Exploring the Application of Cognitive Science in Nuclear and Radiological Security

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Abstract

The introduction of new technological solutions has prompted an overall expansion of the role of technology in nuclear and radiological security. This in turn has impacted the role assumed by the human element which is one of many reasons why a thorough evaluation of the latest advancements in cognitive science is needed. Cognitive science is the interdisciplinary, scientific study of the mind and its processes that examines the nature, tasks, and functions of cognition (e.g., thinking, reasoning, remembering). Over the past several decades, the number of studies focusing on human behavior and the application of cognitive science in high-risk, high-impact areas has grown tremendously, including cybersecurity and international nuclear safeguards. Nuclear and radiological materials and facility security should not be an exception as humans play a significant role within that space. It is evident that some aspects of cognitive science can be used in designing more effective elements of physical protection systems (PPS) and associated operating procedures and introducing elements for more effective deterrence. Nonetheless, in this work we explore the connection between the field of cognitive science and the nuclear and radiological security space by engaging a group of nuclear security experts and cognitive scientists to identify areas of cognitive science relevant to nuclear and radiological security. The analysis included differentiating between human protective and adversarial tasks specific to nuclear and radiological security, followed by connecting those tasks to a variety of research areas in cognitive science. A substantial spectrum of topics were identified connecting the two fields, several of which could potentially have a high impact on security. This includes topics such as trust in automation, prevalence effect, deceptive environment, and cognitive bias. An overview of the analysis conducted along with major findings and conclusions are presented in this paper. Practical recommendations are also developed for future research and implementation in training and systems design.

Introduction

Cognitive science is an interdisciplinary study that examines functions of cognition by studying the mind and its processes [1]. Although there has been an increased interest in assessing the application of cognitive science in various fields, human performance in the nuclear and radiological security space is often overlooked or does not receive a proper level of attention. This should not be the case since humans play a crucial role in nuclear and radiological security and often becomes the failing point of the overall system. The objective of this work was to identify potential areas where cognitive science can provide a positive impact on nuclear and radiological security. Particularly, it is of interest to assess whether or not cognitive science can aid in the design of more effective security systems or if it can be leveraged to identify and mitigate potential weaknesses and vulnerabilities.

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Analysis Framework

A systematic process was needed to effectively identify all areas cognitive science may potentially impact nuclear and radiological security. Thus, a framework was developed as part of this effort to achieve that. The analysis process consisted of a number of steps that aimed to relate specific areas of cognitive science to nuclear and radiological security. These steps included:

1. **Nuclear and Radiological Security Human Task Analysis:**
   This step aimed to reduce the nuclear and radiological space to a set of tasks that are regularly performed by security professionals.

2. **Relevant Cognitive Science Areas Identification:**
   This step aimed to select the cognitive science areas that would be relevant to nuclear and radiological security in order to efficiently draw connections between the two fields.

3. **Development of Cognitive Science Applications within the Context of Nuclear Security**:
   The final step was to draw connections between the two fields and identify areas where cognitive science could potentially impact the nuclear and radiological security space.

Lastly, the framework enabled the development of practical recommendations for nuclear and radiological security stakeholders.

Human Tasks in Nuclear & Radiological Security

The first step was to identify a list of human tasks and activities that are common in nuclear and radiological security systems. At a high level, the tasks were split into two major categories: *protective* and *adversarial*. Specifically, tasks that are usually performed by protective personnel and security systems designers were separated from tasks that would be performed by a potential adversary. Both categories were further divided to identify specific tasks for analysis with respect to cognitive science. Figure 1 illustrates a general outline of the tasks identified.

Protective Tasks

Protective tasks in nuclear and radiological security are described as the activities within a security program aimed at defending public health and safety by guarding against threats, theft, and sabotage [2]. These tasks encompass the implementation of PPSs, including detection, deterrence, and response procedures and operational tasks such as onsite guard duty, physical response, maintenance, and training [3][4]. Thus, tasks within this category were further subdivided into two types:

> *Operational Tasks:* Tasks that are primarily focused on the supervision and direction of security at the day-to-day level. Generally, it is a security officer onsite or nearby who monitors the protection of a source or device [5].
>
> *PPS Design Tasks:* Tasks that are usually planned and performed long before a source or facility is needed to be protected. They include building design, training, and procedure development [6].

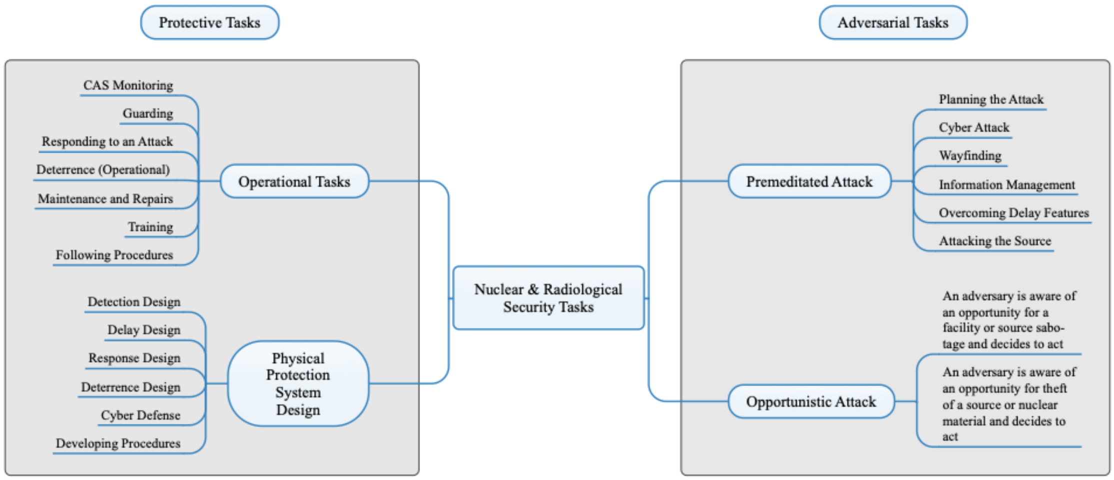

Figure 1: Outline of Nuclear and Radiological Security Task Analysis

Tables 1 & 2 provide the full list of operational tasks and PPS design tasks considered, respectively.

Table 1: Operational Protective Tasks and Definitions

Task	Definition
CAS monitoring	A central alarm station (CAS) surveillance system that allows operators to monitor and respond appropriately to specific sensor information and/or video images
Guarding	The physical act of watching over in order to protect or control; carried out by on-site facility personnel
Responding to an attack	The element of a PPS designed to counteract adversary activities and interrupt the threat
Deterrence (operational)	Discouraging an adversary from attempting an assault by making a successful assault appear very difficult or impossible
Maintenance and repairs	The maintenance and repair of systems or devices; such maintenance could possibly introduce a temporary vulnerability
Training	Cooperative interactive activity that contributes to the development of persons, techniques, infrastructure, and culture
Following procedures	Carrying out a series of steps followed in a regular, defined order to achieve a specific outcome

Table 2: Physical Protection System Design Tasks and Definitions

Task	Definition
Detection design	The design of PPSs to effectively determine that an unauthorized action has occurred or is occurring; detection includes sending the action, communicating the alarm to a control center, and assessing the alarm
Delay design	The element of a PPS designed to impede adversary penetration into or exit from the protected area
Response design	The design of the element of a PPS dedicated to counteracting adversary activities and interrupting the threat; response design considers the response force as well as response time
Deterrence (design)	The design of PPSs to discourage an adversary from attempting an assault by making a successful assault appear very difficult or impossible
Cyber defenses	The element of a protection system dedicated to defending against any cyberattacks
Developing procedures	The development of procedures, guidelines, and policies that enable and enhance the capacity to protect and secure nuclear and radiological materials

Adversarial Tasks

Adversarial tasks in nuclear and radiological security are defined as actions taken by individual(s) in an attempt to gain unauthorized entry to the protected or vital areas of a site's critical systems for the purposes of committing an act of theft or sabotage [5]. The adversarial attacks considered in this study to determine such tasks were sabotage, theft, rad/nuc attack, and smuggling. Although these attacks differ in many aspects, within the scope of cognitive science, tasks required for each attack are shared across all four types. Therefore, adversarial tasks were grouped into two subcategories:

> *Premeditated Attack:* Planned attacks that are coordinated and require the intentional actions of the attacker to be carried out. They take into consideration the different levels of security and response and attempt to subvert these measures. A list of the tasks involved in premeditated attacks is provided in Table 3.
>
> *Opportunistic Attack:* Attacks conducted by actors whose methods are generally not easily repeatable and who must be in the right place at the right time. A window of opportunity opens and they seize it. Capability can vary, but generally, attackers possess commercially available tools and weapons.

Identification of Relevant Cognitive Science Areas

The second step in this analysis was to identify a list of cognitive science areas potentially relevant to the nuclear and radiological security space. However, the list of cognitive functions that impact or influence human behavior is very broad. Any human behavior or activity can be described by a set of cognitive functions. Thus, an open-source literature search was performed to identify a list of various cognitive science areas. That list, in conjunction with the protective and adversarial tasks previously mentioned, were then used to identify a subset of cognitive science areas that are

Table 3: Premeditated Attack Tasks and Definitions

Task	Definition
Planning the attack	The preparation process of an attempt by an adversary to defeat the PPS and achieve the attack objective; attack tactics include force, deceit, and stealth, used singly or in combination
Cyber-attack	An attempt to damage, destroy, illicitly modify, or overwhelm a computer network or system
Wayfinding	The process or activity of ascertaining one's position and planning and following a route
Information management	The means by which an adversary chooses to maintain any information gathered during the planning process (commit to memory, written notes, map, etc.)
Overcoming delay features	Actions carried out by an adversary to overcome features designed to impede their penetration into or exit from the protected area
Attacking the target	The physical act aimed at deliberate sabotage or theft of nuclear/radiological material in use, storage, or transport

relevant to nuclear and radiological security. This was done through a collaboration between cognitive science SMEs and nuclear and radiological security SMEs at Sandia. The analysis resulted in a total of 14 cognitive science areas that were selected for further consideration:

Prevalence Effects	Change Detection
Repetitive and Mundane Tasks	Cognitive Fatigue
Situational Awareness	Heuristics and Cognitive Biases
Sleep Deprivation	Communication
Spatial Knowledge	Deceptive Environments
Time Pressure	Decision-making
Trust-in-Automation	Cognitive Off-loading and Knowledge Transfer

Stress, multi-tasking, task switching, and attention were also considered but did not make the final list due to their generality and broad coverage. Instead, they were subcategorized into more specific topics that are more relevant to the nuclear and radiological security space.

Development of Cognitive Science Applications within the Context of Nuclear Security

The technical literature in both the nuclear and radiological security and cognitive science domains has expanded tremendously in the past several decades. However, it appears only a small amount of existing literature directly relates cognitive science to nuclear and radiological security. While this presented a challenge during the literature review phase when selecting cognitive science topics for analysis, it also opens a wide range of opportunities to fill existing gaps in the future. Nonetheless, an in-depth literature search was conducted for each cognitive science area individually to better understand its relevance and potential impact on the nuclear and radiological security space. The literature search findings for the cognitive science area of *heuristics and cognitive biases* is provided here as an example of what was completed during this step of the analysis.

Heuristics and Cognitive Biases

A *heuristic* is a strategy that ignores part of the available information with the goal of making decisions more quickly, frugally, or accurately than with more complex methods [7]. As an important aspect of problem-solving and decision-making, these mental shortcuts allow people to function without constantly stopping to think about their next course of action. However, more often than not, they lead to systematic errors in thinking that prejudice decision quality due to their deviation from reality. This can result in inaccurate and often irrational conclusions, a phenomenon otherwise known as *cognitive bias.* Perhaps the best explanation of such phenomena is provided by Daniel Kahneman in his book *Thinking Fast and Slow*, where the author illustrates that the human brain has two operating systems, system 1 and system 2 [8]. The first is what is sometimes referred to as a 'gut feeling,' the fast, unconscious reasoning or judgments that are made based on intuition; this system processes information quickly by relying on heuristics to save mental energy. The latter is thought to be the complete opposite; a system that is more logical, processes information slowly, and makes decisions based on examination. In the context of this description, system 1 can be viewed as the use of heuristics in play. To better understand how heuristics and cognitive biases can impact the nuclear and radiological security space, the literature search within the scope of this topic set out to investigate two questions: why humans rely on heuristics, and when might cognitive biases arise?

Numerous definitions have been put forth by psychologists, each suggesting a different theory for why we rely on heuristics. The most popular theories are summarized as follows:

- *Attribute Substitution:* this theory is based on the simple hypothesis that people tend to answer a simpler, but related, question when confronted with a difficult one [9]
- *Effort Reduction:* under this theory, heuristics are viewed as some sort of cognitive laziness and primarily serve the purpose of reducing the mental effort associated with a task [10]
- *Less-is-More:* contrary to the popular belief that people save effort with heuristics at the cost of accuracy, this theory argues that heuristics are actually more accurate than they are biased [11]

As for situations where cognitive biases emerge, a vast collection of papers describe the cognitive biases that influence human thinking, but perhaps the most comprehensive is the Cognitive Bias Codex [12]. Here, the author identifies over 180 cognitive biases classified by four scenarios that may give rise to cognitive biases: too much information, not enough meaning, need to act fast, and not knowing what one should remember. Examples of cognitive bias that may impact nuclear security include:

- *Availability bias,* in which people tend to overestimate the global frequency of an event or the likelihood of its occurrence, based on the ease with which instances come to mind [13]
- *Confirmation bias,* which is the tendency to overvalue information that supports an existing belief [12]

Results & Discussion

Upon completion of the analysis phase relating cognitive science to nuclear and radiological security, five cognitive science areas were identified as being the most impactful and relevant to nuclear and radiological security. These areas were:

- Trust in automation
- Deceptive environments
- Heuristics and cognitive biases
- Prevalence effects
- Cognitive fatigue

These areas of cognitive science all impact a wide range of protective and adversarial tasks within the nuclear and radiological security mission space. Results of this study were provided in the form of practical next steps that can be carried out within nuclear and radiological security systems. All suggested potential next steps were divided into three main categories: research, design, and training. The *research* category shows potential additional research activities that can be conducted at an intersection of cognitive science and nuclear and radiological security. The *design* category provides suggestions for the integration of cognitive science into the design of nuclear and radiological security systems. Finally, the *training* category provides suggestions on how the body of cognitive science knowledge can be applied in training to improve human performance in nuclear and radiological security. The objective of this categorization was to provide a systematically organized set of practical and actionable suggestions that can be considered for future work in this area. Results of the analysis for *heuristics and cognitive biases* are provided for illustrative purposes.

Heuristics and Cognitive Biases

Nuclear and radiological security professionals are faced with complex tasks on a daily basis. Tasks range from protective operations, such as monitoring and guarding, to PPS design where individuals are presented with a great deal of information and are expected to use it in problem-solving and decision-making. In such situations, resorting to heuristics and ignoring parts of that information to make quick and frugal decisions is not uncommon. However, if these mental shortcuts were to lead to cognitive biases, such systematic errors could have major consequences. There are numerous cognitive biases that influence human thinking. Although they are often helpful since they allow for efficient decision-making, they can also be problematic and lead to errors. Not all cognitive biases are relevant to the nuclear security space, but some have the potential to greatly impact specific protective tasks. The tasks identified that are believed to have the highest likelihood for the emergence of cognitive biases were deterrence, cyber defense, and design basis threat (DBT).

As an example, a deterrence system can be designed with the assumption that an adversary has certain biases, or it can be biased toward information that supports the designer‘s existing beliefs. The same can be applied to cybersecurity, where systems might be biased towards a design set to respond to certain cyberattacks by overestimating the likelihood of their occurrence. As for a DBT, the perception of threat or what constitutes a threat could be biased, resulting in an inaccurate, or restricted, threat analysis. Further investigation would immensely advance nuclear and radiological security by assisting in the exploitation of adversarial biases and avoidance of systematic biases in PPS design. The potential impact of heuristics and cognitive biases on the nuclear security space is summarized in the following research questions:

1. Where are biases in decision making most likely to arise in current systems? (Research,Training)
2. Can some human cognitive biases be exploited in the design and implementation of cyberdefense systems? (Research, Design)
3. How can the effect of cognitive biases be minimized in DBT development? (Design,Training)

Training can also be effective for reducing the impact of cognitive biases in decision-making. Research in the intelligence community has shown that providing analysts with training and frameworks for considering alternative hypothesis can help them avoid biases as they gather and evaluate information [14]. Research on the questions outlined above would also help to identify instances where training on cognitive biases could be useful for minimizing decision errors.

An in-depth analysis identifying a list of all cognitive biases relevant to nuclear and radiological security would be a pivotal first step in understanding the effects and possible exploitation of cognitive bias. Such analysis will help identify situations that could give rise to cognitive biases within nuclear and radiological security as well as methods for mitigating those biases. Considering that not all heuristics result in cognitive biases, some analysis should also be conducted to differentiate heuristics that have a negative impact from those with a positive impact. Finally, the knowledge acquired by adversaries when planning an attack could bias their decision-making. An analysis of how particular types of information, or knowledge acquisition in general, could bias adversarial decision-making would be beneficial for exploiting adversarial biases. As for system design, case studies of times where heuristics and cognitive biases introduced jeopardized the security of a system should be taken into consideration as lessons learned. Finally, the existence of heuristics and cognitive biases should be integrated into training to raise awareness of situations where cognitive biases may emerge. The outcome of the research recommendations outlined above on how to avoid and manage cognitive biases should also be incorporated into training

Conclusions

The objective of this scoping study was to explore the connections between the field of cognitive science and the nuclear and radiological security mission space. Humans have always played a crucial role in nuclear and radiological security. However, the recent introduction of new technological solutions and overall expansion of the role of technology has changed the role of humans in nuclear and radiological security. This is just one of many reasons proving that a thorough evaluation of the latest advancements in cognitive science is needed and adoption of relevant findings would be of great benefit to nuclear and radiological security. In this study, the role of humans in nuclear and radiological security systems was explored and relevant areas of cognitive research were identified. The analysis process included mapping out human protective and adversarial tasks, followed by connecting those tasks to a variety of research areas in cognitive science. A total of 14 cognitive science areas were chosen for further exploration and the top five most impactful areas were identified through the analysis process. Recommendations were developed for these five cognitive science areas and categorized into potential further research, design, and training opportunities

The developed recommendations serve as the basis for future work connecting cognitive science to nuclear and radiological security, which would in turn create opportunities for discovering additional benefits that cognitive science can provide. Additional areas that were not explored in detail within the scope of this study, but may have a significant potential for future work are insider threat and deterrence. Those subjects would require a much deeper investigation that spans beyond the limits of the scoping study presented here. Overall, this study has shown that there is a substantial spectrum of topics connecting cognitive science to nuclear security. Thus, it is important that future work in this space bridges the gap to ensure that the human factor within nuclear and radiological security is well understood and that the latest advances in cognitive science are properly utilized for continued improvement in the nuclear and radiological security mission space.

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