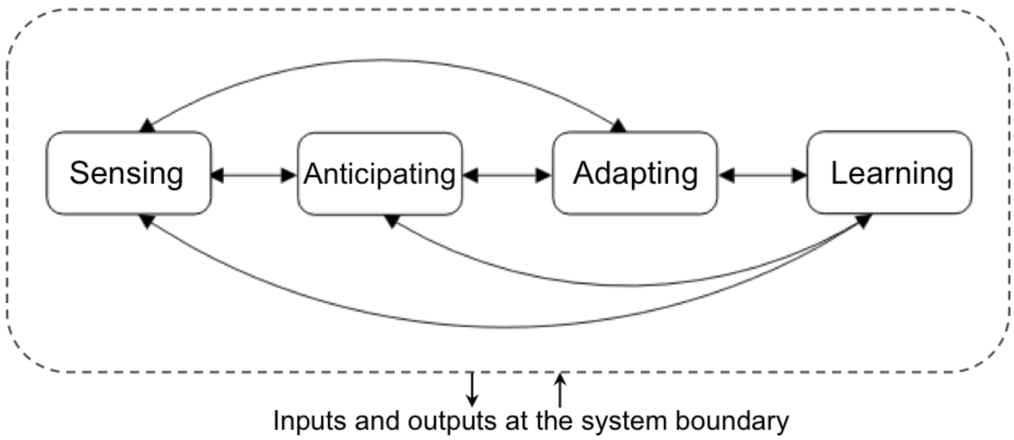

Figure 7 SAAL socio-technical resilience processes.
The feedback loops represent the recursive and reciprocal relationships between processes. The boundary condition represented by the dashed line defines the physical and functional areas of consideration for a given scenario. The resilience processes interact with the proximal environment at the boundary. (Thomas, Eisenberg, & Seager, 2017)

The dashed line in Figure 7 represents the boundary conditions that contain the coupled social and technical systems within a region of inquiry and assessment. Thus, transactional inputs and outputs of coupled systems refer to a region of inquiry framed by the boundary condition. Moreover, the SAAL processes shown in Figure 7 offer a common framework for understanding resilience within each of the four time blocks shown in Figure 6 corresponding to planning and preparation, absorption, recovery, and adaptation. This means the processes can provide a mechanism for observing dynamic changes in resilience corresponding to shifting emphasis of one process over another across the four time blocks. The following are summary descriptions for each of the four SAAL processes (Park et al. 2013; Hollnagel and Fujita 2013; Hollnagel et al. 2011; Linkov 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 impacting 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 means humans are a vital component of complex socio-technical systems and serve an important role interacting with the resilience processes. Learning informs anticipating, which subsequently informs sensing and adapting processes. Thus, anticipating is dependent on learning to know what to expect.
- *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 essential functions and a viable level. 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. Learning and anticipating inform adapting processes. Moreover, the relationship

between learning and adapting is reciprocal because each informs the other and can cause changes that impact the system resilience.

- *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 recursive processes can serve as a guide to interrogate a system and to access its capacity to navigate resources and adjust functioning in response to changes in its environment. Thus, the SAAL processes offer a practical approach to considering the resilience of a complex system like infrastructure that includes people interacting with technology and influencing system resilience. Although the SAAL processes accommodate the cognitive and behavioral dimensions, it is less apparent how they consider the affective dimension of human resilience in socio-technical systems. This is largely because the affective dimension is ignored in the resilience engineering and socio-technical systems literature. The SAAL processes offer a mechanism for exploring the relationship between the cognitive, behavioral, and affective dimensions of human resilience and infrastructure resilience in a coupled socio-technical system. Thus, a better understanding of the resilience processes of an infrastructure system can inform methods and adjustments to improve system performance.

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 (Masten 2001; Rutter 1987; Luthar, Cicchetti, and Becker 2000; A. Masten 2014b). In a context of infrastructure, human resilience capacities combine with dynamic processes to characterize the resilience of people interacting with coupled complex systems. That is, the interactional processes are the coupling mechanism linking human resilience capacities with infrastructure system capacities. 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 1968) to human development (Ungar, Ghazinour, and Richter 2013; A. S. Masten 2007). 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. Resilience capacities, processes, and systems are combined to provide a conceptual method for relating human and infrastructure resilience.

Methods

An essential consideration for integrating human and infrastructure resilience is to include the capacities and processes of the systems involved along with the interactional dynamics between them. To accomplish this, we apply the person-process-context model describing how a person interacts with their environment (Bronfenbrenner 2005). There are two key motivations for this approach. First, the model is foundational in the psychology literature influencing a wide stream of human resilience and development research (Sameroff 2010; Ungar, Ghazinour, and Richter 2013; Masten 2014a). The established theory and concepts of have been applied to human resilience in a range of studies involving children and families (Masten 2014b; Lerner 2006) and among diverse cultural groups (Ungar 2006). Second, the model provides a simple and convenient structure for integrating human and technological concepts. The structure of the model supports the rationale for relating human and technical resilience capacities by engaging the dynamic processes that characterize the relationships and interactions between humans and infrastructure. We incorporate the concept of a person-process-context model 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 technical resilience capacities. Examining the relationships between the different capacities involved a five-step process.

1. A review of resilience engineering literature produced a list of 18 system capacities presented in Table 5. We compiled the list with description and references (Appendix B).
2. We assessed the list of 18 system capacities (Table 5) by assuming a dominant (first order) relationship with one of the four SAAL processes (Figure 7). That is, we identified each system capacity to correspond with one of the four SAAL processes.
3. A review of the psychology and psychiatry literature produced a list of 23 variables (Table 5) representing a range of human resilience capacities for an individual person. We organized the capacities by cognitive, affective, and behavioral dimensions, and listed them in alphabetical order with summary descriptions and citations (Appendix B).

4. We assessed each human capacity by assuming a dominant (first order) relationship with one of the four SAAL processes. That is, we identified each capacity to correspond with one of the four SAAL processes.
5. Finally, we examine the relationships between the capacities by comparing the overlap of human and system dimensions for each of the four SAAL process.

After completing the five steps, we examine how the human and technical resilience capacities combine with the SAAL resilience processes—sensing, anticipating, adapting, and learning—to characterize the resilience of coupled socio-technical systems like infrastructure.

Results

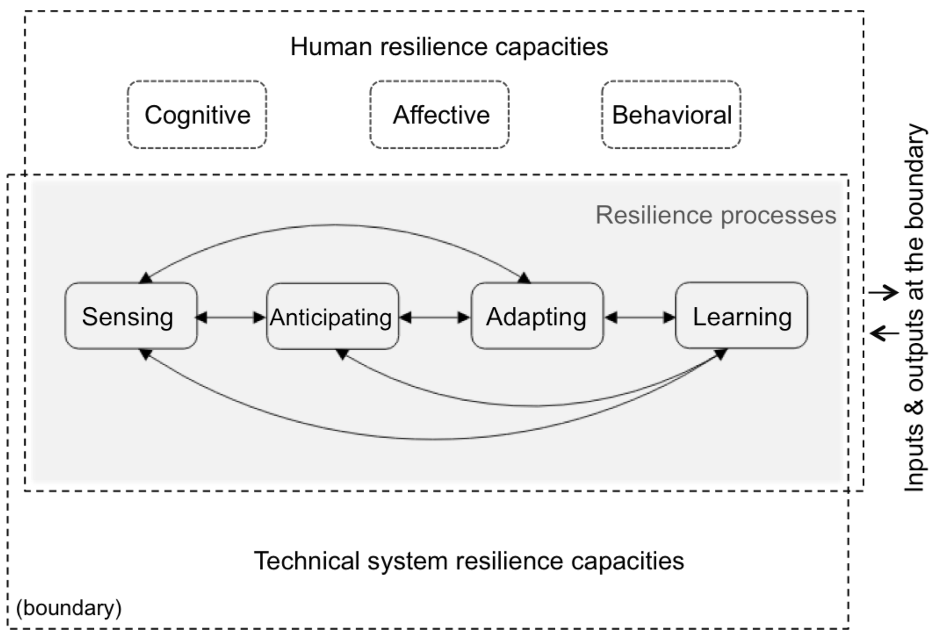

Figure 8 Coupled human and technical resilience capacities.
Cognitive, affective, and behavioral dimensions organize the human capacities. The resilience processes are the coupling mechanism corresponding to sensing, anticipating, adapting, and learning. The dashed lines represent the boundary conditions and the shaded area represents the domain where human and technical systems overlap.

Figure 8 illustrates the conceptual framework applied to the human and technical resilience capacities by their common association with the SAAL resilience processes. Table

7 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 for an individual person.

Table 7 Resilience capacities distributed by relationship to the SAAL processes. Distribution of 18 technical and 23 human capacities (see Appendix B) by their relationship with the SAAL resilience processes. For example, hopefulness and patience are affective human resilience capacities that contribute to anticipating processes along with cognitive human capacities personal and collective goals and technical system capacities like compensation, goals, and maneuverability.

	Sensing	**Anticipating**	**Adapting**	**Learning**
System	• Avoidance • Cohesion • Flexibility • Margin • Pinging • Tolerance	• Compensation • Goals • Maneuverability	• Adaptive capacity • Autonomy • Control • Coping • Diversity • Efficacy • Survival	• Buffering • Efficiency
Human *Cognitive*	• Perceive benefits of stress • Moral reasoning • Self-esteem	• Personal, & collective goals	• Fortitude, conviction & 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

Technical system capacities

The heuristic for relating the technical capacities with the SAAL processes includes the descriptions of each process provided in section 4.2.1 above and the descriptions of the capacities provided in Appendix B. Seven of the 18 human capacities are assigned to adapting processes and six to sensing with anticipating and learning receiving three and two respectively. 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.

Human capacities

The heuristic for relating the human capacities to the SAAL processes includes the descriptions of each process provided in section 4.2.1 above and the descriptions of the capacities provided in Appendix B. The human capacities in Table 7 are organized by cognitive, affective, and behavioral dimensions described in section 3.2 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. Appendix B provides detail descriptions and references for each capacity.

Discussion

By effectively characterizing a common operational state space (i.e., resilience), the SAAL processes were used to identify specific relationships between human and technological capacities that contribute to the resilience of coupled socio-technical systems such as infrastructure. Additionally, each of the SAAL processes—sensing, anticipating, adapting, and learning—can serve as a linking mechanism that shows how the cognitive, behavioral, and affective dimensions of human resilience capacities are interconnected, interrelated, and interdependent. Finally, this study suggests that the affective dimension of human resilience contributes to the resilience of socio-technical systems in addition to the more often recognized cognitive and behavioral dimensions.

Human and technical resilience capacities are interconnected

The relationships between human and technical resilience capacities point to the interconnectedness of these capacities within coupled human and technological systems. This is important to recognize because the NIPP 2013 stresses the physical and functional interconnectedness among infrastructure without consideration for how human resilience can contribute to infrastructure resilience. Moreover, the capacities are interconnected because they share a structural relationship with the SAAL processes, which serve as a linking mechanism between human and technical domains. That is, certain psychological capacities conceptually correlate with the resilience of an individual human and also correlate with certain resilience capacities of a technical system. As shown in Table 7, we describe the various capacities as interconnected because each is conceptually linked to one of the SAAL processes—sensing, anticipating, adapting, and learning—that characterize the relationships between socio-technical systems that include humans and technology. In other words, the capacities listed in each column of Table 7 are interconnected by their common relationship with the corresponding SAAL process. This means the capacities that characterize the resilience of humans are associated with the capacities that characterize the resilient operation and performance of socio-technical systems such as infrastructure when applied to the SAAL processes.

Human and technical resilience capacities are interrelated

The human capacity 'locus of control' found in the psychology literature has a conceptual correlate in the resilience engineering literature with the capacity 'control.' Other human and socio-technical system capacities sharing similar terms and descriptions include coping, efficacy, and goals. Thus, the capacities identified as conceptual correlates are interrelated because they share meaning in a context of coupled systems. The shared meaning is significant because it shows how each capacity contributes to the same phenomenon (i.e., infrastructure resilience).

A locus of control describes perspectives of control over one's internal resources that enable abilities to make decisions and take action (Richardson 2002). Within seconds of losing thrust on U.S. Airways 1549, Captain Scully affirmed his control of the aircraft with his co-pilot and proceeded to execute a series of complex tasks with precision and skill. Reflecting on his experience later, Captain Scully described himself as 'hyper-focused' and with a sense of knowing that he could ditch the aircraft successfully in the Hudson. An internal locus of control inspires a belief in one's own effectiveness in relation to extreme adversity (Werner 2014; Noltemeyer and Bush 2013; Olsson et al. 2003). 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). Captain Scully expressed a strong sense of confidence in his ability to maneuver the aircraft toward a successful outcome.

Compared to psychological concepts of control, resilience engineering considers the control of a resilient system as the ability to manage adaptive capacities (Woods 2015). In other words, a controlled system is able to achieve specified or desirable states of operation while avoiding undesirable states (Dinh et al. 2012). In applications such as infrastructure, control refers to the ability of a system to regulate brittleness by making specific performance adjustments in response to surprise events (Woods 2015). 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 means operator training and experience are important factors in establishing and maintaining system control. Adapting is the resilience process shared by human and socio-technical capacities for control. That means each capacity contributes to the same socio-technical process. The comparison between capacities for humans and technical systems shows the interrelated nature of coupled systems.

Human and technical resilience capacities are interdependent

Although addressing interdependencies among the resilience capacities presented herein is beyond the scope of this paper, the reciprocal relationships noted between the capacities (i.e., human and infrastructure) and the SAAL processes elucidates their interdependence. The capacity to cope, for example, can have both social and technical implications to system resilience. In the psychology literature coping is often described as a resilience characteristic (Connor, 2006; Kaminsky, McCabe, Langlieb, & Everly, 2007), an outcome (Garcia-dia et al., 2013), or a part of the resilience process (Masten, Best, & 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 & Moskowitz, 2004). By comparison, a resilient technical system must be able to cope with unexpected perturbations that extend beyond designed features (Hollnagel & Fujita, 2013) and can lead to system failure. Resilience engineering describes failure as the inability of a system to cope with increasing complexity (Hollnagel et al., 2006) and to maintain control over operational performance amid adversity (Madni & Jackson, 2009). This means that in coupled systems the human capacity to cope with adversity is dependent on the technical systems' capacity to cope and vice versa. Thus, coping and control are examples of interdependent resilience capacities because they have a mutual influence on one another.

Other researchers have also acknowledged the reciprocal influence of certain coupled human and technological systems. Hollnagel et. al. (2011), for example, suggest that the adaptive capacity of people (i.e., individuals and groups) and engineered systems are interdependent because coupled socio-technical systems rely upon the human ability to accommodate unknown changes and disruptions. Part of the reason is that engineered systems are intentional, which means humans rely on and interact with socio-technical systems in complex ways. The built environment consist of socio-technical systems designed, constructed, and maintained by humans to perform specific functions and to provide certain products and services to communities and to society (Hassler and Kohler 2014; Hollnagel 2014). Examples include roads, bridges, buildings, damns, power generation, water treatment, and electrical distribution systems. Critical infrastructure systems are a subset of the built environment that are essential to public health, safety, and well-being (DHS 2013; Laugé, Hernantes, and Sarriegi 2015; Labaka, Hernantes, and Sarriegi 2016) of community and society members. Moreover, from a psychological perspective the interdependencies of multiple overlapping social and physical infrastructure systems have significant implications for large-scale disaster scenarios (A. Masten and Obradovic 2010).

The reason is because the properties and processes that characterize the relationships between coupled human and technical systems represent human resilience and adaptive capacity. This means socio-technical systems such as infrastructure are mutually dependent on their human and technological dimensions. These interdependencies are compounded in disaster scenarios (e.g. hurricanes, tornados, or terrorist attacks) where multiple overlapping domains can result in cascading impacts across spatial and temporal scales. Thus, the resilience of human systems must be taken into consideration when investigating the resilience of technological systems like critical infrastructure.

Human affect contributes to the resilience of socio-technical systems

Although natural and man-made disasters can create human loss and suffering while rendering infrastructure systems diminished, destroyed, or inoperable, resilience engineering literature effectively ignores the affective dimension of human resilience. While descriptions of the SAAL processes in literature focus on the cognitive (Hollnagel 2014) and behavioral (Park et al. 2013) dimensions of coupled social and technical systems, and there is little consideration for how human affect may contribute to resilience processes. This may be somewhat understandable given that research is scarce investigating the dynamic relationship between human resilience capacities and dynamic processes even in the psychology literature (Ong et al. 2006; Luthar, Cicchetti, and Becker 2000; Lipsitt and Demick 2012). However, our analysis shows the affective dimension with the largest number of human resilience capacities among the group of 23 reviewed. In this group, nine are ascribed to the affective dimension and seven each are ascribed to the cognitive and behavioral dimensions. Three of the nine affective capacities are assigned to the adapting processes and two each are ascribed to the sensing, anticipating, and learning processes. This means human affect dominates the group of capacities reviewed and is related to each of the four socio-technical processes contributing to resilience. Together with the SAAL framework, the individual psychological capacities reviewed include the cognitive, behavioral, and affective dimensions of human resilience.

Furthermore, there is considerable research suggesting how affect contributes to human resilience. The adaptive properties of human resilience are noted in positive psychology literature, which expounds on the relationships between positive emotions and human resilience (Galatzer-Levy et al., 2013; Seligman, & Csikszentmihalyi, 2000; Tugade, 2004). Positive psychology takes a proactive approach by focusing on 'what works' and seeks to implement plans to adapt and sustain physical and psychological health and effectiveness amid adversity (Avey, Wernsing, and Luthans 2008; Burnard and Bhamra 2011). Although research suggests that humans who are considered psychologically resilient can still experience negative emotions, their strategic use of positive emotions can serve as a buffer from negative effects in the wake of a crisis (Fredrickson et al. 2003). Thus, based upon our analysis as well as upon the research linking positive emotions and human resilience, we argue that resilience engineering research can be enhanced by including the affective dimension of human resilience together with cognitive and behavioral dimensions when applied to complex systems such as infrastructure.

Conclusion

Although humans are often viewed as dynamic components of the built environment, Federal directives seeking an integrated approach to strengthening the resilience of critical infrastructure fail to consider how human resilience may contribute to technological resilience. Yet catastrophic system failures like the Fukushima power plant disaster and U.S. Airways Flight 1549 suggest that the people responsible for the design, operation, and management of infrastructure can impact system resilience and outcomes. In this work, we apply resilience engineering concepts and tools to describe the resilience of complex socio-technical systems like infrastructure by relating human and technological resilience capacities to a common set of dynamic processes. The resilience processes represent the dynamic interactions among coupled socio-technical systems and 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 in relation to the SAAL resilience processes. Moreover, they suggest that the affective dimension of human resilience is 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.

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CHAPTER 4

AN ONTOLOGICAL FRAMEWORK INTEGRATING HUMAN DEVELOPMENT AND TECHNOLOGICAL RESILIENCE IN SOCIO-TECHNICAL SYSTEMS

Introduction

Disaster events such as the Three Mile Island accident in 1979, the Challenger explosion in 1986, and the New Orleans Levee breakdowns in 2005 illustrate how the complexity of human interactions with technology can exasperate failures among coupled systems (Perrow 2011). In stark contrast, events like the ditching of US Airways Flight 1549 in the Hudson River on 15 January 2009 (NTSB 2010) and the safe return of Apollo 13 in 1970 (Madni and Jackson 2009) demonstrate how individuals and working groups interacting with technology can potentially overcome fatal system breakdowns. Each situation involved variations of unanticipated changes in operational complexity and performance. Although these examples are extreme, other similar scenarios play out across multiple domains and scales that go unnoticed by the public or academia. In a worse case scenario, unexpected and unknown changes can lead to catastrophic system failures propagating across spatial and temporal dimensions and operating domains such as the Fukushima power plant disaster in 2011. As a result, the people involved are often faced with making decisions and taking actions based on mental models—psychological renderings of perceived or imagined conditions (Olson, Arvai, and Thorp 2011)—that are no longer relevant. This means mental models can fail when faced with unanticipated emergent phenomena requiring an adaptive response to ambiguity and uncertainty (Sweet et al. 2014). Therefore, disaster events can create conflict between preconceived conditions and direct experience (Hollnagel et al. 2011) that can impact human interactions with technological systems.

The unanticipated differences between actual and preconceived experience of a person in a disaster scenario may be incompatible with their designated roles and responsibilities corresponding to thoughts, actions, and behaviors. As such, effective adaptation can require dynamically adjusting individual roles to accommodate unknown or unexpected conditions. In the examples above, human lives were dependent on the ability of the pilots, crew, operators, engineers, and others interacting with the relevant technical systems to comprehend the situation and make adjustments to maintain system performance. From a resilience engineering perspective, resilient outcomes are a factor of the recursive processes describing the capacities of intentional systems—sensing, anticipating, adapting, and learning (Park et al. 2013). Thus, the resilience processes involved with navigating actual versus preconceived experience are partly determined by the complex interactional dynamics between humans and technical systems striving to restore and maintain viable operating levels. Moreover, dynamic adjustments to roles and responsibilities can require reinterpreting existing information while giving rational meaning to new and sometimes conflicting information in response to unanticipated or previously inconceivable events (Hollnagel et al. 2011). As a result, human interactions with technological systems like infrastructure in response to disruptions can expose both known and unknown interdependencies impacting the resilience of coupled systems.

National policies and guidelines for critical infrastructure resilience effectively acknowledge the complex, multi-organizational, and socio-technical integration of people and technical systems (The White House 2013; DHS 2013). These policies support the concept of critical infrastructure resilience as a function of coupled social and technical systems' physical and functional characteristics (Madni and Jackson 2009), which includes the dynamic relationships between systems (Hollnagel, Woods, and Leveson 2006). The physical and functional characteristics are considered in a context of spatial and temporal dimensions. These are standard dimensions for analysis using traditional systems theory and other deterministic methods well suited for technological systems. However, the incorporation of human systems requires an additional dimension of symbolic meaning be included (Holling and Gunderson 2002) together with space and time. The added dimension accounts for the dynamic properties of complex adaptive human systems embedded within technological systems and operating environments proximal to physical infrastructure. That is, the human capacity to assign meaning and to dynamically interpret events and information relevant to critical infrastructure operation in response to disruption can impact the resilience of human coupled infrastructure systems. Therefore, without a better understanding of the human capacity to construct meaning, reductionist views of resilience and the tacit assumptions they make about the complex roles of humans interacting with infrastructure will prevail.

Although humans behave like complex adaptive systems, resilience research linking the dynamic interactions between humans and infrastructure is limited (Thomas et al. 2017). As a result, it is difficult to communicate complex resilience concepts and collaborate across disciplinary boundaries such as psychology and engineering (Thomas, Eisenberg, and Seager 2017). Moreover, the meanings and interpretations of knowledge, operational dynamics, and events influence human perspectives of system performance, which can vary across people and cultures involved. Other factors include the context of certain roles and responsibilities for a given scenario and corresponding environmental conditions. Thus, in addition to the epistemological perspectives representing multiple ways of knowing coupled systems across relevant spatial and temporal dimensions, critical infrastructure resilience must integrate ontological diversity reflecting how different human systems comprehend and interact with technological systems. This requires understanding how humans assign meaning and interpret knowledge and experience in relation to infrastructure resilience and how the processes can change across time.

The ontological diversity of coupled human-infrastructure systems cannot be reduced to a deterministic set of rules or actions because humans have individual and collective agency, intentions, and motivations that can be unpredictable and uncertain. This means a risk based strategy alone is insufficient, as risk management is based on known hazards (Korhonen and Seager 2008). Moreover, responding to adversity with incompatible preconceived responses can further exasperate failures and make conditions worse (Hollnagel et al. 2011; Hollnagel and Fujita 2013), which means the roles played by humans can be pivotal to critical infrastructure resilience. In other words, human ingenuity can either enhance or diminish resilience because the intentions, motivations, and judgments of a single individual can influence infrastructure meta-systemic (whole-system) dynamics and outcomes. Moreover, while it may seem apparent why "preparing a large population for any kind of disaster will require a developmental perspective on human resilience, risk, and vulnerability" (Masten & Obradovic, 2010, p-11) the dichotomy of possible roles played by humans in disaster scenarios highlights this important point. With potential near-term outcomes ranging from widespread environmental contamination to loss of life, the cascading impacts of disasters can have long lasting social and economic consequences that are less apparent (Cardona, 2003). The human ability to adapt to climate change is an example of a long time scale event with broad impacts linking complex relationships reflecting values, ethics, and world views (Adger et al. 2009) with human development (O'Brien and Hochachka 2010) and built infrastructure.

Human psychological development contributes to a body of knowledge and understanding about how people make meaning of the world and interpret experience. Disaster events identify knowledge gaps between the relationships of human resilience, development, and the ability of people to respond and recover (Masten and Obradovic 2010), which is dependent on critical infrastructure. Although human agency influences behaviors, actions, and interactions with other systems (Brown & Westaway, 2011; Nelson, Adger, & Brown, 2007), there is little research integrating resilience and adult human development perspectives with the resilience of critical infrastructure. Although less is known about how resilience appears in adults given a significant research focus on youth (Campbell-Sills, Cohan, and Stein 2006), progress in adult human development research has advanced and offers new insights about adult resilience. Moreover, there is a growing body of research that describes how human development endures well into adulthood and throughout a lifespan (Kegan 2002; Loevinger 1976; Cook-Greuter 2004a; Vincent, Ward, and Denson 2015; Kohlberg 1973). Thus, a better understanding of the relationships between human development and critical infrastructure resilience is needed.

In this paper, we address a gap in the resilience engineering and infrastructure resilience literature to consider how the psychological meaning-making of humans interacting with infrastructure can influence factors related to perceptions and interpretations of resilience. To accomplish this we apply a holistic approach to resilience research (Thomas, Eisenberg, and Seager 2017) that allows for multiple simultaneous perspectives drawing on the resilience engineering, psychology, and human development literature. We review multiple frameworks, synthesize diverse concepts, and propose a conceptual ontological model for investigating the relationships between the developmental capacity of meaning-making and critical infrastructure resilience. The model effectively integrates the socio-technical resilience processes—sensing, anticipating, adapting, and learning—with human developmental capacities. Our analysis suggests that each stage of human development brings new psychological resources contributing to the capacity to comprehend and respond to increasing levels of complexity and uncertainty thereby enhancing the effectiveness of the socio-technical resilience processes. We contribute the concepts of the ontological model along with three propositions to guide future research. We argue that progressive stages of human development corresponding to more complex forms of meaning-making bring new qualities and capabilities for designers, operators, and managers that can strengthen and enhance critical infrastructure resilience.

An ontological perspective of resilience engineering processes

The inclusion of both epistemological and ontological diversity adds to the complexity and uncertainty of maintaining a viable operating performance level for critical infrastructure. Whereas a focus on anticipating known failures related to operational disruptions and human interactions with infrastructure can enhance risk mitigation efforts (Cardona et al., 2012), preparing to be unprepared may require circumventing deterministic preparations and responses (Park et al. 2013). Moreover, the adaptive capacities of people, organizations, and engineered systems are interdependent on an ability to accommodate unknown *internal* and *external* changes (Hollnagel et al. 2011). In other words, adaptation to unpredictable system shocks may sometimes require abandoning prescriptive actions while dynamically constructing novel solutions. With regard to human systems, interactions and feedback loops maintain a sense of (rational) equilibrium by forming psychological structures that either filter incoming data to fit existing worldviews or creating new worldviews (Manners and Durkin 2000). Thus, an ontological framework of critical infrastructure resilience must integrate the endogenous human factors corresponding to the adaptive capacity of people and working groups interacting (proximal) with technology in addition to sensing, anticipating and learning. Without consideration of human dynamics and developmental predispositions, which includes how people interpret and make meaning of information and events, even seemingly comprehensive analyzes of coupled social and technical systems risk offering partial solutions by ignoring critical dependencies.

The 'SAAL' processes (Figure 7) describe four abilities of resilient systems: sensing, anticipating, adapting, and learning (Hollnagel 2014; Park et al. 2013). Sensing is the ability to detect system state variables; anticipating is the ability to imagine changes in system conditions and state variables; adapting is the ability to adjust system performance while maintaining viable operation; learning is the ability to absorb, retain, and access knowledge from experience. The processes represent the recursive and reciprocal relationships between complex socio-technical systems that influence resilience. Taken together, the SAAL processes provide a coupling mechanism for linking dynamic interactions between humans and critical infrastructure (Thomas et al. 2017). For example, in addition to planning and preparation, humans are integral to the management and operational response to disasters and catastrophic events (Madni and Jackson 2009). Moreover, officials and civil servants as individuals, teams, and organizations must coordinate and maintain critical infrastructure technical mitigation and recovery (and adaptation) resources while also providing a diversity of rescue (recovery) and support services across other systems, (e.g. public health and safety). The four abilities are a way to describe the resilience of the coupled human–infrastructure system. Thus, the SAAL processes provide a means for describing the dynamic relationships between people and infrastructure. In addition to adaptive behaviors, the relationships can also include maladaptive behaviors (Masten and Obradovic 2010), as observed during Hurricane Katrina (Westrum 2005) or the lead water poisoning in Flint, Michigan (CNN 2017).

Given the complex, interdependent, and interconnected nature of infrastructure systems, certain critical roles (e.g., control room operators) require individuals to make sense of systems in complex ways that can involve high degrees of ambiguity and uncertainty. Evidence from research in developmental psychology suggest that human factors such as interpersonal awareness, the capacity to consider alternative perspectives, complex systems thinking, and adaptive capacities emerge and advance in later stages of human development (Cook-Greuter 2004b; Vincent 2015). Moreover, research by Cook-Greuter (1999) find that advanced forms of these types of capacities are rare human traits only accessible after passing through an invariant sequence of developmental stages. Other evidence suggest that individuals are often discouraged from developing by existing educational institutions and management structures (Torbert et al. 2004). Furthermore, Cook-Greuter's data (n=4,510) indicates that fewer than 20% of the adult population arrive at the later stages of development (Cook-Greuter 1999). As a result, certain catastrophic infrastructure breakdowns may exceed the capacity of some individuals to effectively function and cope with high degrees of complexity and uncertainty. The developmental stages provide an ontological structure for linking diverse concepts of resilience involving human interactions with infrastructure. Thus, in addition to the potential to enhance anticipation of possible threats and outcomes, a key benefit of an ontological framework integrating development and critical infrastructure resilience processes is to improve the alignment of roles and responsibilities with individual strengths and adaptive capacities of people.

Human development framework and implications for infrastructure

A human development perspective incorporates ontological diversity by accounting for differences in how people make meaning and interpret knowledge in different contexts across time. That is, the way in which individuals experience resilience concepts and how those concepts and definitions influence relationships and proposed solutions over time correspond to the human capacity to develop more complex ways of interpreting and interacting with their environment. In this section, we examine different human development theories to identify one able to support an ontological framework for critical infrastructure applications.

Background

As a pioneer and visionary among adult development researchers, Robert Kegan (1980) was first to frame a new branch of human development research known as constructive-developmental psychology. Kegan recognized an underlying theoretical foundation of meaning-making *and* a conceptual framework of stages common among differing perspectives of a select group of adult [constructive] developmental theorists (1980; 1982). A central tenet of constructive-developmental theory is that people construct and interpret meaning in an ongoing manner to understand changing life conditions and experiences. In other words, humans construct meaning to negotiate resources and navigate complex environmental conditions. With regard to infrastructure, the environmental conditions reflect the dynamic relationships between people and technological systems for a given scenario like natural disaster or catastrophic system failure. Other perspectives on human development are focused more on how children may be clinically (empirically) observed to learn and grow (develop) in different contexts. Such perspectives offer valuable insight to child development by emphasizing the a behavioral perspective of the interactions of individuals exposed to different environments such as risk and adversity (Masten 2001), social ecology (Bronfenbrenner 1999; Ungar, Ghazinour, and Richter 2013), and culture (Ungar 2006).

Constructive developmental theory

In contrast to a behavioral approach, a constructive-developmental approach extends behavioral observations into adulthood *and* provides a structural framework for anticipating growth (development) and adaptive potential across a lifespan (Kegan 1980). Thus, constructive-developmental theory offers an integrated perspective of human developmental complexity *and* adaptation that represents an ontology of meaning in relation to critical infrastructure resilience concepts. Although observed behaviors of individuals and groups (i.e. agents in systems models) can provide useful insight to system interactions and outcomes, developmental complexity and adaptive capacity underpin and influence world views, human intentions, motivations, and behaviors (Cook-Greuter 1999; Kegan 2002). These factors, which are endogenous to human-coupled system interactions and outcomes, can influence how complex problems are perceived and approached and how solutions are proposed. Moreover, the inclusion of human development provides an ontological framework for integrating the socio-technical processes—sensing, anticipating, adapting, and learning—as a means of understanding how perceptions and interpretations of knowledge and events are established and change over time.

As the complexity and uncertainty of life conditions and environments increases, developing individuals encounter more comprehensive psychological meaning-making systems (Cook-Greuter 2004a) with an increasing capacity for positive adaptation (Hauser 1999). In other words, meaning-making describes an amalgamation of recursive processes of gathering, sorting, and making sense of—acquiring, differentiating, and integrating—

information and adapting to life experiences. Life conditions include factors such as family, education, work, and interpersonal relationships in a context of life events; environments include social, ecological, and technological dimensions of the same contexts. These factors influence how a person interacts with their contextual environment, which includes individuals embedded in critical infrastructure. The gradual accumulation of new interpretations and ways of making meaning formulates an invariant sequence of structures identified as levels or stages of development (Loevinger 1983; Cook-Greuter 1999; Kegan 1982; Kohlberg 1969) representing increasingly complex and creative ways of interpreting and navigating life conditions and experiences. Each level brings new capacities while strengthening and building on existing capacities.

The ontological structure of human development stage theories (Figure 9) provides a way to understand the relationships between coupled human – infrastructure systems. Although universal agreement on how or why adult development does or does not continue is lacking, a notable framework of homologous levels or stages is prevalent among many constructive-developmental theories including cognitive development (Kegan 2002; Murray et al. 1979; Piaget 1954), moral development (Kohlberg 1969; Gilligan 1982), ego [self] development (Cook-Greuter 2004a; Loevinger 1976; Loevinger 1966) values development (Graves 1970; Beck and Cowan 2006), and socio-emotional development (Goleman 2006). A range of developmental psychology stage theories are illustrated in Figure 9. Our approach incorporates the Loevinger (1976) ego development framework as enhanced and extended by Cook-Greuter (1999) to study the relationships between adult human development and resilience, and critical infrastructure resilience. The framework provides a way to combine theoretical concepts of human resilience and development reflecting positive adaptation and the ability to cope with uncertainty amid adversity. This combination is relevant to critical infrastructure resilience in response to disasters because human developmental properties characterize how human systems comprehend and interact with other complex systems like infrastructure. Cognitive, moral, and ego development are three prominent human development stage theories considered.

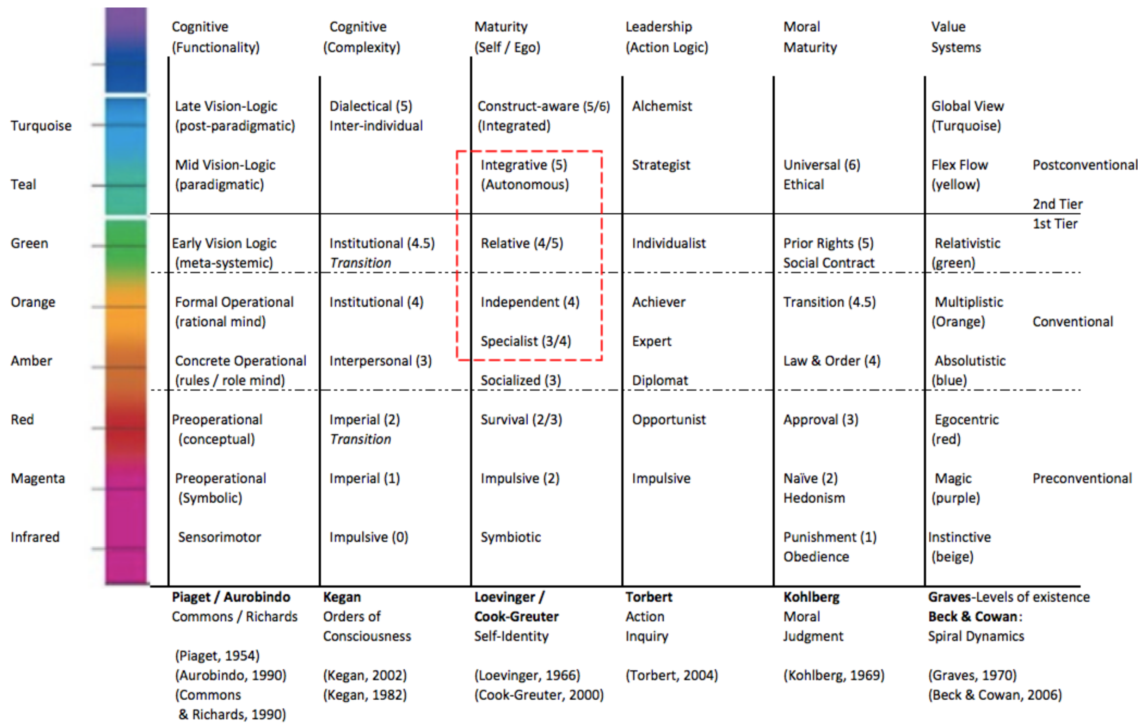

Figure 9 Developmental psychology stage theories.
The Y-axis represents an invariant sequence of levels or stages of development (earlier stages at the bottom and later at the top) and the X axis shows different developmental perspectives including cognitive, ego, leadership, moral maturity, and values. The red dashed lines identify the focus areas of this research. Although there is a general correspondence in the number and differentiation among stages, each perspectives represents a body of knowledge, measurement instruments, and methods. (Esbjörn-Hargens and Zimmerman 2009; Wilber 2000)

Cognitive development—Jean Piaget

Jean Piaget (1954) developed a structural model of cognitive development called "genetic epistemology" and created a comprehensive method using data to assess the capacity for rational thought and describe how patterns or stages of cognition emerge in developing children and adolescents. In epistemological terms, Piaget succeeded by adding a temporal dimension to human psychological development research with his stage theory of cognitive development. The inclusion of a time dimension provides a way to consider how adaptive properties and processes of human psychological development could impact interactions with other complex systems like infrastructure. Piaget viewed rational thought as a continuous process of discernment and differentiation between subject [the observer] and object [the observed] (Murray et al. 1979) that could be measured by logical scientific methods. Moreover, Piaget considered the capacity for rational thought as a basis for how people reason to construct meaning from experience by interacting with their environment according to a given genetic predisposition that changes with age (McCauley et al. 2006).

Moral development—Lawrence Kohlberg

Built on the work of Piaget (Stein and Heikkinen 2009), Lawrence Kohlberg's moral development theory describes six types of moral reasoning (Kohlberg 1969; Kohlberg 1973) corresponding to different stages of moral development. The six stages appear amongst three tiers—preconventional, conventional, and postconventional (Kohlberg 1969; Kohlberg 1973). Preconventional describes the period in a child's development when cognitive differentiation, or early meaning-making, is at its simplest level or structure representing opposing factors such as good and bad, right and wrong, or punishment and reward. In contrast to conformity, which is dominant in the preconventional domain, associations and actions with others in the conventional domain are based on loyalty and identification with chosen groups (e.g. family, peers, community, or nation). Unlike the previous two domains bounded by association with rules and social norms, the postconventional domain affords a critical perspective of moral value regards the *context* of a given situation or circumstance. Because circumstances may change, individual and group moral perceptions in this domain may not align with earlier forms of moral self-identity found in the conventional stages.

Moral development theory is relevant to critical infrastructure resilience engineering partly because an individual's capacity for moral reasoning may be viewed as a protective factor for people (Stokols, Lejano, and Hipp 2013) that contributes to human resilience. That is, moral capacity is interrelated to the dynamic interactions between and among humans and technical systems as shown by the events of 9/11 and Hurricane Katrina.

Ego development—Jane Loevinger

In contrast to Kohlberg's approach to assess moral maturity with qualitative methods, Jane Loevinger constructed an instrument for measuring ego development calibrated by quantitative scientific methods (Stein and Heikkinen 2009). Thus, there are two important reasons why Loevinger's ego development model and measurement instrument are relevant to the present research. First, the model offers a comprehensive perspective of human maturity and social development over a lifespan (Cohn and Westenberg 2004), that has been extensively validated (Manners and Durkin 2000), and applied to a wide range of studies (Cohn and Westenberg 2004; Vincent, Ward, and Denson 2013) and disciplines. In other words, there is substantial credible evidence that ego development theory is sound, and that measures are reliable. Moreover, the assessment tool was designed and calibrated using scientific methods (Stein and Heikkinen 2009; Loevinger 1985), which bolsters theoretical claims of objectivity. The second reason, which is a consequence of the first, is that a scientific approach to assessing ego development can be useful for identifying potential predictors of resilient outcomes when applied to a critical infrastructure scenario that involves people. That is, a developmental perspective of human resilience can help identify what type of adaptive responses may be possible when critical infrastructure resilience includes people. The consideration of human development capacities may assist, for example, with aligning key roles and responsibilities of people holding critical roles involving proximal interactions with infrastructure.

Loevinger's seminal work in adult ego development theory revealed how individuals construct a personal sense of self over a lifetime by multiple recursive processes of meaning-making (1966). The theory posits how individuals interpret life experiences to make sense of the world by constructing new meanings and perspectives and forming patterns that can change over time (Loevinger 1976). The concept of a temporal dimension of structural patterns of ego development is useful because it offers an established framework for a developmental perspective of resilience relevant to the present research. That is, the construct of ego development offers a conceptual framework describing how people mature and develop over a lifespan (Loevinger 1983), which can serve as a reference for interpreting perceptions of resilience and development. Unlike other constructive theories emphasizing single dimensions of character development such as cognitive capacity (Piaget 1954) or moral maturity (Piaget 1997; Kohlberg 1969), Lovinger's model accommodates multiple coherent dimensions (Loevinger 1976) manifesting across stages. Ego development processes appear across an invariant sequence of stages at widely varying rates with each stage presenting increasing complexity of a myriad of factors including cognition, self and interpersonal awareness [affect], and behavioral capacity (Loevinger 1976; Loevinger 1979). These three factors—cognitive, affective, and behavioral—represent core dimensions of Lovinger's ego development theory and measure (Cook-Greuter 1999; Loevinger 1976). Furthermore, these core dimensions align with prior work relating human and technical resilience capacities by using the SAAL socio-technical processes (Thomas et al. 2017). Thus, ego development presents an ontological framework representing how the cognitive, affective, and behavioral resilience capacities of individuals can change and mature over time in relation to technical system resilience capacities.

As people encounter and negotiate environmental conditions, experiences, and varied life stressors, psychological processes ensue and gather meaning-making data that either fits with an existing schema of the world or creates new one (i.e. transforms or constructs a new schema) to *accommodate* the new data (Manners and Durkin 2000). In other words, ego development stages may be viewed as psychological structures that support human adaptation (Manners and Durkin 2000; Vincent, Ward, and Denson 2015) to changing and evermore complex life and environmental conditions. Thus, the process of gathering and constructing meaning can influence the resilience of complex adaptive systems that include people such as critical infrastructure.

Ego development—Susanne Cook-Greuter

Cook-Greuter's research enhanced and extended the seminal work of Jane Loevinger. Her work was enhanced because Cook-Greuter's model describes higher orders of complexity and differentiation among cognitive, affective, and behavioral dimensions of ego development at postconventional levels (Cook-Greuter 1999). Loevinger's work was extended with the addition of a new fourth postconventional stage (Cook-Greuter 2000). Data collected from 4,510 participants over a period of 15 years were used to characterize a new postconventional structure and to verify adjustments to the measurement instrument (Cook-Greuter 1999). Table 8 identifies the action logic—system of meaning making, and central focus for each stage along with the distribution of stages among research subjects. The stages in Table 8 correspond to the third column in Figure 9 representing ego development. The red dashed lines identify the stages most relevant to the present research and are discussed in more detail in the next section. Cook-Greuter's research showed that the 'integrative' stage or structure in Loevinger's model appears as two distinct stage structures. The research also provided new details about the postconventional stages such as an enhanced capacity to cope with complexity and uncertainty and an improved ability to adapt to change (Cook-Greuter 1999; Vincent, Ward, and Denson 2015; Manners and Durkin 2000). These considerations can have both causal and prognostic implications for the resilience of infrastructure systems within which human systems are embedded.

Table 8 Ego development stages, action logics, and central focus
***Stage* names by Cook-Greuter and (Torbert), Stage id no. identifies alternating phases of integration (single number) and differentiation (double number) between stages; *Action Logics* are meaning-making systems with increasing complexity; Central Focus describes a psycho-social disposition or frame of reference dominant for each stage; *% Adults* are the results of a 15 year study involving 4,510 adults across a broad range of demographics. (Cook-Greuter 2004b; Torbert et al. 2004) The red dashed lines identify the focus area of this research.**

Stage—Cook-Greuter, **(**Torbert) [Stage id no.]	**Action Logic**	**Central Focus**	**% Adults** (N=4,510)
Preconventional			
Survival [2/3] (Opportunist)	Needs rule impulses	Own immediate needs, opportunities, self-protection	4.3
Conventional			
Socialized [3] (Diplomat)	Norms rule needs	Socially expected behavior, approval	11.3
Specialist [3/4] (Expert)	Craft logic rules norms	Expertise, procedure and efficiency	36.5
Independent [4] (Achievers)	System effectiveness rules craft logic	Delivery of results, effectiveness, goals, success within a system	29.7
Post-conventional			
Relative [4/5] (Individualist)	Relativism rules single-system logic	Self in relation to system, interaction to system	11.3
Integrative [5] (Strategists)	Most valuable principles rule relativism	Linking theory and principles with practice, dynamic systems interactions	4.9
Construct-aware [5/6] (Alchemists)	Deep processes and inter-systemic evolution rules principles	Interplay of awareness, thought, action, and effects; transforming self and others.	2.0

The distinction between horizontal and vertical growth and transformation offers an enhanced perspective of human development that may help align individuals with roles and responsibilities in work environments (Cook-Greuter 2004a). Horizontal growth, which strengthens and expands existing worldviews, is growth occurring within a given stage by acquiring and assimilating new knowledge, skills, and life experiences from multiple pathways. In contrast, vertical development is growth and expansion that constructs new world views by revising and restructuring interpretations of existing pathways, and by creating new stage structures and integrated perspectives with increasing complexity. Moreover, The temporal dimensions are different for horizontal and vertical development, in part because transformation in adults is less common (Cook-Greuter 2004a). In other words, although knowledge accumulation and personal resource management can continue in adulthood, shifting from one stage of ego-development to another occurs over extended periods of time and is less frequent in adults. These considerations can apply to critical infrastructures whereby roles and responsibilities are impacted by the resilient development of the designers, operators, and managers involved. That is, psychological meaning-making structures supporting the different ways of interpreting events, experiences, and changes associated with stages of development can impact how people interact with and influence the resilience of complex technological systems like infrastructure. Thus, in addition to the reasons above, we favor the Loevinger human development theory and framework as adapted by Cook-Greuter because it provides a comprehensive method for assessing and understanding the developmental dispositions of people interacting complex systems like infrastructure.

Ego development framework and assessment tool applied to infrastructure

Longitudinal studies linking human resilience and development

An added benefit of the Loevinger framework is the opportunity to learn from prior research linking human resilience and development. Two longitudinal studies apply the framework to measuring ego development in individuals from adolescence to adulthood. We provide a brief analysis of each and highlight the connections to this paper.

In the first study, data gathered at the beginning and end of a nine-year period showed a strong positive relationship between ego-resiliency and ego-development measures (Westenberg and Block 1993). This study is relevant to the present work because, in addition to showing how the two constructs relate to one another, it provides evidence of how they can change over time. Thus, measuring ego-development can provide a means for understanding how human resilience may vary at different stages of development, and how the differences can influence critical infrastructure resilience. A potential benefit is the alignment of short and long term roles and responsibilities with consideration of individual human strengths and growth opportunities. Empirical evidence suggests that ego resiliency and ego-development are interrelated, and that development may occur at different rates among individuals within the same age group (Westenberg and Block 1993). Ego-resiliency, which describes "flexible and resourceful adaptation" was divided into three subdomains, and each proved interrelated to ego development. Although the relationship did not contrast or change among ego stage transitions, a strong, coherent relationship was apparent. Another important finding relevant to our paper is the anticipated and observed strong positive relation between interpersonal integrity and ego development. Interpersonal integrity, which describes a capacity for authentic relations, was subdivided into two subdomains, and each revealed a strong, coherent relationship with ego-development. *This* *study is most relevant to the work herein because it provides evidence of the interrelatedness between concepts of human resilience and human development*. The data suggest that the properties that correlate with the resilience of a person also correlate with patterns of ego development. Thus, a better understanding of the relationships between the resilience and ego development of a person and the capacity to interact with critical infrastructure can influence outcomes in response different types of disturbances and infrastructure system failures.

In the second study, multiple sets of data collected over a 20 year period found associations between ego-development and a set of themes characterizing a group of people demonstrating resilient outcomes in young adult life despite extreme adversity in childhood (Hauser 1999; Gralinski-Bakker et al. 2004). The research posits a perspective of resilience as the positive adaptation in response to adversity (Masten, A., Best, K., & Garmezy 1990) and includes measurements and assessments of both internal states of being *and* observed actions and outcomes (Hauser 1999; Gralinski-Bakker et al. 2004). The research findings are relevant to our integration of human resilience and development with critical resilience for two reasons.

First, whereas the research described above reviewed data collected at the end points of a nine year period, this longitudinal study collected data over a period of 20 years, in addition to the endpoints, including adolescence and young adulthood. Although single cross-sectional or time-point assessments can yield valuable insights, a temporal dimension of research data is vital to understanding potential trajectories of resilient development in humans (Gralinski-Bakker et al. 2004; Hauser 1999), technical systems (Park et al. 2013; Linkov et al. 2013), and social systems (Walker et al. 2004; K. Brown and Westaway 2011).

The second reason this study is relevant to the present work is the comprehensive research approach, tools, and methods used. The instruments, which included Loevinger's ego development tool, provided reliable and repeatable measurements of the protective factors, which were later used as predictors of outcomes (Gralinski-Bakker et al. 2004) in the third phase of data collection. The factors characterize a perspective of resilience as an *internal* state of being and positive adaptation to adverse events and changing life and environmental conditions (Hauser 1999). In other words, the research included both endogenous and exogenous measures and assessments of resilient human development. The rigor of data collection, analysis, and published findings of Hauser's research supports our conceptual framework for integrating a perspective of resilient human development with critical infrastructure resilience. The evidence of predictors in the study holds promise for enhancing anticipation of possible and unknown future conditions and outcomes for different infrastructure scenarios. Moreover, the ontological structure of developmental stages can have implications regarding potential resilient pathways and outcomes for critical infrastructure systems amid unanticipated adversity, complexity, and uncertainty, which includes natural and man-made disasters.

Ego development stages influence on the SAAL processes

Although stages may be viewed as coherent personality structures, Loevinger considered ego as a reference frame or a "lens" influencing an individuals' perceptions of the world (Cohn and Westenberg 2004). In simple terms, this means ego development describes changes in a person's meanings and perceptions of experience over time. Thus, the stages summarized in Table 9, which are a focus of this study, represent coherent patterns of interrelated cognitive, emotional, and behavioral properties and processes (Cook-Greuter 2004a). That is, the stages provide a structural framework corresponding to a sequence of psychological dispositions describing how individuals can become aware of and interact with their environment. Moreover, whereas "the depth, complexity, and scope of what people notice can expand throughout life," (Cook-Greuter, 2004a, p4), protective factors like resilience and adaptive capacity are enhanced in later stages of development (Hauser 1999; Gralinski-Bakker et al. 2004; Westenberg and Block 1993). This means identifying stages of development for individuals with certain roles and responsibilities can contribute toward understanding how the dynamic interactions between humans and critical infrastructures may impact infrastructure resilience. Ego-development stages can be measured using scientific methods (Loevinger and Wessler 1970; Loevinger 1979; Cohn and Westenberg 2004; Hauser 1993), which means it is possible to investigate the relationships between human development and protective factors related to human and critical infrastructure resilience. In other words, the stages are identifiable by a rational, logical, and repeatable method of psychological pattern recognition. Thus, stages offer a ontological structure for investigating the relationships between human resilience, development, and the SAAL processes coupling human and technological systems. Although individuals tend to operate at a dominant stage, measurements reveal a Gaussian type distribution among different stages revealing a peak with leading and trailing edges reflecting growth and transformation.

We emphasize the four stages in Table 9 as a focus of our human development framework for two reasons. First, the distribution of stages in Cook-Greuter's data suggests that over 80% of the sample are at or below the conventional tier. Other researchers report similar findings whereby the majority of the adult population appear to reside at either the specialist or independent stages (Vincent 2015; Manners and Durkin 2000). We have excluded the survival and socialized stages based on our opinion that individuals at these stages are not likely found in infrastructure design, operation, and management environments.

Table 9 Ego development stages considered with the present work. Column one are stage names by Cook-Greuter and (Torbert), and stage id number. The methods of influence characterize how individuals at a given stage tend to interact with others when seeking influence. The response to feedback indicates how individuals are able to receive and integrate information about them from others. (Cook-Greuter 2004b; Torbert et al. 2004)

Stage—Cook-Greuter, [Stage id no.], (Torbert)	**Methods of influence**	**Response to feedback**
Conventional		
Specialist Self [3/4] (Expert)	Gives personal attention to detail and seeks perfection, argues own position and dismisses other' concerns	Takes feedback personally, defends own position, dismisses feedback from those who are not seen as experts in the same field
Independent Self [4] (Achievers)	Provides logical arguments, experience, makes task/goal-oriented contractual agreements	Accepts feedback, especially if it helps them to achieve their goals and to improve
Post-conventional		
Relative Self [4/5] (Individualist)	Adapts or ignores rules where needed, or invents new ones, open to discussion of issues and airs differences	Welcomes feedback as necessary for self-knowledge, and to uncover hidden aspects of their own behavior
Integrative Self [5] (Strategists)	Leads to reframing, reinterpreting situation, so that decisions support overall principle, strategy and foresight	Invites feedback for self-actualization, conflict is seen as an inevitable aspect of viable and multiple relationships

Second, post-conventional stages appear to reveal qualities of people associated with enhanced human resilience and adaptive capacity, which can have positive influence on the SAAL processes in relation to infrastructure resilience. Thus, there is an opportunity for growth and expansion from conventional to post-conventional ways of interpreting experience and interacting with environments like infrastructure via sensing, anticipating, adapting, and learning. Moreover, individuals at post-conventional stages can more readily adapt to more complex environments and changes because they are more flexible, and have more personal resources available to them. For example, these individuals have the ability to perceive another person's frame of reference and are more likely to respond in a way that is most effective to the task at hand by adapting their message to best be received by the other

(Cook-Greuter 2004a; Cook-Greuter 1999; Vincent, Ward, and Denson 2015). Thus, an integrated perspective of resilient human development reflecting the resilience of humans embedded within and among complex systems like critical infrastructure can enhance the resilience of the composite meta-system. Many of the properties of postconventional stages have been correlated with leadership effectiveness across a range of studies reporting similar findings (Vincent, Ward, and Denson 2015; Torbert et al. 2004; Cook-Greuter 2004a; Manners, Durkin, and Nesdale 2004). Common themes and characteristics include a higher toleration for ambiguity and uncertainty, increased ability to comprehend complexity, and a greater capacity to manage multiple and conflicting perspectives and emotions. These factors are relevant to certain roles and responsibilities in an infrastructure environment whereby people are interacting with other people and with technological systems. The dynamic interactions can influence potential resilient pathways and outcomes. Whereas the current stage for a given individual represents established psychological structures that can be measured, transitions to later stages are pathways of development representing a potential for growth that can be anticipated and thereby enhance critical infrastructure resilience. Further implications for infrastructure resilience include an enhanced capacity for complex interactions and adaptive response when faced with adverse conditions and technical system disruptions.

Ego development assessment tool and the SAAL processes

The widely adopted Washington University Sentence Completion Test (WUSCT) was created to make scientific measures of ego development (Loevinger & Wessler, 1970). The WUSCT has been administered to thousands of individuals participating in hundreds of research studies (Vincent, Ward, and Denson 2013), and translated into over ten languages (Cohn and Westenberg 2004). Examples of research topics using the WUSCT to support developmental perspectives include personality differences (Westenberg and Block 1993), leadership (Vincent, Ward, and Denson 2013; B. C. Brown 2011), management and organizational development (Torbert et al. 2004), and individual resilience (Hauser 1999; Gralinski-Bakker et al. 2004). In the 45 years since its introduction, Loevinger's ego development theory and conceptual model receive consistent recognition as one of the most comprehensive constructs of developmental psychology (Westenberg and Block 1993; Vincent, Ward, and Denson 2015; Manners and Durkin 2000; Cohn and Westenberg 2004). Loevinger's valued contribution to constructive stage theory of human development provides an established, verified, and reliable theoretical foundation, conceptual framework, and operational model for understanding adult psychosocial development. Thus, the ego development assessment tool provides a scientific means of obtaining empirical measurements indicating how actors in critical roles are capable of interacting with complex infrastructure systems when faced with disruptions. The SAAL processes coupled with the assessment tool can provide a developmental perspective of humans interacting with infrastructure. Such measurements can contribute toward understanding how and why human development can influence critical infrastructure resilience.

Discussion and future research

A developmental perspective of resilience can have broad application to large-scale natural or man-made disaster scenarios (Masten and Obradovic 2010). Disaster scenarios and catastrophic events include disruptions to infrastructure critical to public health, safety, and well-being that supports conditions for development to occur. Thus, we propose a method for investigating the relationships between human resilience, development, and critical infrastructure resilience.

An ontological framework is proposed that combines the conceptual frameworks of human resilience, development, and critical infrastructure resilience to form a single meta-framework. The SAAL processes are adapted from resilience engineering concepts and frameworks representing the resilience of a socio-technical system (Park et al. 2013; Hollnagel 2014; Woods 2015) as applied to critical infrastructure (Thomas et al. 2017). Common theoretical foundations consisting of cognitive, emotional, and behavioral dimensions of resilience (Reich, Zautra, and Hall 2010; Mischel and Shoda 1995) and human development (Cook-Greuter 1999) serve as a basis for linking the frameworks. Moreover, data from prior research revealing a strong, coherent relationship between resilience and development in adults (Hauser 1999; Gralinski-Bakker et al. 2004; Westenberg and Block 1993) further supports our rationale for research linking frameworks. With an emphasis on coupled social and technological systems, we offer three propositions for future research. The propositions serve as a starting point to operationalize an integrated framework of resilient human development and critical infrastructure.

Proposition 1: human development and infrastructure ontological framework

<u>Proposition 1a</u>: *The endogenous and exogenous properties and processes corresponding to sensing, anticipating, adapting, and learning at each stage of development are progressively more differentiated, enhanced, and effective amid higher degrees of complexity and uncertainty than earlier stages.*

<u>Proposition 1b</u>: *The shift in effectiveness from one stage to another within and among the social-technical processes can be significant, especially when transitioning from the last conventional stage to the first post-conventional stage.*

The proposed ontological framework integrating human resilience, development, and critical infrastructure is shown in Figure 5. The rows are the four stages of development identified earlier, and the columns represent the four social-technical processes, which are dynamically coupled to human resilience and critical infrastructure resilience (Thomas et al. 2017). The SAAL processes serve as a coupling mechanism linking infrastructure resilience concepts with human development concepts and structures. We posit that endogenous and exogenous properties and processes corresponding to sensing, anticipating, adapting, and learning are progressively differentiated for each stage of development as identified in the first column of Figure 5. Each stage reveals capacities for sensing, anticipating, adapting, and learning that are more enhanced, complex, and integrated compared to the prior stages. We also posit the differences between stages can have a significant influence on critical infrastructure resilience. For example, as an individual's development unfolds from conventional to post-conventional, there is a shift in capacity toward autonomy, sense of freedom, along with a higher tolerance of ambiguity and uncertainty (Cook-Greuter 2004a). The shift can impact how individuals interpret and respond to high degrees of complexity such as catastrophic system failures and disasters such as U.S. Airways flight 1549. Moreover, a capacity to comprehend complex systems is emergent at the post-conventional levels (Cook-Greuter 1999), which can impact critical infrastructure resilience.

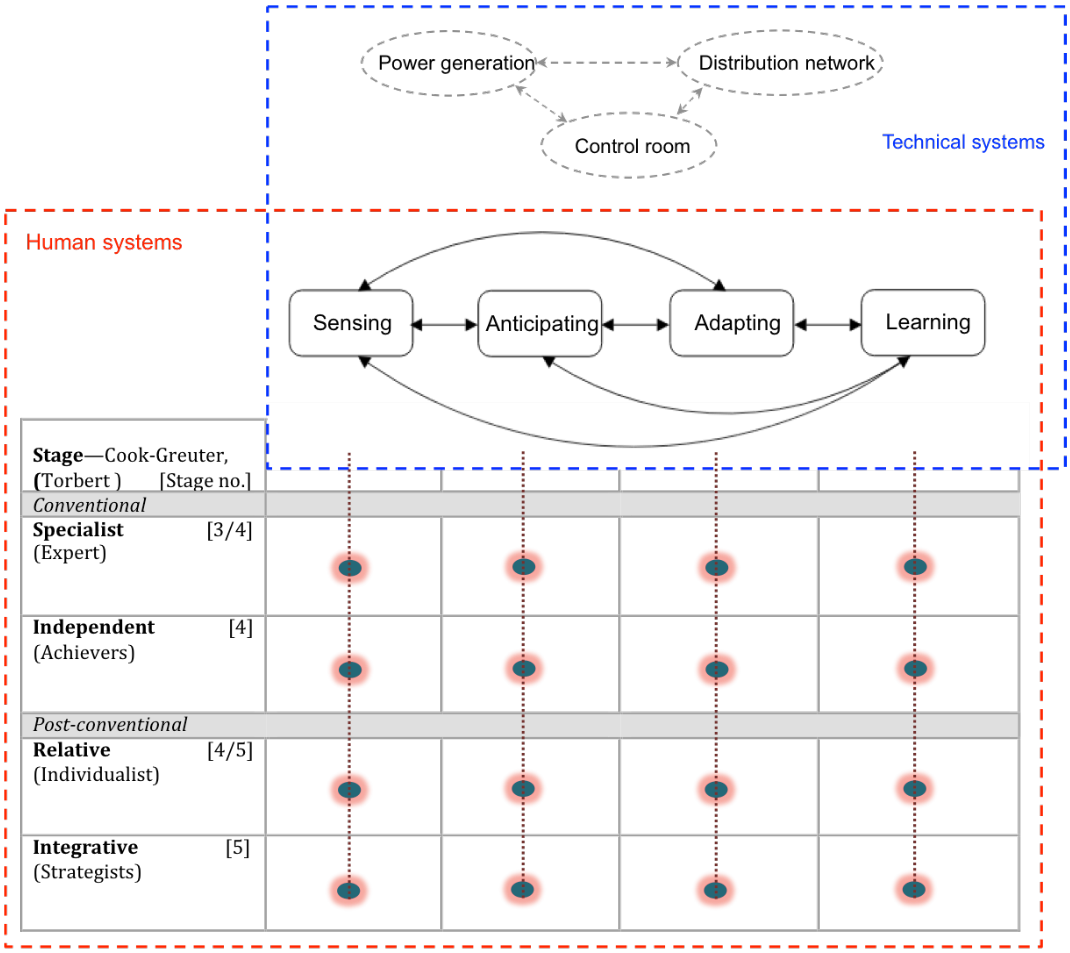

Figure 10 An ontological framework integrating human and technical systems. The framework integrates technical systems' resilience capacities with human meaning-making via the SAAL socio-technical processes. As development moves from the specialist toward the integrative stage, each cell describes the internal and external developmental properties representing the SAAL socio-technical processes—sensing, anticipating, adapting, and learning.

Proposition 2: Spatial and temporal scales and predictors

Proposition 2a: *The ontological framework in Figure 10 can accommodate continuous, contiguous, and heterogeneous spatial and temporal scales of critical infrastructure.*

Proposition 2b: *Knowledge of the relationship between the four stages of development and the SAAL processes can enhance infrastructure resilience across spatial and temporal scales.*

The integrated framework in Figure 10 can accommodate any spatial or temporal scales. That is, properties for a given scenario are relevant to the physical location where individuals interact with systems or heterogeneously by technology extension to remote locations. Moreover, properties corresponding to the social-technical processes—sensing, anticipating, adapting, and learning—can appear and shift over a lifespan from earlier to later stages of development.

We posit knowledge of the properties that appear at each stage of development assist with aligning strengths and capacities of individuals with roles and responsibilities for designers, operators, and managers thereby improving critical infrastructure resilience. Moreover, because stages occur as an invariant sequence over time (Cook-Greuter 1999; Loevinger 1976), knowledge of how the properties change at each stage can serve as a predictor of potential outcomes correlating with the SAAL processes representing critical infrastructure resilience. This is because individuals tend to respond according to a developmental center of gravity (Cook-Greuter 2004a), which means their cognitive, emotional, and behavioral dispositions are better understood. Thus, knowledge of how a person is capable of responding and interacting with complex systems can improve critical infrastructure resilience by providing an enhanced situational awareness and a more effective allocation of resources. For example, possible responses to varying levels of complexity and uncertainty related to infrastructure disruptions can be informed by an individual's stage of development thereby increasing the potential of aligning system requirements for sensing, anticipating, adapting, and learning with human resilience and developmental capacities.

Proposition 3: meaning-making dimension

Proposition 3: *Human meaning-making offers a third dimensional perspective of resilient social-technical systems like critical infrastructure whereby meanings and interpretations of problems and solutions can change with increasing complexity in later stages*

In addition to spatial and temporal dimensions of resilience, Holling & Gunderson (2002) argue that a third dimension representing symbolic meaning is relevant when people are involved with coupled systems. That is, human interpretations and perspectives are viewed as dimensions of resilience that can change in unpredictable ways among individuals or groups of people representing coupled social and ecological systems. The same principle of symbolic meaning applies to coupled social and technical systems like critical infrastructure. Changes in meanings across both short and long time scales give rise to resilience paradigms or schools of thought thereby extending the ontological diversity of critical infrastructure resilience. Thus, at any given time there could be multiple ways of viewing complex resilience problems and proposing solutions that are dependent on meanings and worldviews held by individuals and groups interacting with infrastructure.

Similar to the adaptive properties of other human coupled systems that are unpredictable due to novelty and uncertainty introduced by humans (Martin-Breen and Anderies 2011; Holling and Gunderson 2002), we posit that symbolic meaning offers an important dimensional perspective of resilient social-technical systems like critical infrastructure. Thus, another reason for incorporating ego-development in our framework linking people and technical systems is that ego-development theory and model rely on measurement of adult capacity for meaning-making. Moreover, Cook-Greuter's (1999) evolution of Loevinger's (1976) model offers a comprehensive and validated method for measuring the adult capacity for meaning-making relevant to the present application.

Because stages of development correspond to structures of adult meaning-making, we argue that ego-development is an effective way to account for the third dimension of resilience, in addition to space and time, influencing complex adaptive systems like critical infrastructure.

Conclusion

Human resilience, development, and critical infrastructure resilience can have reciprocal influence on one another. The ontological model shown in Figure 10 links resilience and development with technical systems by incorporating the endogenous and exogenous factors influencing the resilience of complex systems like infrastructure. The endogenous properties include the cognitive, emotional, and behavioral factors linking ego-development and human resilience. These factors form a developmental basis for human intentions, motivations, and agency that subsequently influences and informs social-technical processes of sensing, anticipating, adapting, and learning. The endogenous and exogenous properties are both recursive and reciprocal in nature, which means each system can interact and exchange influence in a repetitive manner, and each system can influence the resilience of other coupled systems. Future research designed to identify, apprehend, and validate the theoretical and conceptual frameworks presented herein with empirical data is recommended. Knowledge of the properties and processes corresponding to sensing, anticipating, adapting and learning for each stage of development will ground the theoretical and conceptual frameworks in practical research. A proven operational model can elucidate how each stage of resilient human development contributes unique qualities and capabilities needed by designers, operators, and managers to ensure the resilience of infrastructure critical to public health, safety, and well-being.

CONCLUSION

Federal directives calling for a holistic approach to infrastructure resilience fail to consider how humans may impact the adaptive capacity of socio-technical systems. This work presents a holistic perspective of socio-technical systems like infrastructure that incorporates the interior dimensions of human resilience and development with technological resilience concepts. The chapters of this thesis present a theoretical and conceptual analysis that builds upon one another to construct an ontological framework to support empirical verification in future research.

Chapter 2 examines the concept of holism in relation to critical infrastructure resilience and presents an Integral map as a holistic framework for organizing resilience knowledge across disciplines. A heuristic is presented that identifies the characteristics or each quadrant of the Integral map corresponding to experience, behavior, culture, and systems along with examples of related resilience concepts. The heuristic is applied to a group of 20 highly cited peer-reviewed resilience research articles from a range of academic disciplines representing different concepts, perspectives, and applications. The results indicate that systems perspectives of resilience dominate the epistemological orientation among the 20 articles reviewed followed by experience and behavioral perspectives. In contrast, none of the articles represent cultural perspectives corresponding to the social interior. Thus, the results suggest that important considerations like ethics, organizational values, and social coherence may be under appreciated in the scholarly literature. Community resilience and social vulnerability are presented as examples that contribute to the social interior and support a holistic perspective. Chapter 2 shows that a holistic approach to infrastructure resilience must incorporate the psychological dimensions of the human interior for both individuals and groups in addition to physical and operational factors related to behavior and systems.

The resilience of coupled socio-technical systems like critical infrastructure is addressed in Chapter 3 by incorporating resilience perspectives corresponding to the human interior dimensions identified in Chapter 2. Although abundant research exists that identifies the social and technological capacities that support the resilience of humans and infrastructure, little is known about how coupling may influence perspectives among separate literature. This chapter draws on concepts found in the resilience engineering and psychology literature to examine the relationships between the resilience of humans and infrastructure interacting with one another. The SAAL processes—sensing, anticipating, adapting, and learning—are used as a linking mechanism between human and technological resilience capacities. The analysis in Chapter 3 suggests that many of the human and technical resilience capacities reviewed are interconnected, interrelated, and interdependent. This work contributes a perspective of socio-technical systems that includes the *affective* dimension of human resilience and shows that the resilience engineering literature is focused more on cognitive and behavioral dimensions of humans. Taken further, the results of this work suggests that resilience engineering of technical systems must consider the cognitive, behavioral, *and* affective dimensions of human resilience representing the people embedded in critical infrastructure.

The holistic concepts of Chapter 2 and coupled socio-technical systems concepts in Chapter 3 are applied to investigate the relationships between psychological human development and critical infrastructure resilience in Chapter 4. Although infrastructure systems are often interconnected, interrelated, and interdependent, less is known about how the human capacity to develop and adapt to unanticipated complexity may influence the resilience of coupled systems. The work in Chapter 4 examines how human development can influence infrastructure resilience by considering how stages (i.e., action logics) representing patterns of meaning-making can impact human perceptions and interpretations of resilience. These factors then help determine how complex resilience problems are understood and what types of solutions are considered. Chapter 4 contributes an ontological framework that integrates human development with infrastructure resilience by using the SAAL processes as a linking mechanism similar to Chapter 3. The framework shows how different stages of development have different levels of influence on the SAAL processes and how knowledge of the differences can help align key roles and responsibilities with human capacities and resources. Finally, the research suggests that the SAAL processes are increasingly more differentiated, enhanced, and effective amid high degrees of complexity and uncertainty in later stages of development compared to earlier stages. The human capacity for meaning-making offers a third scale in addition to time and space thereby offering a more comprehensive and dynamic understanding of resilience. Thus, knowledge of what capacities are available for different stages of development can enhance anticipation of human interactions with infrastructure amid catastrophic system failure and improve socio-technical system resilience.

Novel contributions of this research related to the SAAL socio-technical processes include 1) a conceptual model linking human and technical resilience capacities, 2) identified and illustrated the reciprocal properties, 3) incorporate the affective dimension of human resilience, 4) SAAL properties are more enhanced in later stages, 5) an ontological framework linking technical resilience capacities with stages of development. Each contribution emphasizes how the SAAL processes can be applied toward a holistic integration of human and infrastructure resilience. Taken together, the contributions of this thesis show how the resilience of infrastructure essential to public health, safety, and well-being is related to the resilience of the individuals and groups responsible for the technical system design, operation, and maintenance.

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APPENDIX A

PREVIOUSLY PUBLISHED MATERIAL AND CO-AUTHOR PERMISSION

Chapter 2 is under review to be published in the peer-review journal *Environment Systems and Decisions*

Chapter 3 is under review to be published in the peer-review journal *Homeland Security and Emergency Management*

All co-authors have granted their permission for the use of this material in this dissertation.

APPENDIX B

SUPPORTING INFORMATION FOR CHAPTER 3

Technical resilience capacities

Resilience capacity	Description	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, Brown, and Carlyle 2014), (Dinh et al. 2012)
8. Coping	Capacity to sustain unexpected surprise & 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 & 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)

Technical Resilience Capacities

Resilience Capacity	Description	Authors
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 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)

Human resilience capacities—Cognitive

Human Resilience	Description	Authors
1. Balanced perspective on experience-o	Personal beliefs that promote a sense of meaning and purpose (p95-o); 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, & resolve-o	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 2014) (Dyer and Mcguinness 1996)
3. Moral reasoning-k	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-c	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-c, k	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 (a-147)	(Connor and Davidson 2003), (Connor 2006), (Rutter 1985) adult p106
6. Self-esteem-k, c	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-c	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)

Human resilience capacities—Affective

Human Resilience	Description	Authors
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, A., Parsa, A. & 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.	(Murphy, Johnson, & Lohan, 2003; Park & Folkman, 1997) (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 life's challenges are related more to an individuals 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),

Human resilience capacities—Affective

Resilience Capacity	Description	Authors
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)

Human resilience capacities—Behavioral

Human Resilience Capacities	Description	References
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 & 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), (Rutter 1987) (Olsson et al. 2003) (Skodol 2010)

Human resilience capacities—Behavioral

Human Resilience Capacities	Description	References
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)