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Bridging Psychology and Engineering to Make Technology Work for People

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Engineering grand challenges and big ideas not only demand innovative engineering solutions, but also typically involve and affect human thought, behavior, and quality of life. To solve these types of complex problems, multidisciplinary teams must bring together experts in engineering and psychological science, yet fusing these distinct areas can be difficult. This article describes how Human Systems Engineering (HSE) researchers have confronted such challenges at the interface of humans and technological systems. Two narrative cases are reported—computer game-based cognitive assessments and medical device reprocessing—and lessons learned are shared. The article then discusses 2 strategies currently being explored to enact such lessons and enhance these kinds of multidisciplinary engineering teams: a "top-down" administrative approach that supports team formation and productivity through a university research center, and a "bottom-up" engineering education approach that prepares students to work at the intersection of psychology and engineering.

Keywords: Human Systems Engineering, engineering education, cognitive assessment, medical device reprocessing, university research centers

The National Academy of Engineering's (NAE's) *Grand Challenges* (National Academy of Engineering [NAE], 2017) and the National Science Foundation's (NSF's) *Big Ideas* (National Science Foundation, 2016) exemplify a rising trend toward use-inspired research and problem-driven science. Problem-solving and innovation at this scale demand cooperation between many fields, and scientists and engineers are increasingly collaborating and publishing across disciplines (National Research Council, 2015). These multidisciplinary research teams can be large, diverse, and sometimes dysfunctional (Börner et al., 2010; Hall et al., 2018; Stokols, Misra, Moser, Hall, & Taylor, 2008; Thayer, Petruzzelli, & McClurg, 2018). Team members may be driven by different theories, assumptions, and applications, which in turn leads to conflicts about overarching goals or best practices. Team communication and productivity are connected to differences in terminology, methodology, or epistemology (Bosque-Pérez et al., 2016; O'Rourke & Crowley, 2013; O'Rourke, Crowley, & Gonnerman, 2016), and breakdowns occur when team members cannot "talk to each other" and struggle to appreciate their respective contributions.

In many cases, the problems tackled by these teams also fundamentally involve and affect *people*. Topics such as cybersecurity, personalized learning, robotics, social media, and telemedicine are technological and sociocultural frontiers that demand input from psychological science. For example, one NAE Grand Challenge to "secure cyberspace" entails protecting "critical systems in banking, national security, and physical structure" and combating threats to personal and corporate data privacy. Engineering solutions present one avenue for tackling this challenge, such as developing more secure operating systems, programming languages, authentication methods, and data transfer protocols (e.g., Cherdantseva et al., 2016). However, the human elements of cybersecurity, cybercrime, and cyberterrorism

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are equally important, including the cognitive, social, and cultural factors that explain how and why people interact with computers with malicious intent and the system-level vulnerabilities that emerge from users' behavior and relationships (Gutzwiller, Fugate, Sawyer, & Hancock, 2015; Jang-Jaccard & Nepal, 2014). Similarly, advances in automation are transforming the workforce in various industries and pushing toward teams comprising human and automated agent members (Fiore & Wiltshire, 2016). The growth of automation has also inspired fears about job loss (Frey & Osborne, 2017) and life-threatening failures of autonomy (e.g., accidents involving autonomous vehicles). Engineers and psychologists must collaborate to develop automation and take into account its complex impacts on people and society (Endsley, 2017; Strauch, 2018).

To pursue this bridging of psychology and engineering, a group of researchers and educators at Arizona State University (ASU) have adopted the approach of Human Systems Engineering (HSE). Specifically, HSE is a recently created program within the Polytechnic School of the Ira A. Fulton Schools of Engineering that aims to proactively infuse engineering and engineering education with foundational principles drawn from psychology, cognitive science, human factors, human systems integration (HSI), usability, and allied disciplines. A goal of this article is to discuss the value of HSE in multidisciplinary teaming between psychologists and engineers. To this end, this article outlines principles of an HSE approach (e.g., applied, human-centered, system-oriented, iterative, empirical, and intrinsically multidisciplinary) and presents two narrative cases. Each case summarizes team formation, goals, and contributions along with lessons learned from each multidisciplinary effort. Two ongoing strategies for enhancing multidisciplinary engineering teams are then described: a "top-down" administrative strategy to offer collaborative networking and team science expertise to facilitate team formation and productivity, and a "bottom-up" educational strategy to prepare future engineers and ensure they gain appreciation of the intersection of psychology and engineering.

HSE Principles and Two Narrative Cases

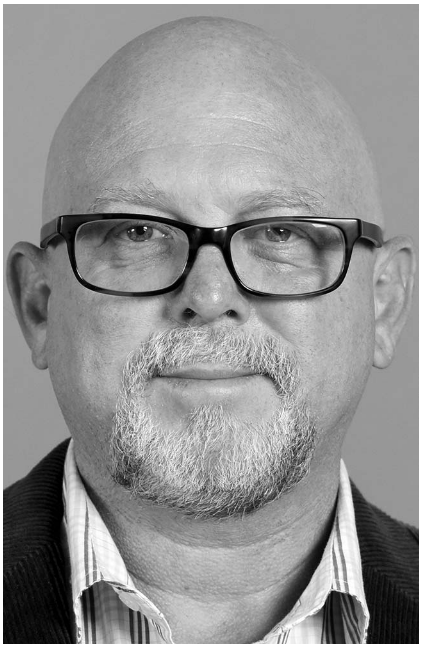
HSE integrates psychological and engineering perspectives to study and solve human-centered technological problems at multiple levels. This approach draws upon expertise from established fields such as human factors, ergonomics, human–computer interaction (HCI), HSI, and other allied disciplines. From these foundations are derived a set of guiding or defining principles for HSE.

First, and fundamentally, *HSE is a human-centered endeavor that applies psychological science toward understanding and designing for human needs, goals, abilities, and limitations*. Addressing these factors contributes to technology functionality, usability, and desirability (Norman, 2013), whereas ignoring human factors can be a source of error in complex, technical environments (Garrouste-Orgeas et al., 2012; Jacko, 2012; Woods, Leveson, & Hollnagel, 2012).

Second, *HSE takes both social and technological systems into account*. HSE recognizes that humans are embedded in networks of people (e.g., teams) and technologies (e.g., social media), that interact and evolve together over time. Such principles are rooted in robust fields such as HCI (Jacko, 2012) that explore how humans use and interact with technological systems, and HSI (Boehm-Davis, Durso, & Lee, 2015; Kozlowski, Grand, Baard, & Pearce, 2015) and macroergonomics (Hendrick & Kleiner, 2002; Kleiner, 2008) that examine the effects of environmental, organizational, and sociotechnical systems on design and performance.

Third, *HSE is iterative and valuable at all stages of design and development*. Engineers have long consulted with psychologists to design functional instruments and displays (e.g., in early military aircraft; Chapanis, 1953). However, in some cases, psychologists have been consulted late in the design process—evaluating "usability" only *after* engineers craft a new device or interface or, unfortunately, after a catastrophe has occurred (e.g., Cooke & Durso, 2008). Among the lessons from decades of human factors, HCI, HSI, and related research is that when human-centered problems are discovered late, the fixes can be time-consuming and expensive (Bias & Karat, 2005; see Cooke & Durso, 2008, for several compelling examples).

Fourth, *these iterative investigations must be scientifically rigorous and empirical*. A common misconception is that human factors, usability, user experience, or similar topics are "intuitive" or merely "common sense" (Norman,



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2013; Russ et al., 2013). However, remarkably diverse research methods can (and should) be carefully employed to understand peoples' needs, evaluate designs, test outcomes, and guide decision making, which contribute to the reliability and validity of problem solutions (e.g., Stanton, Hedge, Brookhuis, Salas, & Hendrick, 2004; Stanton et al., 2017).

Finally, *HSE is inherently multidisciplinary*. Depending on the problem and goals, an HSE approach necessarily integrates expertise from one or more cognitive and social sciences (e.g., psychology, neuroscience, and education) and one or more engineering disciplines (e.g., biomedical, mechanical, and software). Many HSE teams also include practitioners, subject matter experts (SMEs), or end-users whose insights and feedback help to identify problems and test potential solutions (e.g., participatory design; Schuler & Namioka, 1993). No one person can or should represent all stakeholders or fields of study.

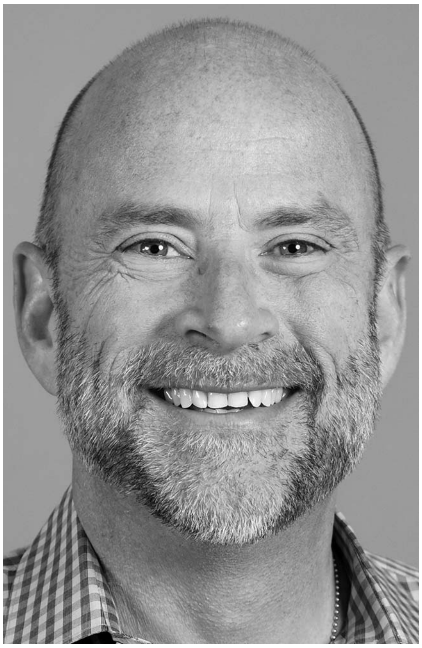
The scope of engineering and design problems that may be addressed via HSE and related approaches is vast. From this broad pool are selected two narrative cases that bridge psychology and engineering within diverse, multidisciplinary teams. The cases are summarized in terms of context, team formation, contributions, and (most importantly) lessons learned. Both cases involve human-centered interactions with technology, in real-world contexts, along with considerations of human thought, behavior, or performance. They demonstrate how "making technology work for people" involves multidisciplinary teaming and a deep understanding of the human aspects of the applied setting. It is important that these cases derive from distinct projects that did not overlap in team members, stakeholders, or research goals. There were no chronological or causal connections such that lessons from one case should be expected to guide the other. Rather, these two separate cases were selected to demonstrate overlapping and potentially generalizable themes related to multidisciplinary teams.

Narrative Case 1: Cognitive Fatigue Among First Responders

As modern work becomes more mentally demanding, understanding cognitive fatigue is critical (Young, Brookhuis, Wickens, & Hancock, 2015). For professionals in emergency and traumatic situations (e.g., firefighters and paramedics), degradations in attention, memory, or decision making may cost lives (Jones, 2017). Unlike physical and emotional fatigue, less is known about how components of cognitive processing are differentially affected by sleep deprivation or stressors. To be clear, physical fatigue refers to bodily tiredness and lack of energy for physical tasks, and emotional fatigue describes affective exhaustion that hinders emotional investment in tasks or relationships (Melamed, Shirom, Toker, Berliner, & Shapira, 2006). Although all three types of fatigue are related, cognitive fatigue refers to mental exhaustion with a reduced ability to think quickly, think flexibly, pay attention, or remember.

Team formation. Self-assessments conducted by the Mesa Fire Department, including a sleep study, revealed a need for a rigorous exploration of cognitive fatigue. Problems were greatest in stations with very high call volumes of more than 3,000 calls per year for each four-person crew, and sometimes more than 5,000 calls per year (Blackwell, Becker, & Adams, 2014). Both internal assessments and national standards warned against call volumes at these levels. For this reason, the Mesa Fire Department initiated collaboration with psychological scientists at ASU to assess the effect of mental workload on their members. Team members initially included an HSE Associate Professor with expertise in cognitive science and programming assessments of emotion-cognition interactions, and a quantitative psychologist with expertise in psychometrics and industrial/organizational psychology. Team goals were established to examine how and whether firefighters' cognitive skills were affected by workload using assessments of real-time declines in working memory, perceptual speed, and emotional distractibility. An important constraint was that measures needed to be quick, accessible, reliable, and valid with respect to fire service demands. Project outcomes had the potential to change how resources were allocated, including long-term plans about where to build new fire stations.

At the outset, fire service team members conceptualized measures of mental and physical exhaustion in terms of self-report (e.g., asking firefighters to assess their own abilities, skills, or mental states). Team psychologists, however, offered a compelling case that subjective self-reports can be



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variable or unreliable (Dunning, Heath, & Suls, 2004). Numerous well-validated, objective measures of cognitive performance were available (Reddick, Unsworth, Kelly, & Engle, 2012), but their tedious time demands introduced implementation barriers. Collectively, team members questioned how valid measures could be streamlined or "gamified." To explore this possibility, it was necessary to recruit software engineers. Thus, team composition grew to include a professional with a background in simulation and applied cognitive science, along with two software engineers in the ASU engineering college and graduate students in engineering.

Through this team formation process, a final multidisciplinary team emerged: (a) SMEs from the first responder community; (b) experts in cognition, social, and quantitative psychology (including faculty and graduate students); and (c) software engineers (including faculty, graduate students, and professionals) who joined the team later than the two other groups.

Contributions. A core need was to ensure that measures were authentic to job tasks. Team psychologists began by exploring the requisite cognitive skills of municipal firefighters as indicated by national guidelines (Occupational Information Network, 1998). Next, in conjunction with SMEs, they verified job performance elements that were most relevant to the Mesa Fire Department. One such cognitive skill was "response orientation," defined as "the ability to choose quickly and correctly between two or more movements in response to two or more signals (lights, sounds, pictures, etc.)" (Occupational Information Network, 1998, Subsection 63008a). Although response orientation could be assessed using traditional perceptual vigilance tasks, fire department consultants argued that such tasks would limit participation and validity because of participant boredom. To overcome this challenge, the software engineers identified multiple computer games with similar features (i.e., complex and time-sensitive visual searching among distractors) that could be exploited for assessment. A similar collaborative method was employed to design cognitive fatigue assessments of other firefighter abilities (e.g., memory of occupied rooms in a structure fire and differentiating between similar medication labels).

Following institutional review board (IRB) approval, ethnographic methods were used to further investigate the job challenges and consequences of cognitive fatigue with real firefighters. The team conducted "ride alongs" in the field and participated in several shifts at the busiest fire station. These immersive observations allowed researchers to better understand the population and task demands, including a more concrete appreciation of firefighters' physical risks. For instance, as firefighters respond to more calls in a shift, there is increased chance that a cognitive error might lead to an otherwise avoidable injury, such as accidental pathogen exposure.

Throughout this process, the team had to carefully manage apprehension from the firefighters regarding the "true purpose" of the research study. There were fears that findings might disrupt schedules, limit overtime opportunities, or undermine retention and promotion. The team had to provide regular reassurances regarding anonymity and aggregate reporting of data, and that none of the results could be used to guide scheduling or overtime policies. A key strategy was to clearly communicate to stakeholders (many of whom did not possess a research background) the kinds of conclusions that could be drawn from a study, and the ethical responsibilities of researchers (e.g., protecting anonymity). Also important was strong administrative support, including the active involvement of firefighters and their union, who endorsed the value of the research and worked to alleviate participants' concerns.

Based on the previous observations, several game-based measures (i.e., a visual search game and another assessing memory for equipment locations) were developed using job-salient stimuli including firefighting equipment images. In contrast to joint efforts between psychologists and Mesa Fire Department experts, collaboration between the psychologists and software engineers was initially less smooth. Tensions regarding software programming and functionality arose because of differences in knowledge and epistemic goals. Whereas the psychologists emphasized research methodology validity (e.g., sufficient number of trials, blocking, and counterbalancing), the software engineers focused on interface responsiveness, visual design, and efficient back-end data archiving. Both sets of standards and constraints were crucial, but were not mutually recognized as such. Thus, across iterative designs and prototypes, each

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group tended to forefront their own disciplinary concerns while inadvertently downplaying or omitting other factors. These conflicts resulted in extended development time.

Fortunately, one team member possessed cross-disciplinary expertise that spanned software development and psychology. Specifically, the lead consulting software specialist also had a background in cognitive science and assisted with integrating software and research designs. Through his efforts, developers gained a better understanding of concepts such as within-subjects testing, counterbalancing, and reliability, as well as how to deliver these goals in an appealing interface and with efficient coding. Likewise, HSE team members better appreciated the flow and storage of data generated by the assessment trials. Resolving this conceptual barrier (i.e., recognizing that their respective design goals were complementary rather than conflicting) facilitated cascading benefits and learning opportunities. For instance, team members collectively realized that creative use of accelerometers and screen swipe motion paths might provide novel indicators of underlying cognitive impairments.

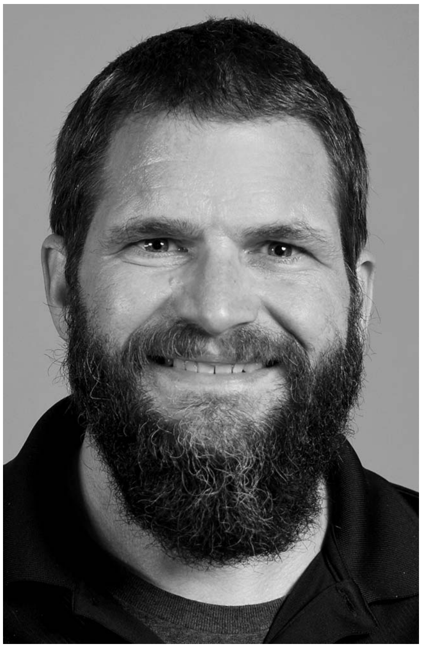
The initial game assessments were deployed on existing fire station computers. Using a multilevel and longitudinal design (i.e., each firefighter was observed several times across shifts nested within station), results showed that higher call volumes led to significant increases in (a) errors made remembering equipment locations and (b) the timing of decisions in the visual search task. In a second phase, additional computers were deployed in six high-volume stations along with several new game-based assessments (e.g., memory for occupant locations in a house fire) and measures of subjective stress and filing of accident reports. Results from this phase replicated the error and reaction time (RT) results of the first phase. In concrete terms, higher call volumes resulted in fatigue effects that slowed responses (e.g., identifying and reacting to safety threats) and could dramatically increase the chance of accidental injury (Blackwell et al., 2014).

The results of this work were presented to the firefighter union, the Mesa Fire Department administration, and the City Council. The findings ultimately led to a new fire station being built in the highest call volume region of the city to ease firefighter fatigue. Building on these successes, a third phase is seeking to redesign the assessments for smartphone (i.e., mobile) compatibility and more flexible deployment.

Lessons. This multidisciplinary team was successful in developing valid, game-based assessments of cognitive fatigue that were used by stakeholders to inform critical decision making. Nonetheless, lessons emerged that might improve future teaming. For example, although team formation was organic and driven by perceived need, earlier recruitment of the software engineering experts might have improved efficiency and communication. Likewise, in addition to discussing goals and anticipated outcomes of the research (e.g., alleviating cognitive fatigue), team members might also have confronted potential fears (e.g., that findings might harm professional status or opportunities). These observations inform two lessons about team formation:

- *Lesson 1:* Multidisciplinary team formation should strive to be comprehensive and inclusive of psychology and engineering disciplines from the earliest stages.
- *Lesson 2:* Multidisciplinary team formation should include explicit dialogs about members' respective knowledge, beliefs, constraints, and anxieties related to the project. These dialogs can help to reveal and resolve epistemological conflicts.

Another observation was that a key individual with a cross-disciplinary background can help to reduce misunderstandings and find common ground within the team. As studied in the organizational and team science literatures, these "boundary spanners" (Fleming & Waguespack, 2007; Mangematin, O'Reilly, & Cunningham, 2014) can operate as translators, negotiators, and leaders who facilitate disciplinary alignment instead of friction. Notably, adhering to Lesson 1 may help to identify boundary spanners within the team, or may reveal that no current team member could fill that role. This observation also relates more broadly to the importance of shared knowledge (Bell, Brown, Colaneri, & Outland, 2018; Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000; Salazar, Lant, Fiore, & Salas, 2012), and the need for teams to make effective use of such knowledge resources via team-level processes of communication, coordination, and negotiation (Cooke, 2015; Cooke, Gorman, Myers, & Duran, 2013). Thus, another lesson states:



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- *Lesson 3:* During team formation, identify or recruit boundary spanning individuals who can bridge psychology, engineering, and other fields of the multidisciplinary team.

A final lesson from this case pertained to the importance of administrative support. Although team goals and successes emerged via contributions from all team members, the initial spark and overarching aim of this project came from high-level stakeholders who encountered a meaningful problem in need of a solution. Moreover, this support continued throughout the project and was integral to recruiting (and reassuring) participants and communicating with other stakeholders. Simply put, this team and project would not have existed if not for the forethought and endorsement of the Mesa Fire Department. This lesson is expressed as:

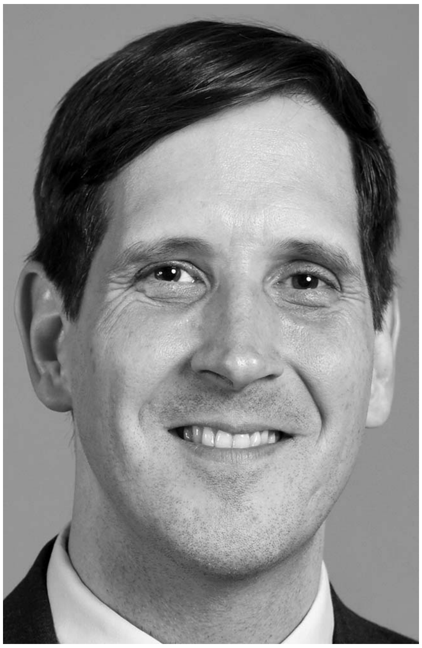
- *Lesson 4:* Administrative vision and support can substantially facilitate team formation, goal-setting, and functioning.

Narrative Case 2: Endoscope Reprocessing

Gastrointestinal endoscopy is a minimally invasive procedure used to diagnose and treat a variety of medical conditions (Xin, Liao, Jiang, & Li, 2011), and approximately 15 million endoscopies are conducted in the United States each year (Jolly, Hildebrand, & Branaghan, 2013). Unfortunately, endoscopes also contribute to numerous infectious outbreaks (Rutala & Weber, 2004)—an improperly reprocessed endoscope can transmit diseases such as HIV, Hepatitis B, and Hepatitis C (Weber & Rutala, 2011). Such problems arise because endoscopes possess long, narrow channels and valves that can be difficult to decontaminate. Procedures for reprocessing endoscopes involve a large number of steps, which are described in lengthy manuals or standard operating procedure (SOP) documents. Moreover, any given hospital may use multiple endoscope models, a single device might be used with multiple patients per day, and an individual technician might reprocess as many as 40 endoscopes per day.

Team formation. In 2009, the previous challenges became frighteningly real when a large hospital system had to contact thousands of patients with news that they may have been exposed to HIV, hepatitis C, or other infectious agents because of improper reprocessing of endoscopes. The Vice President (VP) of Healthcare Delivery was initially perplexed by the scope of the problem, and she questioned whether the hospital's training or hiring practices might be inadequate given that endoscope processing involved "only" a few steps: precleaning, brushing, flushing, leak testing, drying, and storage. To begin to solve this problem, the VP reached out to colleagues at ASU, including a cognitive psychologist with a background in human factors. Together, they outlined specific project objectives including (a) identifying causes of improper endoscope reprocessing and (b) determining how those problems might be reduced through the redesign of devices, procedures, and/or training materials.

A multidisciplinary team was mindfully assembled from the outset, and collegiality and multidisciplinarity were established as core team values. The project lead was an Associate Professor of HSE with an interest in medical human factors, and who possessed a background in cognitive psychology, usability assessment, and 15 years of experience in commercial product design. Central team members included a Biomedical Engineer with expertise in industrial engineering of medical devices, a doctoral-level Health Psychology and nursing researcher with experience in program evaluation and research methods, and two Masters-level HSE graduate students. The team was supported by the VP of Healthcare Delivery (i.e., a hospital administrator who possessed a PhD in Nursing) and the Chief of Sterile Processing Services (a hospital administrator with a BS in Business). Completing the team were several sterile processing technicians as SMEs. Crucially, the administrators endorsed the work and facilitated team formation by introducing researchers to SMEs and encouraging cooperation between the team and hospital staff. Similarly, the manager of the sterile processing department enabled access to critical facilities and a broader network, which allowed the team to observe and interview reprocessing technicians in six hospitals across the United States. Overall, the team spanned multiple institutions (i.e., two universities and several hospitals), specialties (i.e., health psychology, human factors, hospital administration, nursing, and sterile processing), and educational levels.



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Despite inclusive and conscientious team formation, early stages of the collaboration nonetheless encountered epistemic differences between members. First, hospital administrators tended to propose explanations and solutions focused on training or additional instruction. The VP of Healthcare Delivery and Chief of Sterile Processing Services emphasized *people* as possible sources of error, and thus initially sought solutions that (re)trained staff members on correct procedures. In contrast, HSE researchers were more design and product oriented. These team members focused on errors that emerged from confusing *equipment* and *documentation*, and initially hypothesized solutions that made equipment and manuals more usable and understandable. In addition to this difference in the locus of errors and solutions, team members also differed (perhaps predictably) in desired project outcomes. Hospital administrators desired pragmatic solutions that could be implemented broadly whereas team psychologists were committed to rigorous research methodologies and publishable findings.

None of these perspectives are mutually exclusive—effective human systems engineering considers both the “people” and “product” aspects of problem solving, and empirically rigorous solutions can also be practical. Through weekly meetings and ongoing discussions, team members gradually grew to recognize ways in which their goals and approaches were complementary rather than contradictory. However, this process was organic and slow; many team members spent the first few months feeling somewhat misunderstood or undervalued until these epistemic differences were finally recognized, acknowledged, and addressed.

Contributions. HSE researchers initially analyzed example endoscope reprocessing procedures using instructional manuals and SOP documentation (Hildebrand et al., 2010). A hierarchical task analysis demonstrated that there were over 200 steps involved in reprocessing an endoscope, many of which were sequentially dependent—a failure to conduct earlier tasks could make it impossible to correctly complete a later step. A heuristic analysis also revealed over 275 design violations. Most of these problems (76%) stemmed from violations of error-prevention (i.e., system design did not prevent mistakes), memory load (i.e., users had to remember too much information), and feedback (i.e., lack of task status cues). Continuing this effort, researchers obtained IRB approval and conducted a usability assessment with naïve users (i.e., nursing students who had never reprocessed an endoscope) as they reprocessed endoscopes (Jolly et al., 2012). Naïve users were selected because they must rely on available manuals and SOPs to complete the task—they could not use prior expertise or implicit knowledge to bypass poor design or flaws in the documentation. Thus, their errors were potentially more revealing or diagnostic of such problems. None of the participants successfully reprocessed an endoscope and fewer than half of the procedural steps were completed without error. Sources of these errors corroborated prior findings: the designs were error-prone (i.e., poor visibility of parts and tools), placed high demands on memory, and offered insufficient feedback.

Although a long-term goal was to generate design recommendations to improve endoscope reprocessing, actual product redesign involves considerable time and regulatory steps. Input from the Biomedical Engineer revealed benefits that could be achieved more immediately, such as revisions to training materials and SOPs. Thus, the team first revised the supporting written documentation to address visibility, memory, and feedback challenges. This process entailed gaining first-hand experience—the team was trained by experts at multiple hospitals to perform reprocessing. Subsequently, a visual poster was crafted to guide users through the procedures (Jolly et al., 2013). Evaluations found that naïve participants were able to accurately complete 87.1% of the 60 subtasks (also more quickly and confidently) when given the revised materials, as opposed to a 44.7% completion rate for those who received the standard materials.

One challenge that arose during these studies was the extent of medical terminology (e.g., different types of endoscopes) and technical details (e.g., equipment components) that were unknown to several team members. These concepts had to be learned before researchers could develop study protocols or analyze verbal and observational data. In addition, the hospital environment can be a complex and unfamiliar site for research (Blandford et al., 2015; Carayon et al., 2011). The health psychology and nursing researcher contributed substantially in this regard by translating and

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explaining key medical concepts, while also helping the team navigate the physical and administrative aspects of the hospital setting. Also valuable was her cross-disciplinary background in medical research, which allowed her to mentor others on the processes of publishing in medical journals to disseminate findings. HSE student team members gained conceptual knowledge about medical devices, biology, and epidemiology, and also developed methodological knowledge about pursuing research in hospital field settings.

As the collaboration matured, team members developed greater appreciation for the conceptual and methodological value of each other's disciplines. The multidisciplinary team fostered an environment for learning that was driven by both necessity *and* curiosity. For example, health psychology and nursing experts became intrigued by the principles of cognitive information processing underlying cognitive aids (e.g., checklists, see Marshall, 2017). Team members learned about the processes and limitations of prospective memory (e.g., Brandimonte, Einstein, & McDaniel, 2014) and applications to medicine (e.g., remembering to take medications, Zogg, Woods, Sauceda, Wiebe, & Simoni, 2012). Such learning promoted appreciation for solutions informed by these processes, such as visual posters (Jolly et al., 2013) that could help technicians remember key reprocessing steps. Finally, this cooperative environment also encouraged the sterile processing technicians, who might have felt excluded from research, to contribute their perspectives and expertise by teaching others. Indeed, their input was incredibly valuable because they understood the domain and could explain procedures better than any other team member.

Lessons. This multidisciplinary team effectively examined and improved human interactions with an existing medical technology, which in turn can inform safer practices and better device design. Observations from this case corroborate or reinforce all of the lessons learned from Case 1, which speaks to the potential generalizability of these themes.

One of the strengths of this team was that multidisciplinary representation was intentionally sought during team formation (see *Lesson 1*), and team composition ensured that several individuals were positioned to span boundaries between medical settings and research methodologies (see *Lesson 3*). For instance, HSE and Health Psychology researchers understood experimental design and observational research, HSE researchers were more aware of human cognitive processes and limitations, and health researchers were more attuned to issues of risk reduction. This shared knowledge facilitated communication and collaboration, yet distinct perspectives supported ideation and innovation (Bell et al., 2018; Mathieu et al., 2000). In addition, complementary expertise among team members also facilitated opportunities for learning and teaching (see *Lesson 5* below).

Early discussions promoted a commitment to shared work and knowledge, and this collegiality contributed to productivity. Nonetheless, this team struggled initially with epistemic differences in problem-solving strategies. This challenge reinforces the need for team members to express their priorities, assumptions, and related epistemic approaches early in team formation (see *Lesson 2*). Such differences should perhaps be expected and anticipated as a normal aspect of teaming. Regular meetings bolstered by collegial communication can allow disagreements to be revealed and resolved, but confronting these issues directly is more efficient.

Administrative support was crucial for forming the team, establishing the project vision, and ensuring logistic feasibility (see *Lesson 4*). Administrators initiated the connection with HSE researchers and helped to build the multidisciplinary team of psychologists, engineers, and SMEs, as well as enabling access to several authentic research sites. In Case 1, administrative support was needed to reassure participants that their data and findings would not be used to negatively affect job duties or career prospects. Such reassurances were not necessary in Case 2, but administrators continuously reinforced the value of the work and its relevance to the mission of the hospital system and patient well-being.

One additional observation from this team was that collaboration and shared work fostered a team learning environment (see Decuyper, Dochy, & Van den Bossche, 2010; Van der Vegt & Bunderson, 2005). For instance, nursing researchers learned about principles of cognitive psychology and their applications to health care, and HSE researchers (particularly students) learned more about health concepts and research methods in health care settings. Likewise, hospital-based team

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members (e.g., nurses and technicians) took on empowering roles as teachers and mentors to share their expertise with others. In some sense, team members may have engaged in a form of spontaneous "cross-training" (e.g., Salas et al., 2008) to support each other, and such learning was inspired by both the demands of the project (i.e., medical jargon) and use-inspired curiosity. It is worth noting that hints of learning during teaming were also seen in Case 1. Team members expanded their respective understanding of research and software design constraints, and also began to recognize new measurement opportunities as they discussed available technology features. However, themes of learning and teaching were much more salient in Case 2. Together, these observations inform the following lesson:

- *Lesson 5:* Multidisciplinary engineering teams create opportunities for learning, teaching, and mentoring.

Strategies for Supporting Human Systems Engineering Teams

The preceding narrative cases exemplify multidisciplinary and human-centered engineering efforts (i.e., computer-based assessments and medical devices) that required contributions from psychological science and adopted an HSE approach. Psychological expertise (e.g., working memory, perception, ethnography, heuristic evaluation, and task analysis) was provided by HSE team members who enhanced the research with measurable psychological constructs and a range of empirical methods for guiding data-driven decisions, designs, and solutions. Bridging psychology and engineering in this manner resulted in solutions that were grounded in real world constraints, were validated by research, and linked people and technology to their systemic contexts.

Five overlapping and potentially generalizable lessons were inferred from the cases, which reaffirmed key concepts from research on organizations and team science (Salas, Reyes, & McDaniel, 2018) such as shared knowledge (Salazar et al., 2012), interactive team cognition (Cooke, 2015), team learning (Decuyper et al., 2010), and team composition (Mangematin et al., 2014), and lessons for multidisciplinary engineering teams. These lessons suggested forming inclusive multidisciplinary teams intentionally from the outset (Lesson 1), engaging in explicit dialogs about team values and beliefs (Lesson 2), identifying or recruiting boundary spanning team members (Lesson 3), valuing and nurturing administrative support (Lesson 4), and recognizing multidisciplinary teaming as a learning opportunity (Lesson 5). It is important that just as the cases did not exhaustively sample every possible multidisciplinary team or team dynamic, neither are these lessons intended to be exhaustive.

Multidisciplinarity introduces team members to unfamiliar concepts, methods, or constraints. Although team diversity provides a fertile ground for problem-solving, progress can be slowed or thwarted by miscommunications and misunderstandings. For instance, in both cases, divergent project conceptions led psychology, engineer, and stakeholder team members to initially pursue different goals. Lessons 1–3 address these challenges by pushing teams to consider their expert resources and beliefs early in team formation. At that stage, crafting a shared appreciation of the project and multidisciplinary teaming may inspire motivation, collaboration, and resilience. In both cases, teams credited their success to the multidisciplinary nature of the team and recognized that learning was necessary and beneficial. Including administrative representatives in this shared vision only strengthened the endeavor. Administrative advocates granted access to facilities, tools, SMEs, and research participants that were essential to the success of the projects.

HSE researchers at ASU are exploring strategies for enacting these lessons to enhance multidisciplinary engineering teams, and which could be applied in other domains. One strategy is a "top-down" administrative approach (via a university research center) that enables collaborative opportunities, social networking, and team science expertise to facilitate team formation and productivity. A second strategy is a "bottom-up" educational approach (via a university degree program and courses) that prepares future engineers, designers, administrators, and psychologists to appreciate the intersection of psychology and engineering. These two strategies, which are being pursued in parallel, are described briefly.

Strategy 1: Center for Human, Artificial Intelligence, and Robot Teaming (CHART)

Although multidisciplinary teams can form organically (e.g., groups with similar goals may decide to join forces), there are no guarantees that researchers will recognize the full range of expertise that should be included, or that team members will possess the skills to navigate the challenges of multidisciplinarity. One way that universities can support team formation and productivity is through research centers (Boardman & Corley, 2008; Boardman & Ponomariov, 2014; Ponomariov & Boardman, 2010; Salazar et al., 2012). Research centers create administrative support systems (Lesson 4) that can proactively promote unifying epistemological stances toward research agendas and teams (Lesson 2), while also addressing logistical challenges such as recruiting valuable team members (Lesson 3), identifying goal overlap, or mediating conflicts (Hall et al., 2018; National Research Council, 2015; Ponomariov & Boardman, 2010). In short, research centers provide a strategy for overcoming the challenges of forming and managing multidisciplinary teams.

For example, at ASU, a new center (directed by an HSE Professor) is explicitly focused on applying principles of HSE to the study of human-technology teams. Teams of the not-to-distant future will include both humans and increasingly capable machines or robots (Fiore & Wiltshire, 2016; McNeese, Demir, Cooke, & Myers, 2018). CHART strategically assembles multidisciplinary teams of faculty, students, and industry partners to address these looming human-technology problems in the context of self-driving vehicles, battlefield, manufacturing, and medicine. CHART is led by experts in human and robot systems, with specific expertise in team psychology (e.g., Cooke, 2015; Cooke et al., 2013) and robotic swarming (e.g., Berman, Halász, Hsieh, & Kumar, 2009), and actively recruits from a list of over 60 affiliated scholars to build expert teams from multiple disciplines. As opposed to individual, problem-driven projects as in the two narrative cases, CHART is positioned to identify research targets that span multiple areas of expertise, build suitable teams, and articulate a shared vision that unites center members.

CHART employs several methods to assemble and support multidisciplinary teams on this topic (Boardman & Ponomariov, 2014; Ponomariov & Boardman, 2010). In some cases, specific topics cited in a call for proposals will suggest the necessary expertise, and investigators can be personally invited and assembled to form a multidisciplinary proposal or project team. These teams are aided by the Center's research staff, who might provide grant writing or networking support, as needed. In other cases, individuals with diverse and relevant backgrounds are brought together to brainstorm on a focal topic to identify challenges and research opportunities within that critical area. Rather than being tied to a specific funding opportunity, these "think tank" style meetings may result in white papers, workshops, or research agendas that steer the direction of the center, its members, funders, and/or the field. For example, CHART recently brought together biologists, roboticists, and human systems engineers to brainstorm on Biologically-Inspired Resilient and Distributed Systems (BIRDS). From this meeting emerged three grant proposals and a transdisciplinary discussion of robots as a new species. CHART's metrics of success include typical ones of counting publications, proposals, funding, or outreach, but another key metric—in line with contemporary team science evaluation—is the number of new and innovative ideas that emerge from such deeply integrative discussions (e.g., Cummings & Kiesler, 2005; National Research Council, 2015). In other words, CHART aims to be not only productive, but also generative and inventive with respect to team-based research.

Strategy 2: Human Systems Engineering Education

Overlapping knowledge, effective team collaboration, and appreciation for alternative ways of thinking may also be promoted through education (Feland, Leifer, & Cockayne, 2004; Hynes & Swenson, 2013; Litzinger, Lattuca, Hadgraft, & Newstetter, 2011; Zoltowski, Oakes, & Cardella, 2012). That is, in parallel with administrative aid for multidisciplinary engineering teams, targeted engineering education can also prepare students to conscientiously bridge the "technological" and "people" sides of engineering. HSE-focused experiences and coursework may prepare students to *become* boundary spanners who can navigate between psychological science and engineering (Lesson 3), and perhaps instill a sense of necessity or value in multidisciplinary engineering (i.e., encourage them to pursue Lessons 1 and 2). To the extent that students are engaged in multidisciplinary engineering projects and teams (e.g., Case 2), such experiences can be part of their HSE learning experiences and training (Lesson 5).

Researchers and educators at ASU are pursuing this goal through degree programs in HSE that serve two broad student populations. Undergraduates who pursue a Bachelor of Science in HSE are immersed in applied, project-based courses that introduce them to principles of psychology, research methods, and design, and they are also required to take an introductory course in engineering. These students are typically focused on future careers in user experience, human factors and ergonomics, and similar disciplines. Thus, HSE majors are poised to serve as human systems experts on future multidisciplinary teams. In parallel, HSE is becoming a popular "minor" for students majoring in a specific engineering discipline (e.g., biomedical, manufacturing, and software). In these majors, engineers are interested in their prospective end-users, clients, and teams but may not have formal opportunities to acquire such expertise. For these students, HSE coursework prepares them to advocate for human-centered engineering and even to serve as boundary spanners in multidisciplinary teams.

As an entry point, engineering students at ASU can enroll in a unique course, *Introduction to Human Systems Engineering* ("HSE 101"), that situates content encountered in introductory psychology classes within engineering contexts. This new course offers potential to infuse psychological science into the engineering mindset for a new generation of practitioners. As part of a National Science Foundation funded project, researchers are evaluating the curriculum to study how HSE instruction shapes students' attitudes toward engineering and psychology. One project, with IRB approval, surveyed convenience samples of students enrolled in HSE 101 or a parallel engineering course ("EGR 101") near the end of the semester. Several questions elicited students' perceptions of HSE goals, methods, and utility. Preliminary analyses focused on freshman students with a stated intention to pursue a non-HSE engineering major.

Unsurprisingly, many EGR 101 freshmen reported minimal knowledge of HSE. A few students were open-minded but hinted that usefulness was limited to only "specific applications of the engineering process." In contrast, freshmen engineering majors enrolled in HSE 101 were better able to define HSE and its relevance. For instance, one student wrote "human systems engineering is the understanding of how technology relates to and affects humans. It is how we interact, use, and better technology," and that "it broadens our understanding of what engineers do." Another engineering student responded that "HSE means learning about human behavior and why we do certain things. Knowing this allows us to better understand how things work in the world around us and how we can change things to improve human life." Finally, some students began to articulate empirical approaches such as "conducting experiments" and studies "to see if something can be made more efficient for users." That is, students recognized that HSE can empower engineers to adopt a data-driven approach for aligning engineering to human concerns. Engineers could engage in research to gain "a better understanding of how a person will physically or emotionally react" to a design.

Although this survey was preliminary, the responses were suggestive of the benefits of HSE 101. Exposure to HSE principles seemed to help students realize the value of addressing human concerns. For students intending to pursue "traditional" engineering, HSE coursework might lead to greater openness toward multidisciplinary teaming with social scientists and for working on teams that include end-users, SMEs, and stakeholders.

Conclusion

The solutions for many pressing challenges require engineering innovations that are guided by a keen awareness of human goals, needs, abilities, and limitations. Thus, for societal issues like cybersecurity, ensuring water access, or resilient infrastructure (NAE, 2017), a multidisciplinary approach is needed—problem-solvers must bridge engineering and psychology to make *technological* solutions that actually work for *people*. HSE explicitly advocates for the empirical application of psychological science to human-centered engineering problems, and thus provides a valuable approach for multidisciplinary engineering teaming. Across two narrative HSE cases, this article sought to exemplify these ideas while offering concrete lessons learned that might facilitate multidisciplinary engineering teaming. These lessons emphasized team formation processes that proactively recruit diverse and boundary spanning members, and which encourage team members to discuss and reconcile their distinct approaches and beliefs from the earliest stages of teaming. In addition, these lessons highlighted the value of administrative support in facilitating team success, as well as opportunities for team members to learn from and teach each other.

Two potential strategies for enacting these lessons within multidisciplinary HSE teams were outlined. One strategy uses institutional centers to bring researchers and experts together in a productive manner, and the other approach educates engineering students to approach psychology as a valuable component of engineering and problem-solving. These dual administrative and instructional approaches may be highly generalizable. HSE at ASU is meaningfully located within the Fulton Schools of Engineering, which necessarily shapes how HSE faculty engage in research and teaching (e.g., grants and student populations). These strategies, however, might be fruitfully replicated in other disciplines and departments. To build a future in which multidisciplinary teams of engineers *and* psychologists work together seamlessly, it makes sense to consider *both* sides of the equation. At ASU, HSE education might also help traditional undergraduate and graduate students in psychology further appreciate the powerful role of technology in human behavior, and research centers such as CHART can strive to recruit and inspire psychologists who might not realize the essential value of their expertise for solving engineering problems.

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