A Psychological Framework for the Design of System Interventions that Increase Resilience

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ABSTRACT

Increased levels of automation at modern workplaces in industry, business, and transportation generally increase safety and productivity but sometimes negatively impact the ability to withstand unexpected adverse events. A side effect of such high levels of automation can result in humans performing fewer macrocognitive functions which can lead to reduced adaptability. In this paper we address this issue by identifying an integrative psychological framework to guide the design of technological and non-technological interventions for increased system resilience. The framework is derived from approaches in cognitive psychology, human factors, and neurobiology and focuses on the facilitation of positive appraisal processes. We present this framework to solicit feedback and to subsequently apply it to the design of resilient systems in advanced manufacturing and automated driving.

Author Keywords
System resilience; psychological framework; appraisal theory; automation; design guidance; human factors.

ACM Classification Keywords
H.1.2. User /Machine Systems: Human factors.

INTRODUCTION

Trends in modern working environments such as industrial manufacturing, business, aviation, and in the automotive domain show increasing levels of automation that have been changing and partly replacing human tasks. This applies not only to manual tasks, but also to information tasks. The high levels of automation have often increased safety and productivity by allowing to operate closer and more reliably to a system's optimal performance. For example, aircraft flight management systems can fly optimized energy efficient profiles that reduce the burning of fuel over extended flight durations. Also, automated flight planning software finds the most optimal flight path considering winds and weather conditions. International aviation innovation programs use automation to further increase predictability and efficiency of flights beyond what pilots and controllers can achieve through manual interaction ([1] and [2]). In the automotive domain, automated driving is intended to increase fuel efficiency, safety, and comfort [3].

These performance increases however are sometimes offset by decreases in system resilience. Resilience is the ability to prepare and plan for, absorb or mitigate, recover from, or more successfully adapt to actual or potential adverse events [4]. According to, Holling ([5]), increasing a system's ability to operate near a narrow optimum range may actually decrease its ability to recover from non-nominal adverse events that are further away from that optimality.

For examples, business information systems (BIS) represent information automation intended to generate performance improvements through enterprise process standardization [6]. They play a critical role in the daily operation of such enterprises to timely deliver business-relevant information to decision makers [7]. Such automation systems require narrow and clearly defined user interactions, thereby creating increased error opportunities under adverse conditions if appropriate interaction protocols have only been defined for non-adverse conditions. As consequence, managerial decisions can be faulty and lead to organizational crises. Such risks have been investigated, for example, by [8] for a large-scale enterprise.

Decreases in system resilience as results of automation have also been observed in aviation where pilots of highly automated flight decks sometimes report that the automated functions work in unexpected ways, that they are sometimes unsure about whether and when to terminate automation, and that they sometimes experience reduced levels of situation awareness [9]. In July 2013, the pilots of flight Asiana 214 on their approach to San Francisco International Airport missed to manage the aircraft's speed, erroneously assuming that flight deck automation was controlling the air speed [10]. The aircraft stalled as result and crashed on the runway. Similarly, pilots on board of Air France Flight 447 in June 2016 were unable to recover from a momentary disengagement of the autopilot due to failures of the sensed air speed and to manually stabilize the flight. They subsequently crashed into the sea [11].

Similarly, supplier delivery networks that involve complex process and information automation are highly sensitive to the impact of adverse events. For example, Boeing experienced in 1997 an estimated loss of $ 2.6 billion due to supplier delivery failure of critical parts [12]. Similarly, the manufacturing domain with complex automation is sensitivity to adverse events. For example, a fire that erupted at a plant of Philips in New Mexico in 2001 caused losses of sales of high-margin computer chips of a value up to $40 million [13].

One reason why in some cases increased levels of automation and information management may decrease a systems' resilience has been attributed to a decrease in humans' macrocognitive functions [14]. Macrocognitive functions consist of cycles of problem detection, sense-making, replanning, deciding, and coordinating. The execution of such functions allows humans to take control under adverse events. For example, Captain Sullenberger landed an Airbus 320 on the Hudson river in January 2009 after a flock of geese that had been ingested in the jet engines, disabling both engines soon after liftoff [15]. The captain and his crew were able to land the airplane on a river.

On the other hand, humans not only save failing systems, sometimes their decisions make things worse. Inherent limitations in our cognitive abilities can stand in the way of controlling complex systems, like airplanes, organizations, or large scale weather event recoveries. [16] investigated human responses of recovery after major weather events where they report observing the impact of "cognitive framing": humans are influenced by how information is presented rather than its content (see e.g. [17] and [18]).

How could automation be designed that increases productivity and safety but also increases their resilience? One way consists of building additional safeguards into systems. For example, production systems can mitigate the effects of machine disruptions by designing redundant and flexible functionalities [19]. In office environments, BIS have to be designed such that unforeseen conditions can be detected and do not lead to system failures, such as by providing user interfaces that reduce error opportunities and by guiding users how to resolve errors once they have occurred [6]. However, building safeguards into systems can be expensive and in the end not address all previously unforeseen conditions. Therefore we explore alternative ways to increase system resilience, that is by setting interventions that enable humans intrinsic resilience capabilities.

Intervening for Resilience

Resilience engineering addresses the question how systems can be made more resilient; *"When we see things go right under difficult circumstances, we've found that it's mostly because of people's adaptive capacity—their ability to recognize, absorb, and adapt to changes and disruptions—some of which may even fall outside of what the system has been trained or designed to do"* [20]. Resilience engineering postulates four cornerstones that help organizations and humans to increase system resilience [20]:

- Knowing what to look for, ie. to identify signs of crisis before they occur
- Knowing what to do, i.e. to respond to the signs of crisis in appropriate ways
- Knowing what to expect, i.e. how to anticipate future crises
- Knowing what has happened, i.e. to learn from experience to strengthen resilience on these four dimensions

The four cornerstones for resilient systems also point to the importance of human macrocognitive functions ([14]) but it remains unclear how interventions or humans themselves can enable them. In the psychological and neurobiological domains, [21] have proposed a unified theoretical framework for the study of general resilience. The "Positive Appraisal Style Theory of Resilience (PASTOR)" framework postulates that *positive appraisal style, positive reappraisal*, and *interference inhibition* are the key mechanisms leading to resilient behavior and that they mediate the effects of other resilience factors. Positive appraisal styles consist of a generalized tendency to appraise potentially aversive stimuli in a non-negative fashion. Positive reappraisals occur if, after initial negative appraisals of a situation, reappraisal processes ultimately allow for positive appraisal outcomes. Active inhibition processes allow positive appraisals to persist in the presence of possible concurrent negative appraisals that can be prevalent in strongly aversive situations.
To further understand what contributes to positive appraisal processes, [21] refers to a more detailed theory of cognitive appraisal processes, specifically, the "Sequential Check Theory of Emotion Differentiation" by [22] which differentiates four appraisal assessment strategies that allow humans to positively adapt to situations:

- Detect the relevance of a crisis signal
- Assess its implications,
- Determine coping potential, and
- Check for its normative significance, ie. against internal and external standards and ideals.

Integrating the approaches of [20], [21], and [22] allows us to postulate a psychological framework for designing technological and non-technological interventions to increase (ecological) systems resilience.

FRAMEWORK OF INTERVENTIONS TO INCREASE SYSTEM RESILIENCE

The fundamental assumption of the framework is that enabling positive appraisal processes are key to initiate the needed controls to keep a system functioning under adverse conditions. The framework consists of five components, labeled A to E in Figure 1 that enable resilient responses to a sign of crisis. *Component A* describes the precursors for resilience including individual, environmental and social aspects that need to be in place prior to a sign of crisis. Once a sign of crisis has surfaced, appraisal processes (*component B*) lead to an adaptive response, or if not, *component C* describes the reappraisal processes that would revert initially negative appraisals to eventually positive appraisals. Once positive appraisals have been reached, a resilience increasing response can be given. *Component D* describes the inhibition of negative appraisal processes that may invert the initial positive appraisal processes. *Component E* finally describes how people, organizations and systems can hold the learned resilience knowledge and expertise. The framework of resilience combines three different approaches; [21] informed components A., C., D., and to some extent B., [22] informed B. in more detail, and [20] informed E.

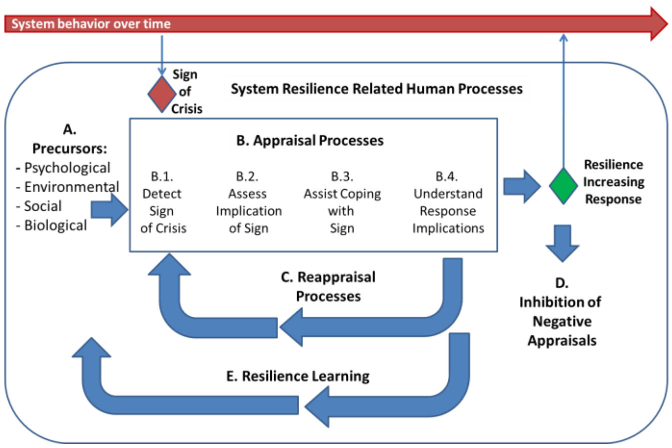

Figure 1 Framework to Increase System Resilience through Facilitation of Appraisal Processes

A. Precursors for Resilience

Multiple precursors for resilience can be found in psychological, environmental, social, and biological preconditions [23] that facilitate people's engagement in positive appraisal styles. [24] describes the concept of *learned helplessness* that explains why people sometimes lose their ability to control a situation and therefore exhibit a reduced likelihood of positive appraisals. [25] describes inter-individual differences in attributing external and internal control; for example, attributing rewards to external circumstances (e.g. "this was pure luck") would decrease positive appraisals. Further, attitudes about individual self-value have an impact on appraisals. For example, [26] describe the effect of brief, stealthy, and psychologically precise interventions that can increase the likelihood of students positively appraising their failures by helping them consider the impact of the situational context. On the biological level, age, gender, fatigue, and health can have an impact on positive appraisals. On the social level, support, cohesion, and level of social participation have an impact. Increased stress levels (e.g. induced through noise, reduced comfort, attentional demands, and distractions in the environment) have a detrimental impact on appraisal processes, see e.g. [27]. In addition, [28] postulates appropriate knowledge as a mediating factor for positive appraisals, such as attained via education, specialized training, or work experience.

Interventions that facilitate such resilience precursors include education (e.g. "what is resilience", "how do people differ", "how can it be strengthened"), training (e.g. "practice engaging in positive adaptive response styles"), psychological support (e.g. through metareflective or psychotherapeutic strengthening of internal loci of control and reduced helplessness), organizational support, and social modeling (providing exemplary behavior for positive appraisals). Most of these interventions are inherently non-technological, though technological support options may exist (such as virtual support, courses, or social media).

B. Appraisal Processes

Once the first sign of crisis has surfaced, individuals may engage in a series of four types of appraisal processes, see [22]. The time interval between the first occurrence of a sign of crisis and the actual crisis may vary considerably.

B.1. Detect signs of crisis

To detect a sign of crisis, an individual needs to scan the environment and perform a *novelty check*. Detection depends on the degree of familiarity with the environment and its structural complexity, as well as the quality of the signal itself. The likelihood of further processing is then influenced by what [22] calls a *pleasant / unpleasantness check*. For example, the captain of the taking-off aircraft KLM 4805 on March 27th, 1977 in Tenerife, a highly trained pilot, ignored a clear sign of crisis that his flight engineer gave when he warned about another aircraft on the runway well prior to the subsequent crash. However, the captain of the B747 discregarded that information and pursued the takeoff [29].

Next a *goal relevance check* establishes whether a potential crisis signal impacts the goals of the observer. A goal-discordant sign may be ignored. For example, the observation of a slight deviation in size of a manufactured good on the production line may not directly impact the worker who observes it but may have a significant impact further down the line [30]. Because the sign is not relevant to the worker who observes it, the sign may be ignored.

Existing technological interventions that increase the likelihood of detecting signs of crisis are warning systems. For example, the Terrain Awareness Warning System (TAWS) warns pilots if they are in immediate danger of flying into the ground [31]. Non-technological interventions could consist of "wise interventions" [32] that trigger specific psychological processes that modify and increase likelihood of crisis sign detection. Also, the reduction of distractions such as acoustic interference during highly stressful situations could increase the likelihood of detection.

B.2. Understand the implications of signs of crises

Once detected, the implications of the sign are assessed. Its *causal attributes* are checked (e.g. could the sign of crisis represent a false alarm or does it originate from a non-well-intending individual) and the *likely outcomes* are assessed.

For this check, contextual information about the situation is needed. Also, it needs to be assessed whether a crisis signal is conducive to one's *individual goal (e.g.* the illuminated fuel reserve indicator light close to the travel destination would not be a severe crisis signal). An *urgency check* determines the immediacy with which an adaptive response may be required. Technological interventions that increase an operators' situational awareness could help understand signs of crisis. For example, moving maps support pilots' location awareness when taxiing on the airport surface or decision support tools or digital assistants can help assess the implications of signs of crisis.

B.3. Understand the coping potential

Coping potential is understood by performing a *control check* that determines to what degree a situation can be influenced at all (e.g. weather situations are not controllable but airplanes generally are) and a *power check* determines whether the individual has the needed abilities to address the sign of crisis (e.g. whether somebody has the knowledge to fly an airplane). Decision support tools could help understand an individual whether and how to cope with an event. If a crisis cannot be prevented, an *adjustment check* could lead an individual to decide to accept the consequences of the crisis. Also, information communication tools may allow individuals to contact experts to better understand or increase coping potential.

B.4. Understand the normative significance

If the outcomes of the positive appraisal processes are inconsistent with the individual's own internal standards and social norms of the environment, a crisis intervention may not be executed despite the ability to do so. Social network technological could be used to facilitate such assessments or disseminate positive examples for resilient behavior.

C. Reappraisal Processes

If initial appraisal processes have not led to a positive appraisal, subsequent reappraisal processes may lead to different outcomes. Under the urgency of an initial crisis signal, high arousal levels can make it difficult to identify positive adaptive options. Also, crisis signals that do not fit into the expected system behavior or do not fit the prevalent social norms may be initially ignored and may need to be reappraised. At this time, new information may emerge to help the individual positively reappraise the situation. Reappraisal processes may become more likely if sufficient time between the first sign of the crisis and the actual crisis exists. The continued display of crisis urgency indicators as well as the display of positive coping options may serve as interventions to lead to positive reappraisals.

D. Inhibition of Negative Appraisals

Positive appraisals may over time discontinue and change to negative appraisals if environmental or individual conditions change, such as increased workload, stress, or physical or emotional exhaustion. The inhibition of negative appraisals is therefore intended to allow positive appraisals to persist. Technological interventions such as social communication of positive appraisal processes may "lock" individuals into their path and reduce the likelihood of inhibiting future negative appraisal processes.

E. Resilience Learning

Over the lifetime of a system, crises may continuously occur and therefore form opportunities to learn and transmit knowledge to later generations about how crises can be effectively handled, thereby increasing the resilience of the overall system. For example, the appropriate farming practices within a given environment have developed over time to reduce undesired erosions or soil-depletion and have been carried between generations. Transmission of such knowledge increases overall system resilience and requires transmission processes [33] that could be facilitated through digital assistance or knowledge management tools.

CONCLUSIONS

In this paper we have proposed an integrated psychological framework for designing interventions to increase system resilience. Our next steps will consist of validating this framework by deriving specific hypotheses that differentiate the implications from other frameworks. Second, we plan to test the framework by deriving technological and non-technological intervention strategies in two different domains, automated driving and advanced manufacturing and evaluate their impact on system resilience.

REFERENCES

[1] Federal Aviation Administration, "The Future of the NAS," Jun-2016. [Online]. Available: https://www.faa.gov/nextgen/media/futureOfTheNAS.pdf. [Accessed: 03-Aug-2016].

[2] Eurocontrol, "European ATM Master Plan," 2015. [Online]. Available: https://www.atmmasterplan.eu/. [Accessed: 03-Aug-2016].

[3] ERTRAC, "Automated Driving Roadmap," Version 5.0, Jul. 2015.

[4] D. D. Walden, G. J. Roedler, K. Forsberg, R. D. Hamelin, T. M. Shortell, and International Council on Systems Engineering, Eds., *Systems engineering handbook: a guide for system life cycle processes and activities*, 4th edition. Hoboken, New Jersey: John Wiley & Sons Inc, 2015.

[5] C. S. Holling, "Engineering Resilience versus Ecological Resilience," in *Engineering Within Ecological Constraints*, Washington, D.C.: NATIONAL ACADEMY PRESS, 1996, pp. 31–43.

[6] G. Müller, T. G. Koslowski, and R. Accorsi, "Resilience - A New Reseach Field in Business Information Systems?," in *Business Information Systems Workshops*, vol. 160, W. Abramowicz, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 3–14.

[7] K. Pan, M. Baptista Nunes, and G. Chao Peng, “Risks affecting ERP post-implementation: Insights from a large Chinese manufacturing group,” *J. Manuf. Technol. Manag.*, vol. 22, no. 1, pp. 107–130, Jan. 2011.

[8] J. W. Wang, F. Gao, and W. H. Ip, “Measurement of resilience and its application to enterprise information systems,” *Enterp. Inf. Syst.*, Apr. 2010.

[9] Federal Aviation Administration, “The Interfaces Between Flightcrews and Modern Flight Deck Systems,” 18-Jun-1996. [Online]. Available: http://ocw.mit.edu/courses/aeronautics-and-astronautics/16-422-human-supervisory-control-of-automated-systems-spring-2004/readings/interfac.pdf. [Accessed: 03-Aug-2016].

[10] Wikipedia, “Asiana Airlines Flight 214 - Wikipedia, the free encyclopedia.” [Online]. Available: https://en.wikipedia.org/wiki/Asiana_Airlines_Flight_214. [Accessed: 03-Aug-2016].

[11] Bureau d’Enquêtes et d’Analyses, pour la sécurité de l’aviation civile, and Bureau d’Enquêtes et d’Analyses, “On the accident on 1st June 2009 to the Airbus A330-203 registered F-GZCP operated by Air France flight AF 447 Rio de Janeiro - Paris.” [Online]. Available: https://www.bea.aero/docspa/2009/f-cp090601.en/pdf/f-cp090601.en.pdf. [Accessed: 03-Aug-2016].

[12] J. Blackhurst *, C. W. Craighead, D. Elkins, and R. B. Handfield, “An empirically derived agenda of critical research issues for managing supply-chain disruptions,” *Int. J. Prod. Res.*, vol. 43, no. 19, pp. 4067–4081, Oct. 2005.

[13] Y. Sheffi, *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage*. Cambridge, MA: MIT Press, 2007.

[14] E. S. Patterson, L. G. Militello, G. Su, and U. Sarkar, “Characterizing a Naturalistic Decision-Making Phenomenon Loss of System Resilience Associated With Implementation of New Technology,” *J. Cogn. Eng. Decis. Mak.*, vol. 10, no. 3, pp. 229–243, 2016.

[15] National Transportation Safety Board, “Loss of Thrust in Both Engines After Encountering a Flock of Birds and Subsequent Ditching on the Hudson River US Airways Flight 1549 Airbus A320-214, N106US Weehawken, New Jersey January 15, 2009,” NTSB/AAR-10/03 PB2010-910403, 2010.

[16] B. S. Caldwell, “Cognitive challenges to resilience dynamics in managing large-scale event response,” *J. Cogn. Eng. Decis. Mak.*, pp. 318–329, 2014.

[17] A. Tversky and D. Kahneman, “The Framing of Decisions and the Psychology of Choice,” *Science*, vol. 211, no. 4481, pp. 453–458, 1981.

[18] S. Plous, *The psychology of judgment and decision making*. New York: McGraw-Hill, 1993.

[19] X. Gu, X. Jin, J. Ni, and Y. Koren, “Manufacturing System Design for Resilience,” *Procedia CIRP*, vol. 36, pp. 135–140, 2015.

[20] S. Dekker, E. Hollnagel, D. Woods, and R. Cook, “Resilience Engineering: New directions for measuring and maintaining safety in complex systems,” *Lund Univ. Sch. Aviat.*, 2008.

[21] R. Kalisch, M. B. Müller, and O. Tüscher, “A conceptual framework for the neurobiological study of resilience,” *Behav. Brain Sci.*, pp. 1–49, Aug. 2014.

[22] K. R. Scherer, “Appraisal Considered as a process of Multilevel Sequential Checking,” in *Appraisal considered as a process of multi-level sequential checking.*, K. R. Scherer, Schorr, A., and Johnstone, T., Eds. New York and Oxford: Oxford University Press, pp. 92–120.

[23] G. Windle, K. M. Bennett, and J. Noyes, “A methodological review of resilience measurement scales,” *Health Qual. Life Outcomes*, vol. 9, no. 1, p. 1, 2011.

[24] M. E. Seligman, “Learned helplessness,” *Annu. Rev. Med.*, vol. 23, no. 1, pp. 407–412, 1972.

[25] J. B. Rotter, “Generalized expectancies for internal versus external control of reinforcement.,” *Psychol. Monogr. Gen. Appl.*, vol. 80, no. 1, p. 1, 1966.

[26] E. Brummelman and G. M. Walton, “‘If you want to understand something, try to change it’: Social-psychological interventions to cultivate resilience.,” *Behav. Brain Sci.*, vol. 38, pp. 24–25.

[27] M. A. Staal, “Stress, cognition, and human performance: A literature review and conceptual framework,” 2004.

[28] J. Y. F. Lau, “Knowledge and resilience,” *Behav. Brain Sci.*, vol. 38, pp. 37–38.

[29] ICAO, “Final Report and Comments of the Netherlands Aviation Safety Board of the Investigation into the Accident with the Collision of KLM Flight 4805, Boeing 747-206B, PH-BUF and Pan American Flight 1736, Boeing 747-121, N736PA at Tenerife Airport, Spain on 27 March 1977,” ICAO, Circular 153-An/56.

[30] J. Denner, P. Heinrich, C. Heldman, and A. Richter, “First version of requirements of workers and organisations,” Factors4Workers Project Deliverable 1.2 Volume 2, 11 2015.

[31] Federal Aviation Administration, “AC 23-18 - Installation of Terrain Awareness and Warning System Approved or Part 23 Airplanes - AC_23-18.pdf,” 24-Jun-2000. [Online]. Available: http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_23-18.pdf. [Accessed: 03-Aug-2016].

[32] G. M. Walton, “The New Science of Wise Psychological Interventions,” *Curr. Dir. Psychol. Sci.*, vol. 23, no. 1, pp. 73–82, 2014.

[33] W. Berry and N. Wirzba, The art of the commonplace: the agrarian essays of Wendell Berry. Washington, D.C: Shoemaker & Hoard, 2002.