Paper ID #26904

Is it Rocket Science or Brain Science? Developing an Instrument to Measure ”Engineering Intuition”

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Abstract

This theory paper describes the conceptual framework behind the on-going development of a survey-style instrument to assess “engineering intuition.” With the prevalence of computer-aided problem-solving in the modern engineering workplace, it is becoming increasingly essential for professional engineers to be able to quickly and accurately assess the results from simulation or problem-solving software. Subsequently, they need to be able to estimate or predict the outcomes from the software, in addition to responding to real-time events on the job. We characterize this ability to assess and/or predict outcomes as a key feature of “engineering intuition,” a highly desirable but vague and abstract essential engineering skill. Well-developed engineering intuition can have the potential to lead to greater efficiency and innovation in engineering, as well as mitigate adverse events. Engineering intuition should be a highly sought-after professional engineering skill, yet it is not explicitly taught within engineering curricula. Here we present the theory behind the on-going development of our instrument, including the importance of intuition in development of discipline-specific expertise, specific significance of engineering intuition in the modern workforce, hypotheses regarding related constructs, and assessment of responses to intuition-engaging engineering problems. We also describe the future intentions of this project, including validity and reliability testing of the instrument and subsequent application studies.

Role of Intuition in Expertise Development

Expertise is highly valued in many disciplines, including engineering. While the explicit definition of expert may vary among scholars, research on expertise has described a number of characteristics. Defined as specialized domain knowledge [1]**,** expertise may be developed through experience [2], [3]. This experience is coupled with an ability to learn from internal and external feedback [3] and a strong ability to build associations and even run mental simulations [4]. Expertise development is often described as a continuum that begins with the stage of novice [5], [1]; a novice is characterized as one who is merely at the beginning of their quest for specialized knowledge within a domain [6], [7].

Patel and Groen describe progression along the novice to expert pathway as occurring in three distinct stages of developing and applying specialized domain knowledge. The first stage describes the process of building content knowledge, or what Patel and Groen refer to as “knowledge-structure representations.” In the second stage, the budding expert is building their processes for discriminating between relevant and irrelevant information when presented with a problem. In the third and final stage, the expert develops efficiency. This progression, in particular the focus on efficiency and ability to assess relevance, is parallel to the idea of intuition as a key characteristic of the expert [1].

Comparatively, Dreyfus takes a more explicit approach in addressing the role of intuition in expertise. The five-level Dreyfus model of skill acquisition explicitly references intuition as an essential characteristic of an expert (level 4 in the original model). Dreyfus describes an expert as one who “intuitively [responds with] appropriate action.” In the original Dreyfus model, expertise precedes the final level, mastery, in which performance becomes automated and unconscious [5]. Mastery is not included in the more recent version of the Dreyfus model, which now have expertise as the fifth and final level and have an additional stage included directly after novice (called "advanced beginner") [8].

In addition to these frameworks of skill acquisition and expertise development, several cognitive frameworks also refer to intuition-analogous characteristics of experts through slightly different terminology [9]-[13]. Table 1 summarizes these cognitive frameworks, which are then described in more detail. Notably, each framework contrasts an intuition analogous construct with an opposing cognitive pathway. We believe that "engineering intuition" is best characterized as a unique construct that lies at the intersection of these frameworks.

Table 1: Analogous Theories of Intuition

Theory	**Intuition Analogous Construct**	**Brief description**	**Citation**
System 1 vs. System 2 Thinking	System 1	Fast, intuitive, emotional response	Kahneman [9]
Fuzzy-Trace Theory	Gist trace	Conceptual, transferable, deep understanding	Wolfe, Reyna, and Brainerd [10]
Domain-specific vs. Domain-general Knowledge	Domain-general	Describes knowledge that is transferable to new contexts and allows for approaching novel problems	Penner and Klahr [11]
Cognitive-Experiential Self Theory	Experiential information-processing	Automatic information processing	Epstein [12]
Heuristic vs. Systematic Information Processing	Heuristic	Characterized by low involvement in cognitive task, relies on non-content cues from information	Chaiken [13]

System 1 vs. System 2 Thinking

One of the most popularized constructions of the idea of "intuition" comes from Daniel Kahneman's "Thinking, Fast and Slow." Kahneman describes two modes of thinking. System 1 is spontaneous—fast, intuitive, emotional. System 2 is reflexive—slower, more deliberate, logical. Intuition is often associated with System 1 thinking, a primal, immediate, "gut" response to something. It is believed that the "System 1 brain" is the older response system in humans. This system is where our automated responses to stimuli arise, and where our modern habits are coded. The "System 2 brain" is thought to have developed later in our evolutionary journey, and includes cognitive processing of more "modern" stimuli such as mathematics [9]. This way of thinking brings up an interesting paradox—how do we develop responses to (modern) stimuli that are both fast and logical?

Many purport that intuition is simply recognition. Through experience our brains may learn to recognize patterns of stimuli, and thus also learn to respond faster and "more intuitively" to these stimuli [9], [14]. What we believe to be our "gut reaction" may in fact be the outcome of an imperceptibly fast analysis of the situation, comparison to past experiences, and subsequent response. This hypothesis supports the common notion of practice as a pathway to expertise development.

Fuzzy-Trace Theory

The Fuzzy-Trace Theory of cognition presents another dual-processing framework. Here intuition is highly analogous to the idea of "gist" trace [10], a deep level of understanding and ability to build connections. The contrasting "verbatim" trace focuses on surface level understanding. For example, in the context of engineering education, let us imagine that students are presented with two separate problems, each using the context of a basketball. The first problem focuses on the concept of gravity and the second on drag. Individuals processing through verbatim trace would likely recognize both problems as featuring basketballs—a surface level understanding of the problem. Those processing through gist trace would be able to look beyond the basketball and identify the underlying concepts that are engaged. When considered a skill, gist trace is also parallel to stage two of Patel and Groen's development of expertise (identifying relevant information) described earlier [1].

Domain-specific vs. Domain-general Knowledge

Historically, the contrasting ideas of domain-specific versus domain-general knowledge have been used to describe and understand knowledge acquisition in science, technology, engineering, and mathematics (STEM) fields, particularly at the primary school level of K-12. A number of studies in the area focus on each construct independently, considering either only domain-specific [15]-[17] or domain-general knowledge [18], [19]. Domain-specific knowledge describes knowledge of the specific "facts" within a domain (e.g., classification of organisms in biology), whereas domain-general knowledge refers to processes and skills that are translatable from one domain to another (e.g., the scientific method) [11]. Some scholars argue that domain-specific and domain-general knowledge are highly interrelated, as analysis and exploration of any new topic is by necessity guided by existing knowledge and impossible to couple from domain-specific knowledge [20]. However, when domain-specific knowledge is entirely lacking, domain-general pathways are thought to be engaged in approaching unfamiliar problems [21], [22]. Domain-general knowledge parallels intuition in its focus on generalizable processes that can be broadly applied for innovative problem solving.

Cognitive-Experiential Self Theory

Cognitive-Experiential Self Theory (CEST) distinguishes between two distinct individual information processing modalities, rational and experiential [12]. Rational information processing is characterized as logical and evidence-based. This processing is contrasted with the automatic, and often irrational, experiential information processing. Like System 1 in the Kahneman model, experiential information processing is thought to be a more historic cognitive pathway driven by prior experience and emotion, and focused on final outcomes at the expense of taking care in the process engaged to achieve those outcomes. Rational and experiential information processing are often presented as being in conflict, and to some offer an explanation of why individuals may make decisions that appear, from a third-party perspective, to be irrational [12], [23]-[26].

Heuristic vs. Systematic Information Processing

Heuristic versus systematic information processing contrasts how individuals value different aspects of information received. Systematic information processing, as the name suggests, refers to logical and content based analysis of information received [27]. Heuristic information processing relies on non-content characteristics, such as the identity of the source [13] and judgement biases [28], [29]. Systematic information processing is associated with high-involvement in the cognitive task, whereas heuristic information processing is associated with low involvement [13]. This model appears prevalent among scholars studying persuasion and argument development, particularly around the 1980s [13], [30], [31]. Heuristic information processing has also been cited as a potential pathway for intuitive judgement or decision making [29], [32].

Intuition—the Intersection of Several Cognitive Frameworks

What we describe as engineering intuition, the ability to assess solutions and predict outcomes in a timely manner, appears to lie at the intersection of many of the cognitive frameworks discussed. Intuition appears to rely on the experience prevalent in System 1 thinking, as well as the speed of System 1 and experiential information processing. We believe intuition is also characterized by the transferable and deep understanding of gist trace or domain-general knowledge. While heuristic information processing may seem in conflict with these definitions, the low involvement in the cognitive task that is characteristic of heuristic information processing is arguably also aligned with intuition as high involvement is not necessarily possible with time-sensitive response. Thus, we build our understanding of the cognition behind intuition from these existing frameworks as a basis for understanding disciplinary expertise.

Discipline-Specific Intuition

While we are interested in *engineering* intuition, much of the literature (cited in previous section) on intuition-analogous cognitive frameworks or expertise speaks to the development of expertise broadly, without being associated with a specific discipline or domain. It is not possible for an individual’s experience, knowledge, and subsequently expertise to be uniform across all domains. Thus, it follows that intuition is likely to be context and domain dependent. Discipline-specific intuition, such as engineering intuition, is a useful construct that seeks to separate general intuition, with its complexity and varying connotations, from the intuition used to make judgements and decisions within the context of specific professions. To date, engineering intuition is neither well defined nor well characterized. Subsequently, we seek insights from disciplines that have studied discipline-specific intuition to further develop our understanding of engineering intuition.

The literature on discipline-specific intuition comes predominantly from the disciplines of nursing and management. In nursing, skill acquisition is modeled by Benner's Stages of Clinical Competence, a five-stage model of competence that maps to the five levels (novice to expert) of the Dreyfus model [33]. Here, an expert nurse is characterized as having an "intuitive grasp" of situations and holistic view that allows them to accurately assess the patient's situation and respond appropriately [34].

Intuition studies in nursing range from grounded theory methods to phenomenological methodologies which have helped to legitimize the concept of intuition in nursing [35]. An ethnography of nursing as a culture not only revealed the prevalence of intuition but that more experienced nurses trust their intuition and rely on it more [36]. Nurses who trust their intuition can positively change the outcomes of their patients [37]. Furthermore, nurses define intuition as an autopilot task which can be learned [38].

Master of Business Administration (MBA) classes, in contrast, are often centered on studying business cases derived from situations in industry. Studies in business have shown an increase in using "real projects" in classes and that internship experiences are critical to university performance [39]. With more experience, managers in business make faster decisions and lean on their intuition when they are missing information [40], [41]. Furthermore, when asked, "What does it mean to make decisions using your intuition?", the majority of these managers (56%) picked experience, with the next most common answer being feelings and emotions (40%) [41].

A common theme for all of these studies in both nursing and management is that intuition is assessed by professionals, thus measuring only expert intuition through self-reported means. For example, in nursing there are several inventories which exists to measure intuition, but these are primarily tested on practicing nurses. Only one of the inventories has been tested on both students and practicing nurses but had a low response rate from practicing nurses [42]. These studies require the participants to have a shared understanding of intuition, and there is little evidence (as shown in our earlier discussion of frameworks) to support that intuition is such a universally perceived cognitive construct. Thus, as the importance of intuition grows, the secrets of its development remain elusive.

Nursing and management are both high-stakes and human-centered disciplines. While the nature of interaction and the consequences of poor decision-making may be different between the two, these shared characteristics may be why these disciplines have been at the forefront in seeking to understand discipline-specific intuition. This reasoning suggests that, engineering, as another high-stakes and human-centered discipline, should also engage in a closer examination of discipline-specific intuition.

The Importance of Intuition in Engineering

Engineering is often described as problem-solving, a task that is intrinsically littered with decision-making opportunities. Engineers respond to societal problems by providing technological solutions that must be feasible and appropriate. They design products, equipment, and facilities that we rely on to perform in a safe and cost-effective manner. In some engineering professions, engineers must make split-second decisions in the event of an unexpected incident, potentially either saving lives or putting lives at risk. Ultimately, engineers are engaging in regular decision making to solve a variety of problems.

Intuition is critical in helping determine the feasibility of a potential solution at all stages of its design, from its inception to its complete implementation. Most seasoned engineering professionals appear to have a strong sense of intuition, but they often find it difficult to explain to younger professionals how they gained their intuition other than simply by experience. By shortcutting this process, early-career engineering professionals will be able to quickly provide and assess solutions, leading to more opportunities to uncover new discoveries and much-needed innovations for society.

Building intuition also fosters confidence [43] and can subsequently foster greater persistence and resilience in engineering majors and careers. Engineering disciplines, often described as “pipelines,” “pathways,” or “ecosystems,” can be difficult to navigate because of the highly structured, and potentially intimidating, curriculum. This can result in a net loss of students over time, as students transfer out, the highly-structured requirements can be an insurmountable barrier to transferring into engineering programs. Students who have more confidence in their abilities are less likely to drop out of engineering majors and more likely to successfully complete their degree [44], [45]. While the tendency to drop out can and does affect all student demographics, it is known to disproportionately affect underrepresented minorities [46]-[48]. In order to meet the number of engineering graduates the workforce requires, as well as promote the diversity in engineering that is critical for continued innovation, it is imperative to reverse the net loss of students. By empowering students with intuition skills early, they will ideally persist in engineering disciplines and help to solve increasingly complex world problems.

Developing intuition in the classroom could also level the playing field for all engineering students. Internship and co-op experience have many positive effects including a higher starting salary, increased retention, and better academic achievement [49], [50]. Intuition development is also thought to be linked to experience, which can be problematic as not all students may have equal access to the opportunities that beget such experience. By integrating interventions that provide similar benefits in the classroom, we can better ensure all of our students have the opportunity to acquire this much-needed skill. Developing intuition is not only a major educational advance in creating stronger problem-solvers and critical thinkers, but also narrows the opportunity gaps that persist in engineering. Furthermore, by creating effective interventions, we will give useful tools to engineering educators that can help promote intuition development.

As we prepare students to become practicing engineers, we must also equip them with both the concrete and abstract technical skills necessary for not only personal success but also positive societal impact. While catastrophic failures of engineering intuition are not often reported, there are key historical events in which a stronger intuition may have prevented a disaster (e.g., Challenger tragedy) [51]. Today, as computer simulations and problem-solving software in engineering become increasingly complex, no one individual can understand the entirety of these programs. It becomes even more imperative for engineering professionals to question the results of computer simulation they complete. How to best prepare our students to question their results is not clear, but if students can practice this during their formal education, they will enter the workforce better equipped for the challenges of real-world engineering.

Does Intuition Stand Alone?

While the theories and constructs analogous to intuition shed some light on the nature and importance of this topic, they still do not present a full picture. From the literature on discipline-specific intuition, and our definition of engineering intuition, it is clear that intuition is closely associated with decision making. In considering (engineering) decision making, we also find connections to problem solving, as well as motivation and identity.

Decision Making

Decision making has long been an area of study, with Classical Decision Making theory tracing back as far as the early 18th century, when Daniel Bernoulli attempted to quantify human assessment of evolutionary risk [52]. Since then, several theories of decision making have been put forth, as summarized in Table 2. Of these, naturalistic decision making is most closely associated with intuition and thus the focus of this section.

Much of the early decision making research was completed through controlled experimentation where study subjects chose among a variety of options. In the late 1980s, a new approach began taking hold as behavioral scientists became more interested in studying how decisions are made in real environments, which became known as naturalistic decision making. Naturalistic decision making has close parallels with intuition, and subsequently strong contrasts with some of the earlier models.

The first conference on naturalistic decision making occurred in 1989 [59], sponsored by the Army Research Institute [60]. This conference brought together decision making researchers who had been working in parallel towards what is now described as naturalistic decision making [58]. What many of the models summarized in the 1993 book chapter on the conference have in common is the principle that, contrary to classical decision making, individuals are not weighing options when coming to decisions [58]. Rather, they are relying on connections between the current situation and past experiences to make their choices [61]-[63]. This reliance is in deep contrast to previous models which assumed that individuals behave rationally in response to assessing a variety of known options.

Naturalistic decision making provides a body of knowledge [58]-[63] that may be leveraged to better understand disciplinary-specific intuition holistically. The reliance on past experience of naturalistic decision making, combined with the ability to make abstract connections as described in many of the cognitive frameworks analogous to intuition and the focus of discipline-specific intuition research on experts in high-stakes decision making fields suggests that engineering intuition lies at the intersection of conceptual expertise and experience.

Table 2: Analogous Theories of Decision Making

Theory	**Summary**	**Citation**
Classical Decision Making	Logical, quantified risk assessment drives decision making. Assumes that decision maker is able to assess all alternatives.	Bernoulli [52]
Behavioral Decision Theory	Characterizes decision making as based in individual values and beliefs.	Barron [53] Slovic, Fischoff, and Lichtenstein [54]
Judgement and Decision Making	Seeks to understand the individual judgements that drive decision making. Typically assumes rational behavior.	Yates [55]
Organizational Decision Making	Rationale process, seeks the best outcome for the organization.	Cyert and March [56] March and Simon [57]
Naturalistic Decision Making	Driven by connections made to past experience.	Lipshitz [58]

Research in management and nursing purport that intuition leads to faster and more accurate decisions [41], [64]. Research of U.S. Navy enlisted personnel show similar results, with intuitive processes leading to higher performance [65]. Like naturalistic decision making, intuition in these studies is described as being developed through experience, and allows the practitioner to fill in the logical gaps when faced with uncertainty in decision making.

Problem Solving

Closely related to decision making, problem solving skills are often considered the crux of the engineering discipline, and several studies have shown key differences between novice and expert problem solving approaches [66]-[68]. Experts are known to have greater working memory to devote to problem solving as their expertise allows them to store information in a grouped (or “chunked”) fashion, rather than storing each piece of information independently

[66]. This mechanism reduces the cognitive load of storing information and allows for greater information processing capacity.

When engaging in problem solving, experts have been shown to participate in systematic real-time "reasonability" checks, contrasted with novices who proceed to the end without taking time to reflect [67]. This behavior of expert problem-solvers perfectly aligns with our definition of engineering intuition as the ability to assess solutions. In real-world engineering, ill-defined problems are of particular interest. Studies have shown that ill-defined problems are often not solved systematically, but rather through reactionary, intuitive processes to navigate the decisions of problem-solving [68].

Motivation and Identity

While the connection may not be as obvious as decision making and problem solving, we also have reason to believe that the constructs of motivation and identity play a role in engineering intuition. Our previous work suggests that if a student's disciplinary identity does not match the problem or scenario they are asked to assess, they are less likely to demonstrate high intuition (measured as accurate assessment) [69]-[71]. Because accurate assessment of engineering solutions and scenarios requires additional effort, it may also be confounded with motivation. The effects of motivation on a number of student outcomes has been extensively studied by others [72]-[75], and identity alignment has also been shown to be linked to professional motivation [76]-[79].

Ongoing and Future Work

This theory paper serves to summarize the literature review and meta-analyses done toward the ongoing development of a user-friendly survey instrument for measuring engineering intuition. The insights we have gained through reviewing a broad range of literature in our attempt to understand engineering intuition have allowed us to better understand the complicated theoretical frameworks behind the construct. From this literature review, we define engineering intuition as the ability to assess whether solutions are reasonable or ridiculous and to predict outcomes and/or options within a scenario. We will use this definition, as well as leverage the literature on the intuition-related constructs presented here, as the basis for developing our instrument. We are currently in the preliminary phases of reviewing the literature on these existing instruments.

In future work, we will describe the instrument, as well as preliminary validity and reliability testing. We seek to equip the engineering education community with a tool that may be used by scholars in the pursuit of understanding discipline-specific intuition and by educators in tracking students' development of intuition in their programs, as well as pursue studies to better understand what experiences contribute to students' development of engineering intuition.

References

[1] V. L. Patel and G. J. Groen, "The general and specific nature of medical expertise: A critical look," in *Toward a general theory of expertise: Prospects and limits*, New York, Cambridge University Press, 1991, pp. 93-125.

[2] C. M. Seifert, A. L. Patalano, K. J. Hammond and T. M. Converse, "Experience and expertise: The role of memory in planning for opportunities.," in *Expertise in context*, Menlo Park, CA, AAAI Press/ MIT Press, 1997, pp. 101-123.

[3] J. K. Phillips, G. Klein and W. R. Sieck, "Expertise in judgment and decision making: A case for training intuitive decision skills," in *Blackwell handbook of judgment and decision making*, Malden, MA, Blackwell Publishing, 2004, pp. 297-325.

[4] G. Klein and R. R. Hoffman, "Macrocognition, mental models, and cognitive task analysis methodology," in *Naturalistic decision making and macrocognition*, Hampshire, U.K., Ashgate, 2008, pp. 57-80.

[5] S. E. Dreyfus and H. L. Dreyfus, "A Five-Stage Model of the Mental Activities Involved in Directed Skill Acquisition," California University Berkley Operations Research Center, No. ORC-80-2, 1980.

[6] R. R. Hoffmann and G. Lintern, "Eliciting and representing the knowledge of experts," in *Cambridge Handbook of Expertise and Expert Performance*, New York, Cambridge University Press, 2006, pp. 203-222.

[7] R. R. Hoffman and J. Smith, Toward a general theory of expertise: Prospects and limits, New York: Cambridge University Press, 1991.

[8] S. E. Dreyfus, "The Five-Stage Model of Adult Skill Acquisition," *Bulletin of Science, Technology, & Society*, vol. 24, no. 3, pp. 177-181, 2004.

[9] D. Kahneman, Thinking, Fast and Slow, New York: Farrar, Straus and Giroux, 2011.

[10] C. R. Wolfe, V. F. Reyna and C. Brainerd, "Fuzzy-Trace Theory: Implications in Teaching and Learning," in *Transfer of Learning from a Modern Multidisciplinary Perspective*, Greenwich, CT, Information Age Publishing, 2005.

[11] D. E. Penner and D. Klahr, "The interaction of domain-specific knowledge and domain-general discovery strategies: A study with sinking objects," *Child Development*, vol. 67, no. 6, pp. 2709-2727, 1996.

[12] S. Epstein, "Cognitive-Experiential Self-Theory," in *Handbook of Personality Theory and Research*, New York, Guilford Press, 1990, pp. 165-192.

[13] S. Chaiken, "Heuristic versus systematic information processing and the use of source versus message cues in persuasion," *Journal of Personality and Social Psychology,* vol. 39, no. 5, pp. 752-766, 1980.

[14] P. Benner and C. Tanner, "How expert nurses use intuition," *AJN, American Journal of Nursing,* vol. 82, no. 3, pp. 402-407, 1987.

[15] C. Gobbo and M. Chi, "How knowledge is structured and used by expert and novice children," *Cognitive Development,* vol. 1, no. 3, pp. 221-237, 1986.

[16] S. Carey and E. Spelke, "Domain-specific knowledge and conceptual change," in *Mapping the mind: Domain specificity in cognition and culture*, New York, Cambridge University Press, 1994, pp. 1690-200.

[17] S. Carey, "Conceptual differences between children and adults," *Mind & Language,* vol. 3, no. 3, pp. 167-181, 1988.

[18] R. S. Siegler and R. M. Liebert, "Acquisition of formal scientific reasoning by 10- and 13-year-olds: Designing a factorial experiment," *Developmental Psychology,* vol. 11, no. 3, pp. 401-402, 1975.

[19] A. L. Fay and D. Klahr, "Knowing about guessing and guessing about knowing: Preschoolers' understanding of indeterminacy," *Child Development,* vol. 67, no. 2, pp. 689-716, 1996.

[20] L. Schauble, R. Glaser, K. Raghaven and M. Reiner, "Causal models and experimentation strategies in scientific reasoning," *Journal of the Learning Sciences,* vol. 1, no. 2, pp. 201-238, 1991.

[21] M. J. Pazzani, " Influence of prior knowledge on concept acquisition: Experimental and computational results," *Journal of Experimental Psychology: Learning, Memory, and Cognition ,* vol. 17, no. 3, pp. 416-432, 1991.

[22] M. J. Pazzani, M. G. Dyer and M. Flowers, "The Role of Prior Causal Theories in Generalization," in *Proceedings of the Fifth AAAI National Conference on Artificial Intelligence*, Philadelphia, PA, 1986.

[23] S. Epstein, "Cognitive-experimental self-theory," in *Advanced Personality,* New York, Plenum Press, 1998, pp. 211-238.

[24] V. Denes-Raj and S. Epstein, "Conflict between intuitive and rational processing: When people behave against their better judgement," *Journal of Personality and Social Psychology,* vol. 66, no. 5, pp. 819-829, 1994.

[25] S. Epstein, L. A, C. Holstein and E. Huh, "Irrational reactions to negative outcomes: evidence for two conceptual systems," *Journal of Personality and Social Psychology,* vol. 62, no. 2, pp. 328-339, 1992.

[26] L. A. Kirkpatrick and S. Epstein, "Cognitive-experiential self-theory and subjective probability: further evidence for two conceptual systems," *Journal of Personality and Social Psychology,* vol. 63, no. 4, pp. 534-544, 1992.

[27] R. P. Abelson, "Script processing in attitude formation and decision making," in *Cognition and Social Behavior*, Hillsdale, NJ, Lawrence Erlbaum, 1976.

[28] A. Tversky and D. Kahneman, "Judgment under uncertainty: Heuristics and biases," *Science,* vol. 185, no. 4157, pp. 1124-1131, 1974.

[29] T. Gilovich, D. Griffin and D. Kahneman, Eds., Heuristics and biases: The psychology of intuitive judgement, New York: Cambridge University Press, 2002.

[30] S. Chaiken, "The heuristic model of persuasion," in *Social influence: The Ontario symposium*, vol. 5, Hillsdale, NJ , Lawrence Erlbaum Associates, 1987, pp. 3-39.

[31] S. Chaiken and A. H. Eagly, "Heuristic and Systematic Information Processing within and beyond the Persuasion Context," in *Unintended thought*, New York, Guilford Press, 1989, pp. 212-252.

[32] J. Cioffi, "Heuristics, servants to intuition, in clinical decision-making," *Journal of Advanced Nursing,* vol. 26, no. 1, pp. 203-208, 1997.

[33] P. Benner, "From novice to expert," *AJN, American Journal of Nursing,* vol. 82, no. 3, pp. 402-407, 1982.

[34] P. Benner, From novice to expert: Excellence and power in clinical nursing practice, Menlo Park, CA: Addison-Wesley, 1984, pp. 13-34.

[35] A. Smith, "Exploring the legitimacy of intuition as a form of nursing knowledge," *Nursing Standard*, vol. 23, no. 40, pp. 35-40, 2009.

[36] D. W. Leners, "Intuition in nursing practice," *Journal of Holistic Nursing,* vol. 10, no. 2, pp. 137-153, 1992.

[37] H. McCutcheon and J. Pincombe, "Intuition: An important tool in the practice of nursing," *JAN,* vol. 35, no. 3, pp. 342-348, 2001.

[38] J. E. Pretz and V. N. Folse, "Nursing experience and preference for intuition in decision making," *Journal of Clinical Nursing,* vol. 20, no. 19-20, pp. 2878-2879, 2011.

[39] R. D. Green and F. A. Farazmand, "Experiential Learning: The Internship and Live-Case Study Relationship," *Business Education and Accreditation,* vol. 4, no. 1, pp. 13-23, 2012.

[40] H. A. Simon, "Making management decisions: The role of intuition and emotion," *Academy of Management Perspectives,* vol. 1, no. 1, pp. 57-64, 1987.

[41] L. A. Burke and M. K. Miller, "Taking the Mystery Out of Intuitive Decision Making," *Academy of Management Perspectives,* vol. 13, no. 4, pp. 91-99, 1999.

[42] A. L. Holm and E. Severinsson, "A Systematic Review of Intuition - A Way of Knowing in Clinical Nursing?," *Open Journal of Nursing,* vol. 6, pp. 412-425, 2016.

[43] G. Lufitvanto, C. Donkin and J. Pearson, "Measuring Intuition: Nonconscious Emotional Information Boosts Decision Accuracy and Confidence," *Psychological Science,* vol. 27, no. 5, pp. 622-634, 2016.

[44] E. Litzler and J. Young, "Understanding the Risk of Attrition in Undergraduate Engineering: Results from the Project to Asess Climate in Engineering," *Journal of Engineering Education,* vol. 10, no. 2, pp. 319-345, 2012.

[45] M. Besterfield-Sacre, C. J. Atman and L. J. Shuman, "Characteristics of Freshman Engineering Students: Models for Determining Student Attrition in Engineering," *Journal of Engineering Education,* vol. 86, no. 2, pp. 139-149, 1997.

[46] B. C. Clewell, C. C. De Cohen, L. Tsui, L. Forcie, E. Gao, N. Young, N. Deterding and C. West, "Final Report on the Evaluation of the National Science Foundation Louis Stokes Alliances for Minority Participation Program," Program for Evaluation and Equity Research (PEER), The Urban Institute, Washington, DC, 2005.

[47] M. T. Jones, A. E. L. Barlow and M. Villarejo, "Importance of Undergraduate Research for Minority Persistence and Achievement in Biology," *The Journal of Higher Education,* vol. 81, no. 1, pp. 82-115, 2010.

[48] M. W. Ohland, C. E. Brawner, M. M. Camacho, R. A. Layton, R. A. Long and e. al., "Race, Gender, and Measures of Success in Engineering Education," *Journal of Engineering Education,* vol. 100, no. 2, pp. 225-252, 2011.

[49] J. A. Raelin, M. B. Bailey, J. Hamann, L. K. Pendleton, R. Reisberg and e. al., "The Gendered Effect of Cooperative Education, Contextual Support, and Self-Efficacy on Undergraduate Retention," *Journal of Engineering Education,* vol. 103, no. 4, pp. 599-624, 2014.

[50] M. K. Schuurman, R. N. Pangborn and R. D. McClintic, "Assessing the Impact of Engineering Undergraduate Work Experience: Factoring in Pre-work Academic Performance," *Journal of Engineering Education,* vol. 97, no. 2, pp. 207-212, 2008.

[51] A. Boin, v. Eeten and M. J. G., "The Resilient Organization," *Public Management Review,* vol. 15, no. 3, pp. 429-445, 2013.

[52] D. Bernoulli, *Exposition of a new theory on the measurement of risk,* vol. 22, 1954, pp. 23-36. Translation of 1738 Specimen Theoriae Novae de Mensura Sortis.

[53] F. H. Barron, "Behavioral Decision Theory: A Topical Bibliography for Management Scientists," *Interfaces,* vol. 5, no. 1, pp. 56-62, 1974.

[54] P. Slovic, B. Fischhoff and S. Lichtenstein, "Behavioral Decision Theory," *Annual Review of Psychology,* vol. 28, no. 1, pp. 1-39, 1977.

[55] J. F. Yates, Judgement and Decision Making, Englewood Cliffs, NJ: Prentice-Hall, Inc., 1990.

[56] R. M. Cyert and J. G. March, A Behavioral Theory of the Firm, Englewood Cliffs, NJ: Prentice-Hall, Inc., 1963, pp. 169-187.

[57] J. G. March and H. A. Simon, Organizations, Wiley, 1958.

[58] R. Lipshitz, "Converging themes in the study of decision making in realistic settings," in *Decision Making in Action: Models and Methods,* Norwood, NJ, Ablex, 1993, pp. 103-137.

[59] G. Klein, "Naturalistic Decision Making," *Human Factors,* vol. 50, no. 3, pp. 456-460, 2008.

[60] R. Lipshitz, G. Klein, J. Orasanu and E. Salas, "Taking stock of naturalistic decision making," *Journal of Behavioral Decision Making,* vol. 14, no. 5, pp. 331-352, 2001.

[61] G. A. Klein, "Recognition-Primed Decisions," in *Advances in Man-Machine Systems Research*, vol. 5, Greenwich, CT, JAI Press, 1989, pp. 47-92.

[62] K. R. Hammond, R. M. Hamm, J. Grassia and T. Pearson, "Direct Comparison of the efficacy of intuitive and analytical cognition in expert judgement," in *Proceedings of IEEE Transactions on Systems, Man, and Cybernetics, SMC-17*, 1987.

[63] J. Rasmussen, "Skill, Rules, and Knowledge: Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models," in *Proceedings of IEEE Transactions on Systems, Man, and Cybernetics, SMC-13*, 1983.

[64] K. H. Hall, "Reviewing Intuitive Decision-Making and Uncertainty: The Implications for Medical Education," *Medical Education,* vol. 36, no. 3, pp. 216-224, 2002.

[65] J. H. Johnston, J. E. Driskell and E. Salas, "Vigilant and Hypervigilant Decision Making," *Journal of Applied Psychology,* vol. 82, no. 4, pp. 614-622, 1997.

[66] B. Adelson, "Problem solving and the development of abstract categories in programming languages," *Memory & Cognition,* vol. 9, no. 4, pp. 422-433, 1981.

[67] D. P. Simon and H. A. Simon, "Individual differences in solving physics problems," in *Children's thinking: What develops?,* Hillsdale, NJ, Lawrence Erlbaum Associates, 1978, pp. 325-348.

[68] J. Metcalfe and D. Wiebe, "Intuition in Insight and Noninsight Problem Solving," *Memory & Cognition,* vol. 15, no. 3, pp. 238-246, 1987.

[69] E. E. Miskioglu and K. M. Martin, "Reasonable or Ridiculous? Engineering Intuition in Simulations," in *Proceedings of the 123rd ASEE Annual Conference & Exposition,* New Orleans, LA, 2016.

[70] E. E. Miskioglu and K. M. Martin, "Is the Answer Reasonable or Ridiculous? Common Factors among Students Who Display High Engineering Intuition on Technology-aided Solutions," in *Proceedings of the 124th ASEE Annual Conference & Exposition,* Columbus, OH, 2017.

[71] E. E. Miskioglu and K. M. Martin, "Work in Progress: Got Intuition? Exploring Intuition in Response to Technology-aided Problem Solving," in *Proceedings of the 125th ASEE Annual Conference & Exposition,* Salt Lake City, UT, 2018.

[72] J. Stolk and J. Harari, "Student Motivations as Predictors of High-Level Cognitions in Project-Based Classrooms," *Active Learning in Higher Education,* vol. 15, no. 3, pp. 231-247, 2014.

[73] C. Stefanou, J. D. Stolk, M. Prince, J. C. Chen and S. M. Lord, "Self-regulation and autonomy in problem-and project-based learning environments," *Active Learning in Higher Education* , vol. 14, no. 2, pp. 109-122, 2013.

[74] C. Baillie and G. Fitzgerald, "Motivation and attrition in engineering students," *European Journal of Engineering Education,* vol. 25, no. 2, pp. 145-155, 2000.

[75] B. D. Jones, M. C. Paretti, S. F. Hein, Knott and T. W., "An analysis of motivation constructs with first-year engineering students: Relationships among expectancies, values, achievement, and career plans," *Journal of Engineering Education,* vol. 99, no. 4, pp. 319-336, 2010.

[76] D. L. Blustein, L. E. Devenis and B. A. Kidney, "Relationship between the Identity Formation Process and Career Development," *Journal of Counseling Psychology*, vol. 36, no. 2, p. 196–202, 1989.

[77] S. Ahlqvist, B. London and L. Rosenthal, "Unstable identity compatibility: how gender rejection sensitivity undermines the success of women in science, technology, engineering, and mathematics fields," *Psychological Science*, vol. 24, no. 9, pp. 1644-1652, 2013.

[78] O. Pierrakos, T. K. Beam, J. Constantz, A. Johri and R. D. Anderson, "On the development of a professional identity: engineering persisters vs engineering switchers," in *Proceedings of 39th IEEE Frontiers in Education Conference*, 2009.

[79] D. Van Knippenberg, "Work motivation and performance: A social identity perspective," *Applied Psychology*, vol. 49, no. 3, pp. 357-371, 2000.