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Testing Human Performance in Simulated In-Field Safeguards Information Environments

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The intersection of the information age and a global increase in commercial nuclear fuel cycle activities has resulted in international nuclear safeguards inspectors being responsible for acting upon unprecedented amounts, and types, of data in the field. Recent proposals have described advanced information technologies to support in-field inspector activities, but have focused on development of conceptual or prototype systems or their deployment options rather than a systematic assessment of their potential added value. To better understand this void in the information system requirements for international safeguards, Sandia National Laboratories has undertaken a study of the interaction between safeguards inspectors and the information they use in the field. In this paper, we describe Sandia's current work to evaluate a variety of information system constructs for simulated international safeguards activities. We describe the cognitive science foundations of the study, a safeguards task analysis used to prioritize activities for various modes of human performance testing, and the framework for the study's experimental design.

INTRODUCTION

In recognition of the vast amount of information international nuclear safeguards inspectors are expected to be able to act upon in the field, numerous proposals for advanced information systems have been explored by the international nonproliferation verification community since at least the 1990's. Such proposals have included, for example, portable computer devices (now known as laptop computers), tablet computers [1], mobile and wearable smart devices [2], and augmented reality headsets [3]. Yet while advanced information systems are being incorporated more and more into industry, the commercial world, and our personal lives, further testing is required to determine if these devices actually improve upon desired inspector characteristics in the field such as situational awareness and accuracy and timeliness in task completion. The appeal for many of these devices today is enhanced multi-tasking, outsourcing activities or skills that once required memory to an "external" source. For example, memorization of phone numbers or navigation by streets and landmarks are now easily accomplished with smart phones. Studies in cognitive science have shown that in some cases, the transfer of cognitive functions to external sources has a significant impact on our own cognitive abilities, leading to decreased awareness and, in some cases, changes in brain structure over time (for example see references 4, 5, 6).

To understand the implications of cognitive science on international nuclear safeguards inspection activities, a detailed safeguards task analysis was conducted. The aim of the task analysis was to identify the detailed procedures that are undertaken in the field, the relevant information available to inspectors while conducting those tasks, and how the information is used. Once the in-field safeguards activities had been described in detail, an overview of those tasks was conducted from the theoretical cognitive science perspective to assess which scientific foundations, theories, or principles were most relevant, and where there were gaps in understanding specific to the field of international safeguards. Then, an analysis was conducted to determine which types of safeguards tasks could be experimentalized for human performance testing in order to yield the most impactful results for both the international nuclear safeguards community and the theoretical foundations in the field of cognitive science.

This paper will describe each of these activities – the safeguards tasks analysis and prioritization, the literature review of state-of-the-art cognitive science and human factors principles, and the cross-referencing of the two activities to identify gaps in scientific understanding that will also have high impact for international safeguards to develop priorities for experimental design – in more detail in the following sections.

SAFEGUARDS TASK ANALYSIS

Safeguards inspectors from the International Atomic Energy Agency (IAEA) perform a variety of tasks in the field in order to verify a state's compliance with their safeguards agreements. These tasks may differ based on the type of safeguards activity an inspector is performing (design information verification, interim or physical inventory verification, or complementary access), or the stage of the nuclear fuel cycle facility at which the safeguards activities are being performed. The tasks also vary based on the safeguards objective they are meant to achieve. The main objectives of safeguards inspections are verification of a state's declaration 'correctness' and 'completeness'. Inspectors are verifying absence of any nuclear material diversion ('correctness'), the absence of facilities or equipment misuse, and the absence of any other undeclared activities ('completeness').

Safeguards activities conducted in the field can range from observation, information corroboration, and a wide variety of data collection activities. For all safeguards activities, inspectors interact with some level of data in the field.

Defining Safeguards Tasks

We began by outlining all the in-field verification activities that inspectors conduct, through literature review and expert interviews. For each activity, we described procedures for how the activity was conducted (and, if available, procedures for using associated safeguards instrumentation) and a description of the information sources available to safeguards inspectors to support their completion of the task. For the purpose of this project, we defined safeguards tasks according to their general alignment with the objectives of high-level safeguards inspection types (physical inventory verification, design information verification, and complementary access). See Figure 1 for graphical representation of how safeguards activities were delineated. From there, more specific task details were identified. Though many safeguards tasks can be performed in relation to multiple inspection types or objectives, this diagram is meant to provide a high-level overview and not to be comprehensive.

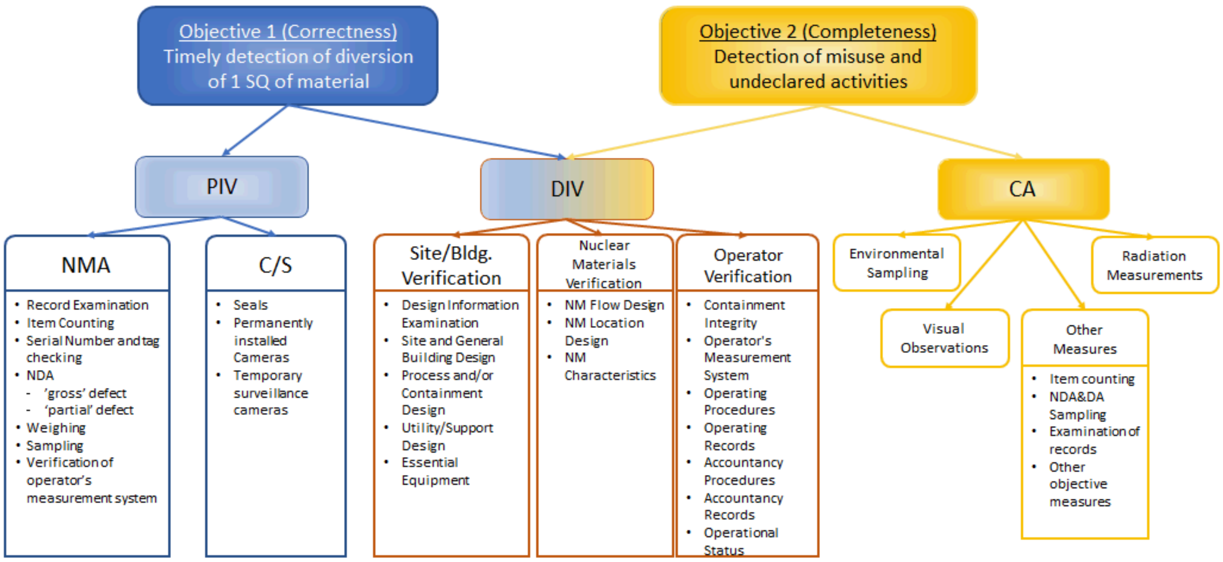

Figure 1A schematic representation of typical safeguards inspector field activities related to main safeguards objectives

Physical Inventory Verification (PIV)

PIV is intended to account for all the nuclear material that is stored at, or has been processed through, a facility under IAEA safeguards. PIV activities are aimed at the "correctness" objective, that is, the timely detection of one significant quantity (SQ) of nuclear materials. At a high level, PIV activities can be broken down into two main categories: nuclear material accountancy (NMA) and verification of containment and surveillance (C/S). Activities under NMA include an examination of operator records, item counting, non-destructive assay measurements to check for gross or bias defect, sampling for destructive assay (including environmental swipe sampling), and verification of an operator's measurement systems. Activities under C/S can include the application and verification of seals, verification of containment structures, and the verification of surveillance data from permanently installed or temporary surveillance systems.

Design Information Verification (DIV)

DIV is intended to address the construction and operation of a nuclear facility based on its design, the support buildings and infrastructure located on the site, presence and status of key pieces of equipment, and other operational activities. DIV can support both the "correctness" and "completeness" safeguards objectives since the examination of operational activities at a facility could lead to the detection of misuse of, or presence of undeclared at activities at, the facility. The three high-level categories of DIV activities used for this project purpose include site and building verification, nuclear materials characteristics verification, and operator verification. Site and building verification can include inspection of site and building design, process and containment design, examination of utility and support design, and evaluation of essential equipment. Nuclear materials (characteristic) verification include an inspection of nuclear material flow design, the location of nuclear materials, and characteristics of nuclear materials present at a nuclear facility. Operator verification includes, for example, verification of operator procedures, verification of accountancy records, and verification of operational status of a facility.

Complementary Access (CA)
CA is not technically a safeguards inspection; rather, it represents access provided by the State to IAEA inspectors for three purposes [7]:

1. To assure the absence of undeclared nuclear material or activities at a site, mine, plant, or other location where nuclear material has been declared to be present;
2. To resolve questions regarding the correctness, completeness, or an inconsistency of a state's declaration; or
3. To confirm the declared decommissioned status of a facility or location outside facilities where nuclear material was previously used.

CA visits can include environmental sampling (including soil, water, or other samples not taken as part of environmental swipe sampling), visual observations, radiation measurements (primarily to confirm the absence of radiation material) or a number of other measures.

<u>Task Prioritization</u>
It would be time and cost prohibitive to test human performance given multiple cognitive information environments for all the safeguards tasks identified in this research. Further, some activities require significantly less information and thus are not as interesting from a cognitive science standpoint. Thus, the research team developed a systematic way to prioritize which types of safeguards activities would be used for testing. This included the development of six measures by which each activity would be judged by the research team:

1. *Amount of information provided* - The quantity of safeguards-relevant information from IAEA headquarters or provided on-site by the operator that is required to successfully complete the task. This may include, for example, state declaration information, operating procedures for safeguards equipment, maps or facility drawings, or working papers in which inspectors document follow-up actions, questions, etc.
2. *Exposure to human error* - The susceptibility of the safeguards task to human error such as transcription, unintentional misuse of equipment, or other errors that could result in anomalous data for a nuclear inspection activity. The exposure to human error may result from the design of the equipment being used, the length or repetitiveness of the task, or the complexity of the procedure that must be followed, for example.
3. *Task difficulty* - The complexity or reported difficulty of accurately completing a safeguards task. This is a similar, but less formal, measure to cognitive load.
4. *Time requirement* – The amount of time required to successfully and accurately complete a safeguards task. This measure refers to the completion of a single instance of completing a safeguards task, for example, the amount of time required to verify one seal.
5. *Task frequency* – The number of times a safeguards task is repeated over the course of an inspection. For example, an inspector may use a Cherenkov viewing device hundreds of times while verifying the spent nuclear fuel in a cooling pond at a nuclear reactor.
6. *Generalizability across nuclear fuel cycle facilities* – The applicability of a task across multiple types of safeguards activities and nuclear fuel cycle facilities. For example, fresh nuclear fuel

verification may be done at nuclear fuel fabrication plants or nuclear power and research reactors, while the application of metal cup seals for containment/surveillance purposes is done at almost all nuclear facilities under IAEA safeguards.

Because of the challenge of measuring safeguards activities for the five objectives defined above, the team used three representative international safeguards inspection examples on which to rate the safeguards activities. The three inspection examples were physical inventory verification at a light water nuclear power reactor, physical inventory verification at a gaseous centrifuge enrichment plant, and design information verification at a fuel fabrication plant. Based on these three example inspections, and augmented with recurring topics from interviews with former IAEA safeguards inspectors, the following safeguards activities were identified as highest priority for the project:

- Comparison of records and inspection data;
- Visual observation of operator processes;
- Visual observation of presence, use, and operational status of equipment;
- Spent fuel verification via Cherenkov viewing;
- Verification of containment;
- Servicing surveillance systems; and
- Equipment troubleshooting in the field.

THEORETICAL FOUNDATIONS FROM COGNITIVE SCIENCE

While findings from cognitive science research have potential applications for international nuclear safeguards activities being conducted in the field, limited studies have been aimed at this specific field. We are especially interested in cognitive science literature that has implications on how international safeguards inspectors are interacting with safeguards information such as information from headquarters, state- or operator-provided information, or information being actively collected during in-field activities. Based on the safeguards task analysis described above and a broad review of cognitive science literature, the following fields in cognitive science were identified as having particular relevance to international safeguards activities and their accompanying information environments in the field:

- Wayfinding;
- Inattentional blindness;
- Situational awareness;
- Troubleshooting; and
- Knowledge transfer.

Each cognitive science concept is defined below, with a description of its applicability to international nuclear safeguards. In addition, we recognize that other factors also impact inspector performance that will make any inspection activity more challenging, including operation in one's non-native language, exhaustion, stress due to time constraints, and working in an industrial or potentially hazardous environment.

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 [8]. Wayfinding can include navigation by map, landmarks, or verbal/written directions outdoors or indoors. When safeguards inspectors navigate within or between nuclear facilities, they rely on wayfinding skills. This includes both indoor and outdoor navigation. For outdoor navigation, inspectors may have access to GPS, maps with landmarks, or other aids. But indoors, inspectors rely on the facility map or their own mental map of the facility based on previous experience.

Even when escorted by an operator, inspectors maintain awareness of their location in order to efficiently traverse work locations within a facility and ensure that they are being taken to the correct location. They should also be able to notice if routes taken at a site or facility appear circuitous or avoid areas that were previously on the regular route.

Inattentional Blindness

Inattentional blindness is the phenomena in which the changing of certain stimuli, considered to be in plain sight, is missed by an observer. The discovery of Iraq's nuclear weapons program in 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 that declaration. This led to a change in expectation that safeguards inspectors would become more investigative, and the addition 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.

One of the most well-known examples of inattentional blindness is from an experiment conducted by Daniel Simons and Christopher Chabris [9], 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 if 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.

Situational Awareness

Situational Awareness (SA) is the term used to describe a person's understanding of "what is going on." The most common model for situational awareness breaks the concept into three key components [10]:

1. Perception - the ability to notice the important things in one's environment;
2. Comprehension - the ability to understand what has been perceived; and
3. Prediction – the ability to foresee what will happen next.

The highly investigative and observational nature of international nuclear safeguards activities, combined with a potentially hazardous working environment, makes inspector situational awareness important for safety and their ability to 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.

Troubleshooting

Humans interact with systems such as technical equipment on a regular basis, most commonly via intuitive action/reaction modes. This is especially the case when they 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 clear or available, and often require the user to know the problem with the equipment to effectively troubleshoot. 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." [11]

IAEA safeguards inspectors use a large variety of safeguards equipment depending on the activity they will be carrying out in the field. 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 required 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.

Knowledge Transfer

Knowledge transfer refers to sharing information and experience across different teams or parts of an organization [12]. This includes knowledge that individuals or teams have gained through experience, as well as routines and procedures that have been developed over time [13]. 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 [12]. 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.

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 to other inspectors or analysts at headquarters. 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, and that knowledge is being transferred mostly through paper/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/countries to occur in a single trip, that in-person brief may have days or weeks' time lapse between interaction and being in 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 (relying much more on memory).

GAP ANALYSIS

From the literature review, we identified a number of areas relevant to international safeguards in which there was more research needed for the specific safeguards information environment. The highest priority cognitive science and human factors areas identified include:

- Visual inspection
- Change detection
- Knowledge transfer
- Wayfinding

While each of these areas has been studied in-depth in the field of cognitive science, there are areas specific to international safeguards in which additional study may make significant impact on the field. For example, knowledge transfer has been studied extensively for shift workers, in which individuals or teams hand information directly from one group to the next. However, the nature of knowledge transfer for international safeguards means that in most instances, weeks, if not months, go by between the two teams' presence at a facility. Further, when an inspector is briefed at headquarters, scheduling of other inspections may mean that several weeks go by between the briefing and the inspector's presence on-site. This means that an inspector's notes and memory are utilized in a different way than that of a shift-worker who will immediately take action upon the information provided during a knowledge transfer process.

In another example, significant research has been conducted regarding wayfinding, and specifically the use of maps, GPS, or other navigational aids. While this research itself is significant for international safeguards inspectors navigating to, and around, a site, little research has been done regarding wayfinding with an escort as would be done for a safeguards inspector inside a nuclear facility during the majority of inspection activities. How to support inspector awareness of location and navigation while being escorted, therefore, may be another area in which this project may significantly enhance the corpus of scientific knowledge in the cognitive science domain while also providing useful, actionable results for international safeguards.

EXPERIMENTAL DESIGN

Based on the intersection between the international safeguards task priorities and the areas of biggest impact in cognitive science, three high-impact areas were selected for human performance testing. These high-impact areas are:

1. List comparisons (to objects or to written text/list/declaration)
2. Knowledge transfer between inspections. Includes the use of inspection reporting, face-to-face briefings, and the impact of time lag between transfer activity and being in the field.
3. Anomaly detection in a 3D environment. This includes comparing a 3D space to an image such as is done in DIV, navigational activities (understanding where you are in an environment compared to a map or diagram, especially while being escorted)

Due to the nature of safeguards activities, these areas are not intended to be mutually exclusive, as comparing lists objects includes interaction with the 3D environment, for example.

The planned human performance experiments will vary the type, quantity, and provision mechanism of information to which users have access during safeguards-like tasks to measure user accuracy, timeliness, and situational awareness during task completion. We envision conducting various types of human performance testing, including testing with both experts (who have experience in inspection-like activities) and non-experts, as well as the use of a variety of testing environments potentially ranging from online testing platforms to in-person laboratory experiments.

FUTURE WORK

Pending the results of human performance testing planned for 2018, the project team will do a number of sensitivity analyses. We will conduct follow-on testing as necessary to further understand the impact of various information environments on users performing safeguards-relevant tasks. We intend to focus 2018 testing activities on the provision of visual information. However, in 2019 we may expand that testing to include other sensory mechanisms by which to provide information to users, for example aural or haptic. Both aural and haptic methods have been explored for information provision in other domains [14, 15] but have not, to the knowledge of the research team, been examined in relation to the unique activities associated with international safeguards inspections.

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