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Brain Science and International Nuclear Safeguards: Implications from Cognitive Science and Human Factors Research on the Provision and Use of Safeguards-Relevant Information in the Field

Zoe N. Gastelum, Laura E. Matzen, Heidi A. Smartt, Karl E. Horak, Eric M. Moyer, Matthew E. St. Pierre

Sandia National Laboratories
Albuquerque, New Mexico, USA

Abstract:

Today's international nuclear safeguards inspectors have access to an increasing volume of supplemental information about the facilities under their purview, including commercial satellite imagery, nuclear trade data, open source information, and results from previous safeguards activities. In addition to completing traditional in-field safeguards activities, inspectors are now responsible for being able to act upon this growing corpus of supplemental safeguards-relevant data and for maintaining situational awareness of unusual activities taking place in their environment. However, cognitive science research suggests that maintaining too much information can be detrimental to a user's understanding, and externalizing information (for example, to a mobile device) to reduce cognitive burden can decrease cognitive function related to memory, navigation, and attention.

Given this dichotomy, how can international nuclear safeguards inspectors better synthesize information to enhance situational awareness, decision making, and performance in the field? This paper examines literature from the fields of cognitive science and human factors in the areas of wayfinding, situational awareness, equipment and technical assistance, and knowledge transfer, and describes the implications for the provision of, and interaction with, safeguards-relevant information for international nuclear safeguards inspectors working in the field.

Keywords: safeguards; inspection; cognition; information

1. Introduction

In today's information age, more safeguards-relevant data is available for International Atomic Energy Agency (IAEA) nuclear safeguards inspectors than ever before. Inspectors are not only responsible for an increasing number of nuclear facilities as the number of safeguarded facilities continues to grow around the world, but more information about those facilities is available. This increased information availability is in part due to enhanced reporting requirements under the Additional Protocol, but also due to the unprecedented growth in availability and diversity of open source information. Providing this information alone will not support more effective safeguards inspections. More important, for both the traditional and emerging sources of information that can be used to support IAEA safeguards inspections, is the actionable provision of that information – providing the right information, in the right format, at the right time.

Since at least the 1990s, proposals have been brought forward to provide advanced information technology platforms for IAEA safeguards inspectors. Some of these proposals, such as deploying Agency laptops with inspectors, have become a reality and now a norm. Other proposals such as the integration of mobile touch screen devices like tablet computers or smart phones into inspection information collection or documentation, or the use of 3D holographic displays, have been more futuristic and less likely to be deployed near-term [for example, references 1, 2, 3]. Meanwhile, new software products have been developed or commercially procured by the Department of Safeguards to support information collection, analysis, and processing both at Headquarters and in the field [4, 5, 6, 7, 8]. While these tools appear to have preliminary positive results, there has been little evidence of formal assessments of how these tools impact a safeguards inspector's or analyst's cognition of the safeguards information being presented.

In this paper, we will explore unique insights from the cognitive science and human factors communities as they apply to international safeguards inspector use of, and interaction with, information during in-field activities. To identify the cognitive science and human factors principles most relevant for international nuclear safeguards activities, we first catalogued the most common safeguards activities conducted in the field. We then documented procedures for commonly used equipment or activities, and the information available to inspectors while conducting those activities. General categories of safeguards activities included, for example, destructive sampling, visual observation, and the use of safeguards equipment for non-destructive measurements of radioactive materials. From the catalogue of in-field safeguards activities and their relevant information environments, a list of relevant cognitive science and human factors concepts was assembled which included the following areas of study:

- Wayfinding;
- Inattentional blindness;
- Situational awareness;
- Equipment troubleshooting; and
- Knowledge transfer.

In addition to these cognitive science and human factors concepts relevant for safeguards tasks, a few common themes were identified that span across safeguards activities, including operation in one's non-native language, exhaustion, stress due to time constraints, and operation in industrial environments. While these factors were also considered relevant to effective execution of international safeguards activities in the field, their pervasiveness and the difficulty to ameliorate them within international safeguards inspection scenarios led to removal from consideration in this aspect of our research.

In this paper, we will describe each of the selected cognitive science and human factors areas of study in turn, including a discussion of their relevance to safeguards activities and the current understanding of best principles or practices that may influence how to interpret their findings for international nuclear safeguards.

2. Application of Cognitive Science and Human Factors Literature to International Nuclear Safeguards

Cognitive science and human factors are scientific fields that study human behavior, activity, and learning from two distinct perspectives. For the purposes of this research, cognitive science studies human thought, learning, and mental organization related to how individuals interact with and understand information related to international nuclear safeguards inspection activities. Human factors, on the other hand, studies human interactions with a system (such as a safeguards procedure or piece of equipment) and can impact how individuals act in their physical environment based upon information they are provided. Thus, both disciplines can provide unique insight into effective and efficient means to provide information to international nuclear safeguards inspectors working in the field.

2.1. Wayfinding

Wayfinding is a form of spatial cognition in which people determine where they are in an environment and how to navigate to where they want to go [9]. Wayfinding can include navigation by map, landmarks, or verbal/written directions outdoors or indoors.

2.1.1. Wayfinding for International Safeguards

When safeguards inspectors move from one part of a facility to another, they must rely on their wayfinding skills to effectively navigate a nuclear site or facility. This includes both indoor and outdoor navigation. For outdoor navigation, inspectors can have access to GPS, maps with landmarks, or other aids. But indoors, inspectors rely on a facility map or their own mental map of the facility based on previous experience. Even if they are being escorted by an operator, inspectors should be aware of where they are so that they can efficiently go from one area to another within a facility and ensure that they are being taken to the correct location. They should also be able to note if routes taken at a site or facility appear circuitous or seem to avoid areas that were previously on the regular route (which may be cause for follow-up questions).

2.1.2. Theoretical Background of Wayfinding Research

Some prior studies have potential relevance for international nuclear safeguards inspections. Several studies [10, 11, 12] have attempted to compare wayfinding using paper maps to wayfinding using mobile maps or GPS devices. These studies have had mixed results, with some finding that users took longer to reach their destinations when using a paper map [11] and others finding that participants took longer when using GPS [12]. The generalizability of the results of these studies is limited by factors such as small sample sizes [10], small screen sizes on the electronic devices [12], and inexperience with mobile maps on the part of the participants [12]. In the years since these studies took place, increasing familiarity with mobile maps and GPS among the general population could lead to very different results. However, one finding that is likely to hold true is that mobile map users tend to have a poorer understanding of the overall layout of the area in which they are navigating [10]. A paper map provides participants with an overview of the area, an aspect of navigation that is often absent when people navigate using point-to-point directions provided by a navigation app. This finding indicates that safeguards inspectors may have very different mental models of a facility if they learn its layout by walking through it as opposed to studying blueprints or diagrams. This in turn may influence how they navigate through a site or facility and how they notice changes or discrepancies.

Another area of wayfinding research that applies directly to the safeguards domain addresses indoor navigation. This is an area of interest for researchers who are trying to understand how to help people navigate through complex buildings, such as hospitals, transportation hubs, or large shopping centers. While navigation apps and mobile maps have been widely adopted for outdoor use, these tools typically fail for indoor environments, where GPS does not work (due to signal weakness) and navigation landmarks such as street names and numbers are absent. Researchers have attempted to address these problems by developing indoor navigation systems that use waypoints rather than continuous information about a person's location. For example, Mulloni, Seichter and Schmalstieg [13] demonstrated a system that provides turn-by-turn directions from one waypoint to another. In another study, Mulloni et al [14] used a similar system in which localization markers were used to help attendees navigate during a conference. Trilateralization from Wi-Fi transmitters is also a possible solution [see 15].

These navigation techniques might be applicable within the safeguards domain to help inspectors navigate a complex facility. However, in any application of navigation aids, it is important to note that there are substantial individual differences in terms of how people navigate [16]. Indoor navigation systems must be designed so that they are robust to individual differences in the users' spatial abilities and navigation preferences. Furthermore, indoor navigational aid deployment would require approval and cooperation from the facility operator regarding placement of such markers, maintenance of their integrity, and the use of mobile technologies to engage or interpret them.

2.2 Inattentional Blindness

Inattentional blindness, also known as "change blindness" or "perceptual blindness", is the concept that the changing of certain stimuli, considered to be in plain sight, is missed by an observer. Studied to a relatively large extent within the academic psychological research community, it has sometimes been relegated to a status of marginal importance due to the historical difficultly ability of drawing practical inferences from the research results [17]. However, human observers' tendency to miss changes that occur right in front of them has been demonstrated repeatedly [18, 19].

2.2.1 Inattentional Blindness and International Safeguards

The discovery of Iraq's nuclear weapons program the early 1990's led to a shift in international nuclear safeguards from the verification of solely the correctness of a state's declaration, to verification of both the correctness and *completeness* (i.e., no undeclared nuclear activities) of the declaration. This led to a change in expectation that safeguards inspectors would become more investigative, and the incorporation of multiple visual observation and detection of anomaly tasks required as part of safeguards inspection activities. However, inattentional blindness research indicates that even highly focused safeguards inspectors may miss key information from their environment. For example, one of the most well-known examples of inattentional blindness is from an experiment conducted by Daniel Simons and Christopher Chabris [20], in which the researchers documented a sustained period in which test subjects asked to count the number of ball passes between a select group of individuals failed to notice the presence of someone dancing in a gorilla suit in the scene. The experiment calls into question whether international safeguards inspectors focused on one type of data collection in the field might inadvertently miss critical information that could indicate anomalous or undeclared activities at a facility or site under IAEA safeguards.

2.2.2. Theoretical Background of Inattentional Blindness Research

Recent research in the field of inattentional blindness has focused on humans in real-world contexts rather than laboratory studies. This research is showing that change blindness occurs often and in many circumstances in the real-world. One such study demonstrated that many observers failed to notice when a conversation partner was replaced in the middle of a real-life interaction [21, 22]. These research efforts have established that attention is needed to see change, and that we possess a finite ability to focus our attention on our environment. Therefore, changes to semantically central items in a scene are detected faster than changes elsewhere [18] which suggests that we assign preferential attention to certain objects based on context [23]. While attention is required for conscious change perception, the focus of our attention can change frequently while viewing a scene. If a change occurs in the scene, we may miss it despite actively viewing the scene [24, 25].

Various studies in change detection have shown that only about four items can be monitored at a time. This supports other research which implies we possess only one mechanism for the formation and maintenance of coherent visual attention, primarily concerned with the perception of objects [26]. This research may have implications on how safeguards inspectors divide tasking within an area of a nuclear facility in order to limit over-burdening the brain’s visual observation capacity.

Additionally, scene representation plays a large part in our ability to visually attend to objects, and we only attend to what we need from the scene for the task at hand [25], reinforced by our experience with the stimuli being viewed. We usually do not need to mentally represent all the objects around us at any given time in order to make sense of our environment. Rather, we need only to represent the objects, and properties of those objects, involved in a task at hand. Thus it is possible that we operate with a dynamic representation of a scene that is highly sensitive to the demands of the current task and the expectations of the observer [27]. For safeguards inspectors working in the field, therefore, their mental models will appropriately shift between broad site-level understanding and smaller, more detailed visual representations needed to complete specific safeguards verification tasks.

Other studies in inattentional blindness indicate that the amount of knowledge or familiarity an individual possesses about the objects in any given scene influences their ability to detect changes to that object [28]. For example, social drug users are more likely to detect changes to drug paraphernalia in photographs than are non-drug users [29] and American football experts are better able to spot changes to football scenes than are novices [30]. This has also been demonstrated regarding change detection with people [21], for objects described to individuals about scenes they view afterwards [18], and objects of interest to the observer [31]. This means we detect changes much more easily for objects we are familiar with or are told are of importance in a particular scene. In this context, international nuclear safeguards inspectors would be expected to have higher than average change detection capabilities in nuclear facilities they are familiar with, but may still suffer from inattentional blindness to changes in a facility when focusing on a specific task or area not associated with the change.

2.3 Situational Awareness

Situational awareness is the term used to describe a person’s understanding of “what is going on” [32, 33]. This topic has received considerable research attention over the past three decades because it is a crucial component of human performance in any dynamic situation. According to the most widely-used model of situational awareness, to perform efficiently humans must be able to 1) perceive the important things in their environment, 2) understand them, and 3) be able to predict what will happen next [32].

2.3.1. Situational Awareness for International Safeguards

The highly investigative and observational nature of international nuclear safeguards activities, combined with a potentially hazardous working environment, makes inspector situational awareness crucial for their ability to safely and effectively observe anomalous or unusual activities during the course of their on-site activities. Inspectors must be aware not only of their current task at hand, but the operation of a nuclear facility or site that provides broader context to their safeguards verification activities.

2.3.2 Situational Awareness Theory

A variety of methods have been employed for improving situational awareness. Experience is a key component of situational awareness, with more experienced individuals generally exhibiting higher levels of situational awareness [34]. Thus, training and knowledge transfer can directly influence situational awareness. The way in which information is presented to an individual also has significant impact on situational awareness, which has led to a great deal of research on how to visualize information for rapid consumption by the user [35, 36, 37, 38].

In general, the design of a system has a substantial impact on situational awareness. A well-designed system or tool should present the user with the right information at the right time and in the right format to support the components of situational awareness: perception, comprehension, and projection. The details of these tasks are often domain-specific, so many researchers have focused on developing methodologies for understanding situational awareness within a specific operational context such as cyber defense [35], emergency medicine [39] and law enforcement [40].

Though situational awareness has not been explicitly studies in relation to international safeguards inspections, the techniques outlined above could be applied to understanding the components of situational awareness for different types of inspection activities. Once these components have been identified, new technologies such as data visualizations or enhanced training techniques could be developed to improve inspectors' situational awareness.

2.4 Equipment Troubleshooting

Humans interact with systems such as technical equipment on a regular basis, most commonly via intuitive action/reaction modes. This is especially true for people who are frequent users of the equipment. However, when equipment malfunctions or breaks, use of that equipment can quickly become frustrating. User guides are not always straightforward or available, and often require the user to know the specific problem with the equipment in order to troubleshoot it effectively. Troubleshooting is a form of problem solving in which users "diagnose faulty systems and take direct, corrective action to eliminate any faults in order to return the systems to their normal states" [41].

2.4.1 Equipment Troubleshooting for International Safeguards Equipment

IAEA safeguards inspectors use a large variety of safeguards equipment depending on the activity they will be carrying out in the field, and facility-specific requirements. Some equipment is brought with the inspector or shipped from IAEA headquarters, while other safeguards equipment is stored on-site. While an inspector might only use a limited number of pieces of equipment for a specific safeguards inspection, there are many types of equipment that they might use over the course of their safeguards activities at different facilities or for different inspection types. In cases where maintenance is scheduled or an especially challenging piece of equipment will be used, a technician may accompany the inspector. However, inspectors often encounter equipment failure or malfunction during the course of routine use of equipment that they are required to resolve in the field.

2.4.2. Theoretical Foundations of Equipment Troubleshooting

Research in novice troubleshooting strategies tends to focus on structured representations of the system in which large parts of the problem space can be discounted early on [42]. (This "pruning of the search tree" is much like the selective search carried out by expert chess players.) The representation of the system as a functional hierarchy can be used to facilitate their troubleshooting in some cases [43, 44, 45].

Kurland and Tenney posit that documentation provided for troubleshooting can be too difficult for a novice to extract, leading to information overload. In other cases, documentation might not be available. According to research conducted by Schaafstal [42] and Kurland and Tenney [46], challenges facing novice troubleshooters can come from one of two areas: 1) their limited experience with and understanding of the system, or 2) lack of a systematic approach in which robust and flexible troubleshooting strategies are applied for goal-oriented problem solving. Both Shaafstal et al [42] and Jonassen and Hung [41] stress the importance of a training regimen for troubleshooting that includes both a systematic understanding of the equipment at hand as well as a system-independent strategy for troubleshooting that prevents information overload and ensures a consistent troubleshooting approach across systems. For international safeguards inspectors, this will require training both on the safeguards equipment the inspectors will use in the field and equipment troubleshooting strategies that are equipment-agnostic.

2.5 Knowledge Transfer

Knowledge transfer refers to sharing information and experience across different teams or parts of an organization [47]. This includes knowledge that individuals or teams have gained through experience, as well as routines and procedures that have been developed over time [48]. Institutional knowledge resides in many places, including individuals, organizational structures, operating procedures, institutional culture, tools and technologies, and in the interrelationships created by combining individuals, tasks, and tools [47]. When one team hands off work to another, or when people move in or out of an organization, transferring knowledge is crucially important for maintaining continuity. Similarly, as new forms of institutional knowledge are acquired, they must be disseminated through the organization in order to improve the performance of the organization as a whole.

2.5.1 Knowledge Transfer for International Safeguards

Knowledge transfer is a critical component of international safeguards inspection activities, to ensure that facility subject matter expertise is passed from experienced to newer inspectors, as well as the transfer of information learned from in-field inspection activities from one inspector (or inspection team) to another. While most of the research regarding knowledge transfer has related to shift workers who have brief periods of overlap, IAEA safeguards inspector knowledge transfer poses a new challenge due to the amount of time between inspector visits to a facility. In this case, knowledge is being transferred mostly through paper or electronic documentation (though some may occur via in-person briefs before an inspection). Due to travel time and the potential for multiple inspections at different facilities or countries to occur in a single trip, an in-person brief may take place days or weeks before visiting the facility. Further, some information may be left at IAEA headquarters with only notes taken into the field to avoid potential loss or exposure of sensitive information (significantly increasing reliance on memory).

2.5.2. Theoretical Background of Knowledge Transfer

Knowledge transfer has been studied in shift work environments, such as manufacturing environments [48], hospitals [49], and nuclear power plants [50]. Handoffs between shifts are crucial for maintaining continuity and preventing duplication of effort in which different teams are independently trying to solve the same problems [48]. Failures of knowledge transfer between shifts have been identified as key components in industrial accidents [51, 52] and medical errors [53]. Research on knowledge transfer in these domains has identified key strategies that are used to facilitate the handoff of information (Patterson et al., 2004) and handoff checklists that could be applied to a variety of domains [52].

Face-to-face meetings are often used to transfer knowledge from one shift to the next, but this transfer can also occur via *boundary objects*. Boundary objects are artifacts that support the translation of information from one group to another, allowing disparate groups to communicate and work toward common goals [54, 55]. Bosua and Venkitachalam [48] explored the use of boundary objects in shift handovers. Of the three shift environments studied, only one had a system for codifying knowledge and making it easily available to all shifts. The culture of codifying and transferring knowledge facilitated handoffs from one team to the next.

The safeguards domain shares some features with shift work environments, such as the need to transfer knowledge from one inspection team to the next. However, it also differs from shift work environments in several key ways. For example, shifts in a hospital setting occur back-to-back, allowing different teams to overlap and share information during the transition between shifts. In contrast, there may be weeks or months between facility inspections and different teams of inspectors may not meet face-to-face. This introduces additional challenges, such as the need for robust boundary objects that can adequately transmit knowledge from one team to the next, as well as the need to account for changes that may occur between inspections. While international safeguards inspectors do complete extensive documentation regarding their in-field inspection activities, the format of this information may or may not support effective knowledge transfer between teams. The question remains as to how safeguards-relevant knowledge from inspections at a specific site is best transferred from one team to the next.

3. Conclusions

Some of the cognitive science and human factors disciplines related to mechanisms by which international safeguards inspectors interact with information in the field are well studied, such as interior and outdoor wayfinding using various navigational aids. Others, such as knowledge transfer, are well studied in specific situations but do not currently capture significant nuances for international safeguards application space. Over the next three years, researchers at Sandia National Laboratories will develop and execute human performance experiments on mechanisms for the effective provision of information for safeguards inspection-like scenarios. We will seek to measure accuracy, timeliness, and situational awareness of test subjects performing safeguards-relevant activities and suitable proxies dependent upon the type, quantity, and provision mechanism of information to which test subjects have access. In this way, the project team seeks to have both an impact on the state of understanding in the cognitive science and human factors fields, as well as provide meaningful and actionable results that can be implemented to support international safeguards inspectors working in the field.

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