Individual Differences in Human Reliability Analysis

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Abstract: While human reliability analysis (HRA) methods include uncertainty in quantification, the nominal model of human error in HRA typically assumes that operator performance does not vary significantly when they are given the same initiating event, indicators, procedures, and training, and that any differences in operator performance are simply aleatory (i.e., random). While this assumption generally holds true when performing routine actions, variability in operator response has been observed in multiple studies, especially in complex situations that go beyond training and procedures. As such, complexity can lead to differences in operator performance (e.g., operator understanding and decision-making). Furthermore, psychological research has shown that there are a number of known antecedents (i.e., attributable causes) that consistently contribute to observable and systematically measurable (i.e., not random) differences in behavior. This paper reviews examples of individual differences taken from operational experience and the psychological literature. The impact of these differences in human behavior and their implications for HRA are then discussed. We propose that individual differences should not be treated as aleatory, but rather as epistemic. Ultimately, by understanding the sources of individual differences, it is possible to remove some epistemic uncertainty from analyses.

Keywords: HRA, Individual Differences, Human Performance, Crew Performance.

1. INTRODUCTION

The nominal model of human error in human reliability analysis (HRA) typically simplifies the variability in how operators respond to initiating events. In the context of procedure use, human success and failure are often treated dichotomously in HRA methods, thereby implying that there is one path to modeling human error (i.e., the operator either used the procedure correctly or s/he did not). Furthermore, individual differences in operator behavior, and crew-to-crew variability in performance, are typically treated as aleatory (i.e., random) uncertainty. Given this treatment as an aleatory factor, most HRA methods address this issue by using a measure of central tendency to represent the characteristics of an "average" operator or crew.

However, there is a considerable amount of literature that shows individuals and teams vary significantly in their performance, and that there is observable and reliable relationship between this variability in performance and antecedent factors. For example, one of the key findings in the international HRA empirical study [1, 2] was that there was variability in how crews responded in given plant upset scenarios. Given the same scenario, the same indicators, the same procedures, and the same training, crews varied in their decisions on what actions to carry out. Braarud and Kirwan [3] further noted that variability in crew performance in the international HRA empirical study was closely related to task complexity in that greater variability in crew performance was seen in more complex scenarios than in simpler ones. Heimdal [4] also noted research showing an interaction between task complexity and procedure adherence. Crews that followed procedures verbatim were faster at simple tasks, but slower on complex tasks. Crews that operated in a culture where verbatim compliance was not required tended to be faster and more accurate on complex tasks, but slower on simple tasks. This finding implies that crew-to-crew variability in performance on simple and complex tasks can vary significantly simply as a function of procedure usage and adherence. Heimdal's findings also show that crew-to-crew variability in performance is present even in simple

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tasks, thereby demonstrating that the assumption in HRA that crews will perform the same on routine tasks is not always correct.

Toquam, Macaulay, Westra, Fujita, and Murphy [5] studying nuclear power plant crews in Japan also observed performance differences between nuclear power plant crews, and noted that three primary antecedent factors contributed to variability in performance between teams. These antecedent factors were task characteristics (e.g., how routine and simple versus unusual and complex is the task the team must perform), team member characteristics (e.g., intelligence, personality types, specific cognitive abilities, etc.), and team dynamics, or team characteristics, such as group cohesion and communication practices. Additionally, Gertman, Haney, Jenkins, and Blackman [6] found that the emotional stability of individual crewmembers' personalities was related to their future performance. Research by Itoh, Yoshimura, Ohtsuka, and Matsuda [7] showed that perceptual speed and memory (i.e., cognitive abilities) are also related to individual nuclear power plant crewmember performance, and as a result, overall team performance. Similarly, many studies show that group cohesion or lack thereof, can have an effect on team performance (for a review, see Evans and Dion [8]).

Recent work by Massaiu, Hildebrandt, and Bone at the Halden Reactor Project [9] also found that behavioral differences can arise in crews operating nuclear power plants, particularly in crew decision-making during emergency operation. They developed the Guidance Expertise Model (GEM), which explains crew behavior, and differences in crew behavior, in terms of the interaction of internal resources and external resources during different control modes (i.e., general or macrocognitive behaviors). Specifically, the two control modes in GEM are (1) narrowing and (2) holistic view, and roughly correspond to times in which the operators are performing procedure driven tasks, and times when operators are trying to ascertain what the bigger picture is for the emergency situation, respectively. Furthermore, whether the crew is engaged in either the narrowing or holistic view control mode depends on external resources (e.g., the availability and relevance of procedures), and internal resources, such as experience and teamwork (i.e., the ability for teams of people with different personalities and proclivities to communicate and work together effectively). With this model guiding their research, they confirmed that even under the same simulator trial and with the same emergency procedures, nuclear power plant crews varied in their performance as a function of the availability and interaction of external and internal resources.

Though this is not a study on variability in individual or crew performance, research by Galyean [10] noted similar issues in HRA in terms of handling individual differences. The focus of that paper was on the use of performance shaping factors (PSFs) that HRA uses to modify a human error probability (HEP) for a given event. Galyean noted that most HRA methods conflate differences between people and differences in the environment in their PSF taxonomies. For example, his analysis noted many HRA methods use a workload PSF, but that the effect size of workload on a nominal HEP is a function of the person performing the task, the task, and the environment. That is, a task that is known to increase workload, such as performing a complex mathematical calculation, likely depends on differences in cognitive ability, such that the overall workload level of those with higher cognitive ability is affected less than those with lower cognitive ability. As such, the workload PSF conflates influences on the nominal HEP that are attributable to differences between people and the differences in the task being performed. To remedy this issue, Galyean proposed a set of three orthogonal PSFs: population capacity, organizational environment, and event specifics, whereby population capacity is the PSF that directly considers differences related to the individual.

Overall, all of the research summarized highlights an important area of human performance that is rarely considered in HRA: individual differences in operator behavior (e.g., responses to initiating events). While HRA methods include uncertainty in quantification, there is the inherent assumption that well trained crews will tend to vary little and that any differences between crews are simply aleatory (i.e., random). While this assumption holds true in some areas (e.g., the ability to carry out well defined actions for understood phenomena), complex situations that go beyond training and procedures will garner differences in responses according to individual operators' understanding and decision making. Control room phenomena – including the communication patterns between operators, the rigidity of the control room command structure, crew openness to new ideas, and safety culture – are areas that can vary considerably across crews and plants. These differences are just a few of the many important antecedents that contribute to individual differences in behavior, and these antecedents and their effects on operator performance must be considered within HRA in order to achieve valid analyses.

This paper explores examples of individual differences taken from operational experience and the psychological literature. The impact of these individual differences in human performance and their implications for HRA is then discussed. We propose that individual differences should not be treated as aleatory, but rather as epistemic – an area of modeling uncertainty caused by lack of knowledge. Ultimately, by understanding the sources (i.e., antecedents) of individual differences, it is possible to remove some epistemic uncertainty from analyses.

2. PSYCHOLOGICAL RESEARCH ON INDIVIDUAL DIFFERENCES

One common feature of the studies on nuclear power plant crews and individual operators in Section 1 is that the antecedent factors contributing to individual differences in behavior originate from one of three general categories: (a) personality traits, (b) characteristics of the environment, or (c) the interaction of both. Examples of personality traits identified as contributing to individual differences in behavior include intelligence [5] and emotional stability [6]. Examples of environmental characteristics include task complexity [3, 5], and availability and relevance of procedures [9]. Examples of the interaction of the person and environment include the finding that crew-to-crew variability in their performance on simple and complex tasks depends on how they use and follow their procedures [4]. We also argue that team dynamics, such as group cohesion and communication practices, are a kind of interaction between the person and the environment, in that a person is interacting with someone else, who is part of their working environment.

This concept of manifested behavior being a function of both the person (e.g., their innate traits and abilities) and the environment is not new. Kurt Lewin made this observation in his book, *Principles of Topological Psychology* [11], where he presented his equation $B = f(P,E)$, which is a simple heuristic formula for 'behavior is a function of the person in their environment'. In the context of individual differences in behavior, Lewin's equation posits that differences arise when different people interact with the ever-changing environment. Given this, one implication of Lewin's equation is that differences in the observed behavior of two different people can occur even when both people are in the same environment, because individual differences can be due to differences between people. Thus, the fact that individual differences can arise solely because of differences between people explains why in the international HRA empirical study [1, 2], despite the fact that all nuclear power plant crews were given the same scenarios and procedures to follow (i.e., the same environment), there were differences observed in their behaviors. This section elaborates on some of the seminal findings in psychology on the nature of individual differences, and in particular, the observable and reliable relationship between antecedent factors, such as personality traits and differences in abilities, and subsequent differences observed in behavior.

2.1. Personality Psychology

The field of psychology has a long and storied history, whereby experimental and clinical psychologists have created a vast scientific literature that has both spanned the breadth and plumbed the depths of human behavior. One of the paradoxical findings of psychology is that some aspects of human behavior are generalizable to all, some aspects of human behavior are common to a subset of the population, and some aspects are unique to a person. As Murry and Kluckhohn [12] put it: "Every man is in certain respects (a) like all other men, (b) like some other men, (c) like no other man."

Because psychology provides this particular insight into what makes humans (a) similar (i.e., nomothetic), (b) similar only with certain unique groups, and (c) unique (i.e., ideographic), some have criticized psychological research as "schizophrenic" in nature in the sense that it appears to draw contradictory conclusions about the nature of human behavior. Others, however, simply view these three foci of psychological research as complementary endeavors. In fact, we argue it is not possible to understand what is nomothetic about humanity, or most any other tangible object for that matter (e.g., pumps, valves, turbines, steam generators, reactor vessels, containment structures, etc.) without understanding what is ideographic, and vice versa. An understanding of one requires knowledge of the other. The discovery of individual differences in a person's behavior, or the ways in which a person is like some other people, could not have occurred without understanding what is nomothetic about that person as well.

As with medicine, where physicians can specialize in different sub-fields (e.g., oncology, pediatrics, neurology, etc.), psychology also has areas of specialization. Personality psychology, more so than cognitive, social, or clinical psychology, has focused on understanding the full range of ways in which people are all alike, like some (but not others), and like no one else. Personality psychology currently studies these three foci through a number of different theoretical lenses. Some of the major theoretical perspectives include the psychoanalytic (i.e., Freudian) approach, behavioral (i.e., Skinnerian) approach, biological approach, dispositional/trait approach, humanistic approach, and the cognitive approach.

While there is value in researching personality through all of the different theoretical lenses, for purposes of understanding individual differences in HRA, special attention should be given to the cognitive approach to personality psychology, primarily because most of the second-generation HRA models (e.g., SPAR-HRA [13], MERMOS [14], and CREAM [15]) are based on a cognitive psychological understanding of human behavior. That is, a central premise of these second-generation HRA models is that in order to model human behavior, it is important to understand how humans cognitively represent and process information. Furthermore, while the terminology varies between cognitive theories and models of personality, the common features among all of them are that information that is external to the individual is cognitively represented and processed in stages, and that stable personality traits of the individual can influence or bias the way in which information is processed. The first stage is when the information is detected or noticed (i.e., information is collected). In the next stage, cognitive effort is applied to interpret or make sense of the information. It is within these first two stages that information is recast into a mental representation, which is a structured way of reorganizing the information to make that information easier to comprehend, as well as store and recall in memory. The third stage involves the human making a decision about what course of action to take, and the final stage is usually described in terms of the human performing the behavior or action.

It is important to note in these cognitive information processing models within personality psychology that antecedent factors (e.g., personality traits, perceptual abilities, etc.) influence an individual's information processing, and that each stage of information processing represents the opportunity for ideographic variability. At the perceptual stage, physiological differences (e.g., visual acuity or color blindness) or experience (e.g., learned perceptual biases) may shape the way different people take in sensory information. At the cognitive stage, knowledge, temperament (e.g., emotive vs. analytical), and experience shape the way decisions are made, and the way decision options are weighted (e.g., near-term vs. long-term strategy). Finally, the individual may even approach action in response to decisions in different manners as a function of some aspect of their personality (e.g., reserved vs. impulsive).

Said in more specific theoretical terms, the cognitive approach to personality psychology has as a fundamental premise the notion that humans create mental representations of, and process information in stages, and that individual differences in behavior can arise from: (1) differences in the external environment (e.g., variability in external stimuli), and (2) the subtle, but meaningful, antecedent cognitive factors that lead to differences in the ways in which people represent and process information. Two well-known and broadly accepted cognitive theories of personality and individual differences are Kelly's Personal Construct Theory [16] and Mischel and Shoda's Cognitive-Affective Systems Theory [17]. Both theories posit that people have mental representations that help people detect, process, organize, and then act upon information, but that personality traits and other antecedent factors lead to individual differences in the formation of people's mental representations. That is, no two people are exactly identical in their genetic make-up, cognitive abilities, and their life experiences, and as a result, even in the same situation, with the same training, people can process incoming information differently. Some examples of potential differences at each stage of information processing are listed below.

Two people in the same situation, with the same training may nevertheless:

1. Detect, notice, and/or attend to different bits of information that are part of the more complex feature set of a given situation
2. Have differing abilities to recall information stored in their respective memories that is needed to aid in comprehending what the bits of information are
3. Evaluate the meaning and importance the various bits of information differently
4. Have different attitudes towards decision making (i.e., one may be risk-averse, and the other risk-seeking)
5. Have different preferences for engaging in some actions and not others (e.g., one may prefer habitual behaviors over novel behaviors)

In short, the cognitive approach to personality psychology explains individual differences as a function of differences in people's mental representations of information. As Burger [18] put it, "A Christmas tree can remind one person of his or her religious values, another of family and seasonal joy, and a third of sad memories from childhood." (pg. 473). These different interpretations of a Christmas tree are a function of different people imparting a different meaning or symbolic significance to it. The cognitive approach to personality psychology would ascribe these differences in meaning or symbolic significance to differences in how people cognitively organize and represent the salient information they can recall from memory that is activated once a person sees a Christmas tree.

2.2. Individual Difference Effects in Information Processing

This section summarizes a number of research studies that demonstrate how antecedent factors (e.g., personality traits, cognitive abilities, etc.) affect information processing; specifically during the processing stages of detecting, processing, organizing, and then acting upon information. One antecedent factor that has been shown to have a robust effect across a number of stages of information processing is cognitive ability (i.e., "intelligence"). First, it should be clear that there is general consensus within the field of psychology, and in society in general, that there are individual differences in cognitive ability. Given this, Stanovich and West [19] studied the relationship between cognitive ability and the ability to, "Evaluate the quality of an argument independent of one's feelings and personal biases about the proposition at issue" (pg. 351), and found that those with greater cognitive ability were better able to suppress their biases when evaluating argument quality versus those with lesser cognitive ability. Additionally, later work by Stanovich and West [20] as cited in Rachlinski [21] found that differences in cognitive ability affected the propensity to make certain kinds of cognitive errors, such as the conjunction fallacy (i.e., Kahneman [22]), and the ability to solve complex problems (e.g., the Wason card selection task). Research by Rachlinski [21] also reported that those with greater cognitive ability made fewer cognitive errors and were less susceptible to using faulty reasoning when solving the complex problems.

There are also a number of other research studies that have looked at how antecedent factors affect the decision-making stage of information processing. Research by Lauriola, Levin, and Hart [23] examined individual differences in decision-making as a function of a person's tolerance for uncertainty. In this research, decision-making under uncertainty is defined as having two distinct subcomponents: decisions under ambiguity, and risky decision-making. Risky decision-making is akin to the kinds of decisions studied by Kahneman and Tversky [24]: where the probabilities of all possible outcomes were known, but the outcome itself was unknown. Decisions under ambiguity are decisions that people must make when the probabilities of outcomes are unknown, and the outcome is also unknown. What Lauriola, Levin, and Hart [23] discovered was that there is a stable dispositional (i.e., personality) trait that explains differences in decision-making where uncertainty is high. First, they were able to assess that some people are generally more risk seeking and others are generally more risk-averse across a number of situations. Then, they were also able to demonstrate that when risk seeking and risk-averse people were presented the same ambiguous situation (where uncertainty was high), that those who were risk seekers consistently made riskier decisions than those who were risk avoiders.

3. IMPLICATIONS OF INDIVIDUAL DIFFERENCES FOR HRA

3.1. General Implications for HRA

Given the literature reviewed in Section 2, there are a number of general implications for the treatment of individual differences in HRA, which are summarized here. First, it is interesting to note that the orthogonal PSFs developed by Galyean [10] share some similarities with Lewin's equation, $B = f(P,E)$ [11], in that the PSF population capacity is similar to P, and the PSF organizational environment is similar to E. The model by Massaiu, Hildebrandt, and Bone [9] (i.e., GEM) is also similar to work by Lewin in that crew behavior is a function of their personalities/internal resources and environment/external resources, and that differences in behavior can arise from either the person, the environment, or the interaction of person and environment. The fact that [9] found crew-to-crew variability as a function of the interaction between internal and external resources gives credence to the notion that factors such as personality traits and task complexity are antecedent factors that contribute to subsequent variability in crew performance.

The research by Stanovich and West [19, 20] and Rachlinski [21] demonstrates how individual differences in cognitive abilities can have a significant and meaningful impact on behaviors, specifically the rate and kinds of mental errors people can make in decision-making. Based on this research on cognitive information processing, a greater cognitive ability generally means that a person is generally better able to:

- Detect/notice/attend to more bits of information that are part of the more complex feature set of any given situation
- Process/comprehend information more quickly and accurately
- Organize/evaluate information more efficiently and accurately

Given these findings, one general implication for HRA is that while HEPs for performance on discrete tasks are typically calculated as if everyone (e.g., nuclear power plant operators) were all alike, it is quite likely that there are a number of meaningful differences between operators that may affect the operator's likelihood for making an error, and therefore affect the calculated HEP for a given task. For example, the research by Lauriola, Levin, and Hart [23] showing how differences in tolerances for uncertainty differentially affect decision-making supports the assertion that the nomothetic treatment of operators is likely an oversimplification. As such, the quantification of HEPs may be an oversimplification in that it is typically based on a single point measure of central tendency, when it is clear there is meaningful variability around that central point.

3.2. Practical Implications for HRA

There are four key areas where individual differences affect the assumptions in HRA:

1. *Human failure events (HFEs):* HFEs are those human errors that are risk significant and contribute to the overall failure likelihood of a system. In much contemporary HRA practice, HFEs are treated as a single path of operator behavior. For example, an HFE might be defined as the failure to isolate a cooling system. Assumed within defining the HFE this way is the idea that the path that led to this failure centered on the operator's failure manually to engage

a close valve switch. However, there are other possible ways such an error could occur (e.g., operator actuates the wrong valve switch). HFEs must not be artificially constrained to a single course of operator action; rather, they should consider multiple paths the operator could take. The ATHEANA HRA method [25] proposes consideration of multiple paths to various outcomes—deviation paths from the nominal path. Such an approach is, in fact, supported by evidence from the international HRA empirical study [1, 2], in which crews followed different paths either to success or failure in a scenario. It should be noted that such multiple possible paths has the opportunity to shape dependence modeling in the HRA, since one path will shape the likelihood of subsequent paths, which potentially primes particular HFEs depending on the path taken.

2. *Performance shaping factors (PSFs):* Performance shaping factors are those aspects of a situation, task, or individual that influence the likelihood of a particular behavior. Most HRA methods consider PSFs, but few consider the extent to which PSFs may manifest differently on the individual. For example, the SPAR-H method [13] treats PSFs as a set of multipliers on a nominal HEP. These multipliers are invariant across individuals. Thus, the effect of high stress is assumed to be constant across individual operators. Indeed, a sharp reduction in performance is accepted in the psychological literature to be a reflection of high stress levels (i.e., the so-called stress cliff). However, there also exists a point where stress can be considered to enhance performance (i.e., eustress). In fact, the optimal level of performance is usually at a level of moderate stress. Within HRA, there is no consideration of the individual thresholds for different levels of stress. One operator may have a high threshold of stress, while another may have a much lower threshold. In other words, given the same situation, one operator may find him/herself at the point of optimal performance, while another operator may find his or her performance sharply degraded by stress. Stress perception is individual; yet, there is no way in SPAR-H or other methods to treat the effects of stress differently across operators. PSFs should not be applied in a manner that overlooks individual differences in the effect of performance.

3. *Human error probabilities (HEPs):* A consequence of not considering individual differences is that a single probability distribution is used when calculating the HEP. In fact, given the possibility of different outcomes due to individual factors, it should be assumed that in many cases the true distribution is multimodal. There is a range of possible outcomes, which is being treated as noise or uncertainty in much of the HRA that is performed. By aligning the HEP to the actual performance range of individual operators, the HRA turns much of what is treated as aleatory uncertainty into epistemic certainty.

4. *Individual vs. crew performance:* It must be noted that individual differences can be modeled to account for both *intra* and *inter* crew differences in performances. Intra crew differences are, of course, those differences that occur because of variability in individuals, while inter crew differences are those sources of variability that occur because crews perform actions differently. There are a number of factors that influence crew dynamics, (e.g., cohesiveness and communication styles), which are simply the meta-level manifestation of the micro-level differences between individuals in the crew. The central point here is that both individuals and crews manifest ranges of behaviors. To date, much of the psychological literature has focused on differences at the individual level, but newer literature [26, 27] is looking at group behaviors such as team cognition and other aspects of team performance. This distinction between individual and crew performance may not be as crucial to HRA at this stage as acknowledging and accounting for variability in performance between individuals or crews.

While the above points emphasize the importance of considering individual differences, not everything is susceptible to individual differences. Reactor operators, for example, are screened through a rigorous curriculum for mental capacity, while the idiographic nature of their performance is minimized through extensive training. Thus, for well-trained and well-understood situations, there is no reason to assume that crews with similar capabilities, background, and training using the same control room and the identical procedures would perform significantly differently. In off-normal situations that present some degree of ambiguity or complexity in diagnosis, certain differences might be expected to surface. HRA has to date done a good job of accounting for nominal behavior in crews. As HRA matures and as it is fine-tuned to reflect a greater range of scenarios (e.g., Level 2 and Level 3 HRA), it becomes important to enhance HRA to capture the spectrum of possible outcomes, including those attributable to individual differences.

4. CONCLUSION

We have attempted to demonstrate in this paper that:

- Person-to-person and crew-to-crew variability in behavior exists
- There is an observable, reliable, and therefore systematically measureable relationship between antecedent factors (e.g., personality traits, communication practices, etc.) and variability in person and crew performance.
- This variability has meaningful and risk significant effects on operator and crew performance

This means it is not necessary to treat variability in performance (i.e., individual differences) as aleatory. Individual differences can be treated as epistemic uncertainty, and can therefore be reduced through the acquisition of more knowledge.

We are not alone in making these points. The researchers involved in the international HRA empirical study [1, 2] drew the same general conclusion from their first experiment, and proposed improvements to HRA methods. Namely, while HRA methods typically do not factor in variability in performance when estimating HEPs, they suggested that sensitivity studies assessing the epistemic effects of antecedent factors on performance variability should be performed. These sensitivity studies would vary an antecedent known to contribute to performance variability (e.g., task complexity, procedural guidance), and then estimate the range of effects it has on performance. Doing this would, "Provide additional insights into the regions of validity of the methods and identify potential improvements in the use of the HRA models." (pg. 3-116). Not only do we concur with this suggestion, we have also proposed elsewhere [27] that there are many aspects of team performance and team dynamics (e.g., communication) that can be modeled using event trees and fault trees, thereby making these factors less aleatory and more epistemic in our understanding of their effects. Specifically, we argued that: (1) errors in teamwork are different than individual errors, (2) teamwork errors contribute to plant risk in ways that are unique from individual errors, and (3) that these teamwork errors can be meaningfully modeled and quantified such that the adverse effects of their under-specification in HRA can be reduced. These are two research ideas that propose concrete and actionable steps that HRA methods can do to consider more completely the effects of variability in operator and crew performance on the assessment of human contributions to plant risk. Of course, we recognize there are many other ideas that can help address the issue of individual differences, and we are supportive of any research that helps achieve the goal of improving HRA.

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