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The Role of Maps in Site Knowledge and Wayfinding: A Human Performance Evaluation for International Nuclear Safeguards Inspections

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Abstract:

International Atomic Energy Agency (IAEA) safeguards inspectors conducting in-field activities are responsible for taking a variety of samples, measurements, and observations, as well as being aware of their environment to notice any unusual activities that might indicate undeclared activities or materials. The data that are collected by safeguards inspectors are highly dependent on location (i.e., they should pertain directly to a material balance area, facility, site, location outside facilities, etc.), thus an inspector's ability to confidently confirm their location within a facility, the route they accessed to traverse a facility, and the location within a facility where they observed specific phenomena is highly relevant.

The cognitive science community has extensively studied wayfinding across multiple navigation environments (indoors, outdoors, over multiple stories indoors) and modalities (paper maps, electronic maps, step-by-step instructions, landmarks, etc.) yet the unique nuances of wayfinding for international nuclear safeguards inspections (indoors, in an industrial environment, escorted, and with the potential for deceit or manipulation) offer exciting research opportunities. We approach this opportunity via the use and interaction with facility map information for international nuclear safeguards inspectors working in the field. In this paper we will describe research within the cognitive science community that is relevant for wayfinding applications for in-field safeguards activities, our experimental design for testing human performance on indoor, escorted wayfinding activities in a multi-story industrial facility across multiple map-based conditions, our results to-date, and recommendations for safeguards inspectors on their use of maps in the field.

Keywords: safeguards inspection; wayfinding; cognitive science; situational awareness; maps

1. Introduction

International Atomic Energy Agency (IAEA) safeguards inspectors carry out highly visible and important tasks for international security under environments of cognitive duress. They may be jet-lagged from travelling across the globe to reach the facility they will inspect, are working in industrial and potentially hazardous environments, their movements are constrained by protective attire, and they may be working in a language other than their mother tongue. Furthermore, some inspectors may be completing activities under the stress of their presence being unwanted by the facility operator – every day that an inspector interrupts normal facility operations represents a financial loss for the operator.

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More information is available to help inspectors complete their tasks than at any other time in history: open source data, overhead imagery, the state's declarations, inspector observations or notes from prior visits, and results from previous sampling activities at the facility. Cognitive science research shows us that providing too much information may be detrimental to performance, and can cause confusion, frustration, errors, or other signs of information overload. We must consider how to best provide information to safeguards inspectors so they are most able to benefit from it and act upon it.

In 2017, our research team conducted an extensive literature review within the cognitive science domain and a safeguards prioritization activity in which we identified safeguards tasks that pose challenges to inspectors that also represent new or emerging research domains within the field of cognitive science [1, 2]. From those activities, we identified three safeguards activities on which to focus our research:

1. Visual list comparisons, in which inspectors compare long lists of items such as inventory lists to operator records [3, 4];
2. Knowledge transfer, in which inspectors record their observations and findings in the field for their future use, for briefing to management, or for use by a future inspection team [5, 6]; and
3. Wayfinding, in which inspectors are escorted through complex, multi-story, industrial facilities and must maintain their awareness of their surroundings and location.

Wayfinding has been studied extensively in the cognitive science community, especially as it relates to outdoor navigation, different navigational support tools (maps, step-by-step directions, landmark cues, and GPS), differences in travel modalities (e.g. walking or by car), etc. [7, 8]. Indoor wayfinding has been studied far less, and the combination of indoor navigation with escorted access posed a new research opportunity. In this paper, we will describe our human performance testing which examined the impact of the provision and format of maps for inspector wayfinding and provide recommendations for enhanced safeguards practice and future research.

2. Research Question

IAEA safeguards inspectors are constantly required to find their way – through new cities, nuclear sites, and facilities. Their ability to know their current and historical locations, follow their routes on maps, and recall locations of observations throughout a facility is crucial to their work. Good navigators can tell if they are being led in circles by an adversarial operator/escort, if they have avoided specific areas of a facility through indirect routing, and recall specific observations according to locations on a map so that they can communicate that information for follow-up in future visits.

In this research, we used a battery of tests to explore how map information impacted an individual's ability to understand their location and surroundings following escorted (guided) access in a multi-story former nuclear facility. Our human performance studies included three map conditions: studying a map but not carrying it through a facility; studying and carrying a map through the facility; or having no map at all. We are currently conducting additional experiments to test the impact of the level of detail provided in a map, so that we may compare human performance on wayfinding tasks between having access to a simple map typical of what might be posted for fire escape routes or staff navigation, a complex CAD drawing, and a three-dimensional rendering.

3. Method

3.1 Participants

Our test population included sixty self-selected staff members of Sandia National Laboratories. The average participant age was 37 years, and our sample included 20 females and 40 males. The females were reasonably distributed among the three test conditions (map study, map study + carry, no map). 50 of the 60 participants had at least a university degree, with 35 reporting advanced degrees (Masters or PhD). None of the participants had prior experience in our test facility.

Participants were asked to self-assess their sense of direction using the Santa Barbara Sense of Direction Scale (SBSOD) [9] after they completed the experiment. To avoid biasing individuals based on their self-evaluations (i.e., stereotype threat; Steele & Aronson [10]), we opted to administer the SBSOD survey post-experiment. Most questions on the SBSOD are different enough from our experimental conditions that we did not anticipate participants degrading their score based on the challenging nature of our experimental tasks.

3.2 Materials

The experiment used two different paper maps. The map used for participant study and carry throughout the facility was a simplified computer-aided drafting (CAD) drawing of the facility showing upstairs and downstairs of the facility. The map included color-coded arrows marking the connections between stairways to help participants identify how the ground floor and mezzanine levels aligned since the mezzanine level only covered a fraction of the ground floor. The participant study/carry map is provided in Figure *1*. The map used for testing was a line drawing of the facility, with some of the CAD markers removed to minimize perceptual overlap with the studied map but retaining the color-coded arrows to facilitate stairway matching between stories (see Section 3.3).

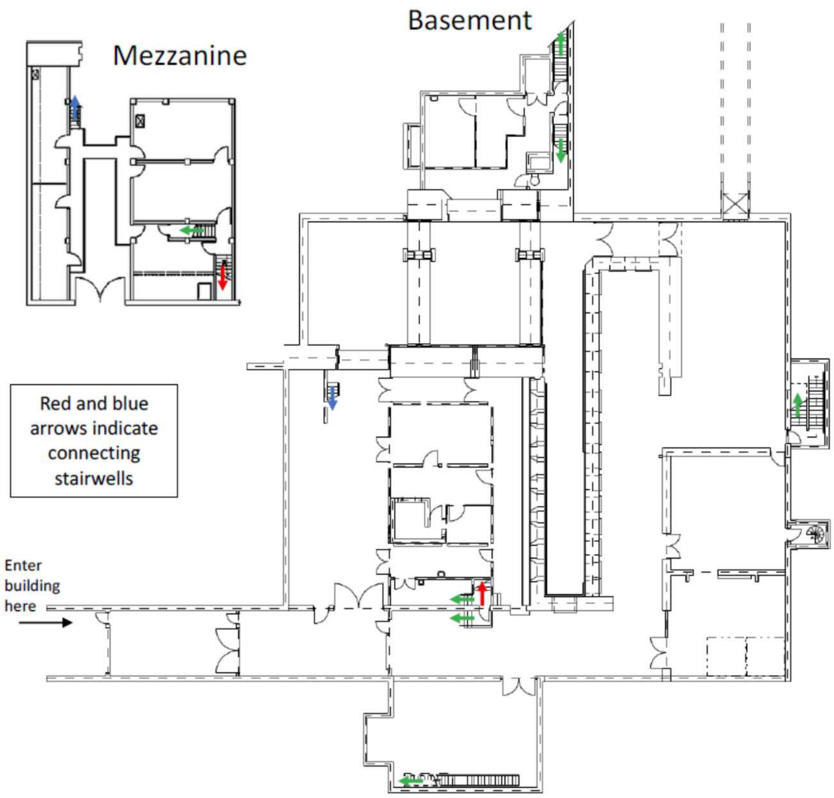

Figure 1 Participant Study/Carry Map

3.3 Procedure

All participants participated in a five-minute study period, in which they were allowed to study either the participant study/carry map or a one-page document about international nuclear safeguards. The participants were provided an approximately three-minute tour of the test facility, which included a three-second pause at each of eight “landmarks” throughout the facility such as a dosimeter charger, a set of remote manipulators, or a water meter that the participants were requested to remember. The starting point of the tour stayed constant, and half of the participants completed the tour in a clockwise manner, the other half counter-clockwise.

Following the tour, the participants completed a battery of four tasks: a pointing task, a shortcut task, a map drawing task, and a memory task. As previously noted, they completed the SBSOD survey at the conclusion of the experiment.

3.4 Tasks

After completing a guided facility tour, participants completed four tasks, in a set order.

The first task was a directional pointing task (adapted from Rand et al. [11]). The participants returned to the starting position of their tour and were faced half-way between the two route directions (so that all participants were facing the same way, and none were facing their exact route). Then they were asked to indicate which direction, according to degrees on a printed circle, each of the eight landmarks were. This included landmarks that were on their current (ground) level and the mezzanine. A compass with four of the landmark directions is shown in

Figure *2.*

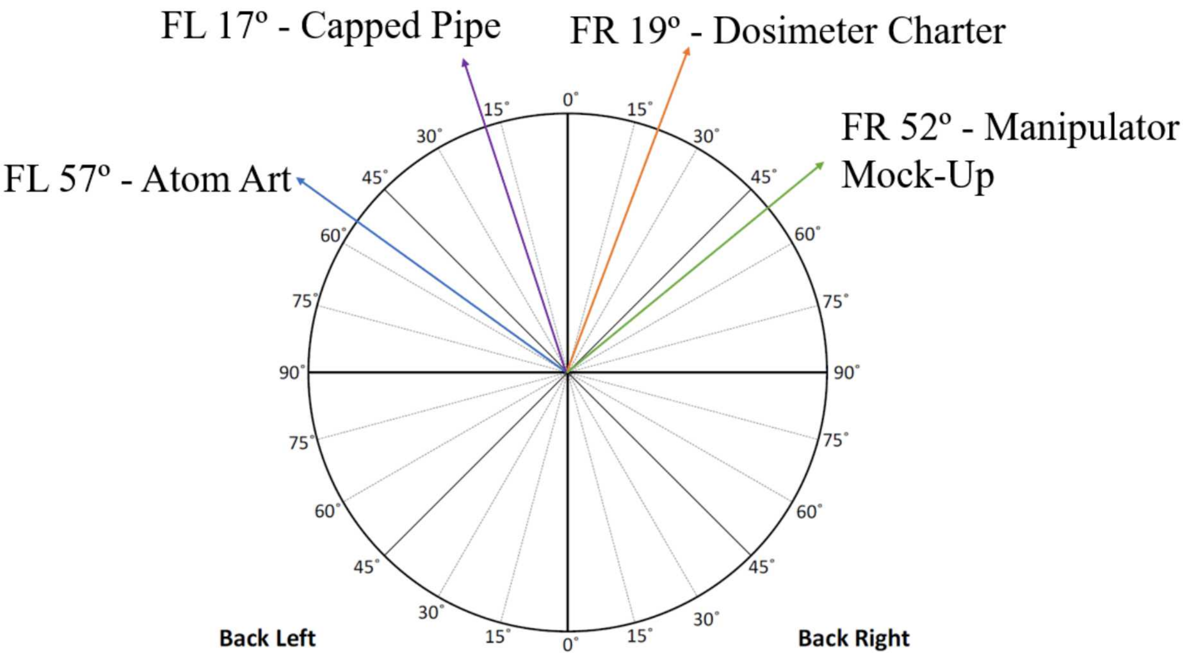

Figure 2 Example Landmark Directions for Pointing Task

Then, participants completed a shortcut task (adapted from Labate et al [12]). In this task, participants were taken to one of the eight landmarks, and asked to find the shortest possible route to another landmark in the facility. In all cases, the shortest route involved the participant traversing a part of the facility they had not previously entered. Three shortcuts were requested, which were the same for all participants regardless of route direction. If the participants got too far off-course during this task, the experimenter would stop and re-direct the participant at pre-defined points.

For the third task, participants traced their route and marked the name and location of the eight landmarks on a copy of the test map, which was a simplified line drawing of the participant study/carry map.

The final task was a landmark recognition task, in which the participants were shown a series of images taken in the facility, including photographs of the landmarks that they had been tasked with remembering, incidental landmarks that were visible along their route, and distractor images of objects from within the facility that the participants would not have seen during the experiment. The landmark recognition task was administered in E-Prime software so that we could track accuracy and response time to different types of stimuli. The participants were requested to say if they had seen the object in the image as part of their tour (which they called an “old” item) or if they had not previously seen the object (a “new” object). Example photographs are shown in Figure 3.

Figure 3 Example Photographs from the Memory Test

4. Results

Results were analyzed by map condition, by SBSOD self-assessment score (under the assumption that people with better sense of direction will perform better regardless of map condition), and by gender. SBSOD scores were not independent from gender: females in our sample had a mean SBSOD score of 61.6 (SD 18.5) and males 75.5 (SD 15) out of a possible 105, which was a significant difference. This scoring difference by gender was reflective of the general population [13].

However, we found anecdotally from our experiment proctors that several male participants in the experiment expressed that they had signed up for the study because they were interested in testing their “superior” navigational skills, a story that was not generally expressed by our female participants. Also anecdotally, we observed that female participants who performed well on the task still did not give themselves the highest ratings on the SBSOD, but many of the male participants gave themselves high ratings that did not necessarily correlate with their performance level.

4.1 Directional Pointing Task Results

The directional pointing task was scored by degrees error, from 0 to 360. Degrees error was determined by calculating the degrees of error between the direction the participant pointed and the actual direction, going both clockwise and counter-clockwise. The smaller error (either based on clockwise or counter-clockwise measurement) was used as the metric.

The no map condition showed the highest overall error, followed by the map study and then map carry conditions, though the difference between all three conditions was not statistically significant. However, planned comparisons with the no map baseline condition showed a statistically significant difference in which the no map *condition performed worse on pointing tasks than the map carry condition. See*

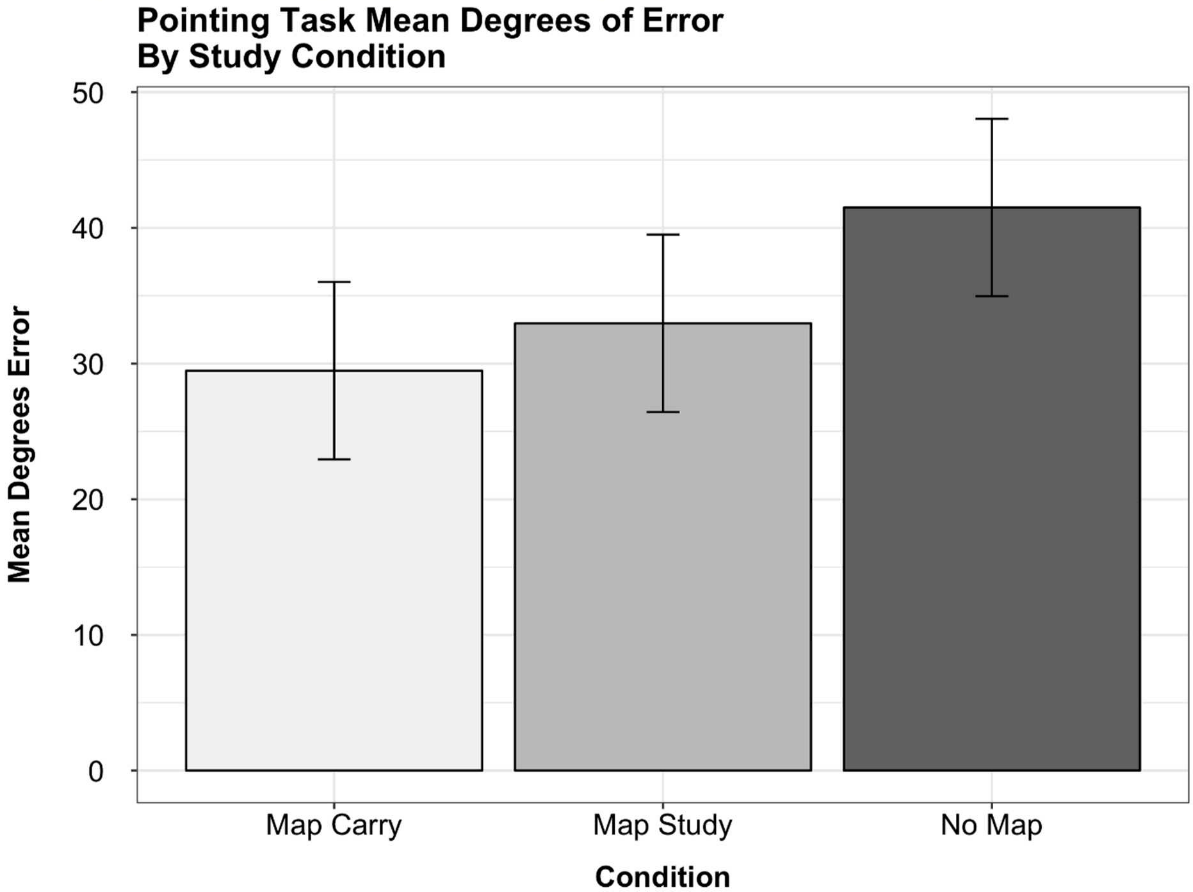

Figure *4* for the pointing error results.

Participants who self-assessed as having better sense of direction on the SBSOD survey performed better on the pointing task and this effect did not interact with the map condition effect.

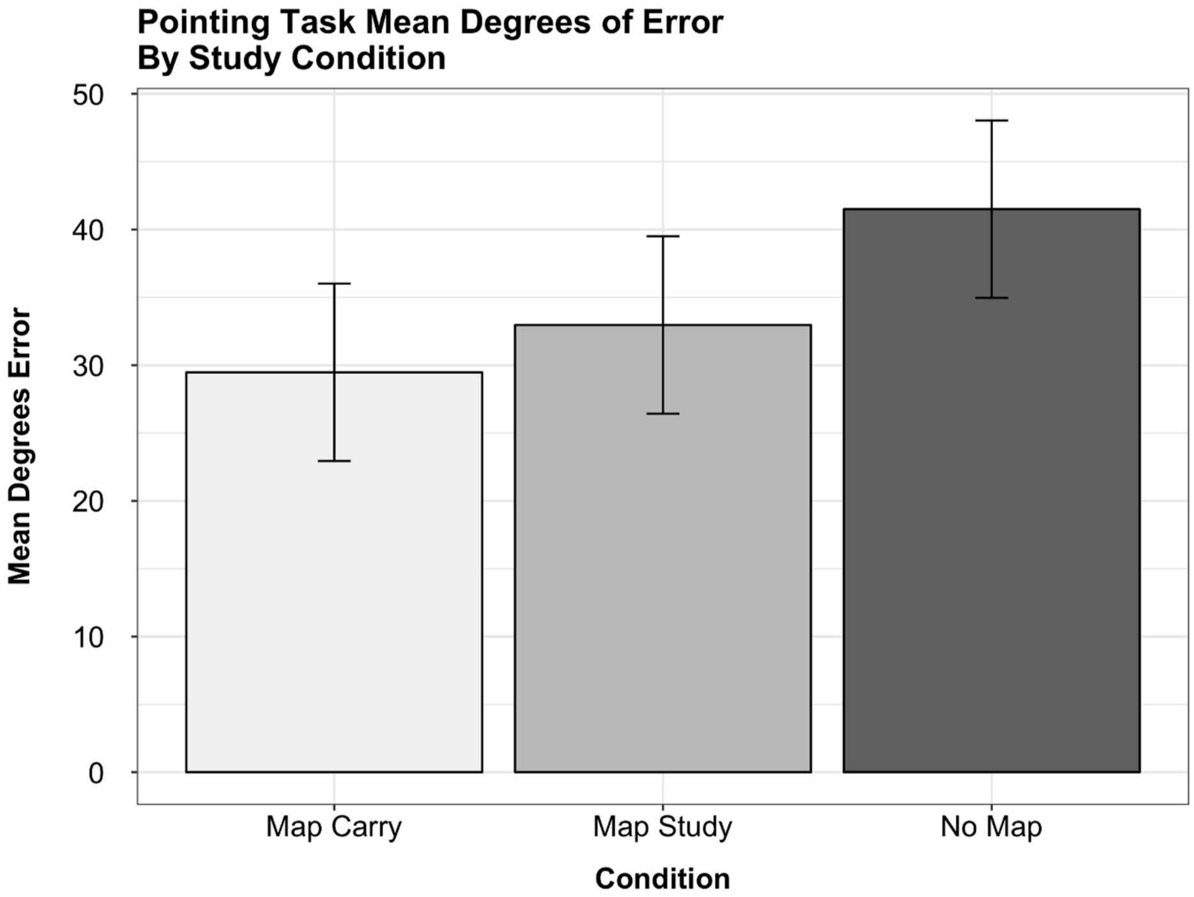

Figure 4 Pointing Error Across Conditions

4.2 Shortcut Task Results

There were no significant effects of map condition on either the shortcut distance or the participants' overall ability to find any shortcut. However, SBSOD scores showed a significant negative correlation with shortcut error when considered separately from map condition, in which people with better sense of direction took shorter shortcuts.

4.3 Map Completion Task Results

Our results showed no difference in map completion scores based on map conditions, including when the route was scored separately from the landmark portion of the task. SBSOD had a primary effect on the overall map completion scores, meaning people with better self-assessed sense of direction were more accurate in tracing their route and marking landmark locations.

4.4 Landmark Recognition Test Results

Performance on the landmark recognition test was assessed in two ways – accuracy, and reaction time. As we expected, participants were better able to identify landmarks than the incidental targets, and had an easier time discriminating between target landmarks and distractor items than incidentals and distractors. The map carry group had the lowest accuracy rate for incidental objects, but the effect was not statistically significant. When SBSOD was included as a covariate, it had a highly significant effect on accurately recognizing target landmarks.

Participant reaction time for incidental landmarks was longer than for target landmarks. This effect was more pronounced in the map carry condition, with an average three seconds longer response time to incidental targets than the no map condition. This marked difference in reaction time is significant and suggests that the map carry *participants were less efficient at creating and retrieving memories of incidental landmarks. Participants in the map study condition also showed a longer reaction time, though not as severe. For the map study participants, the mental effort of trying to mentally compare their location to their previously learned map seems to have lowered their outward attention, compared to the no map participants who were likely also trying to remember their locations but had not previously seen a map of the facility. See*

Figure *5* for response time results. SBSOD did not have a significant effect on response times.

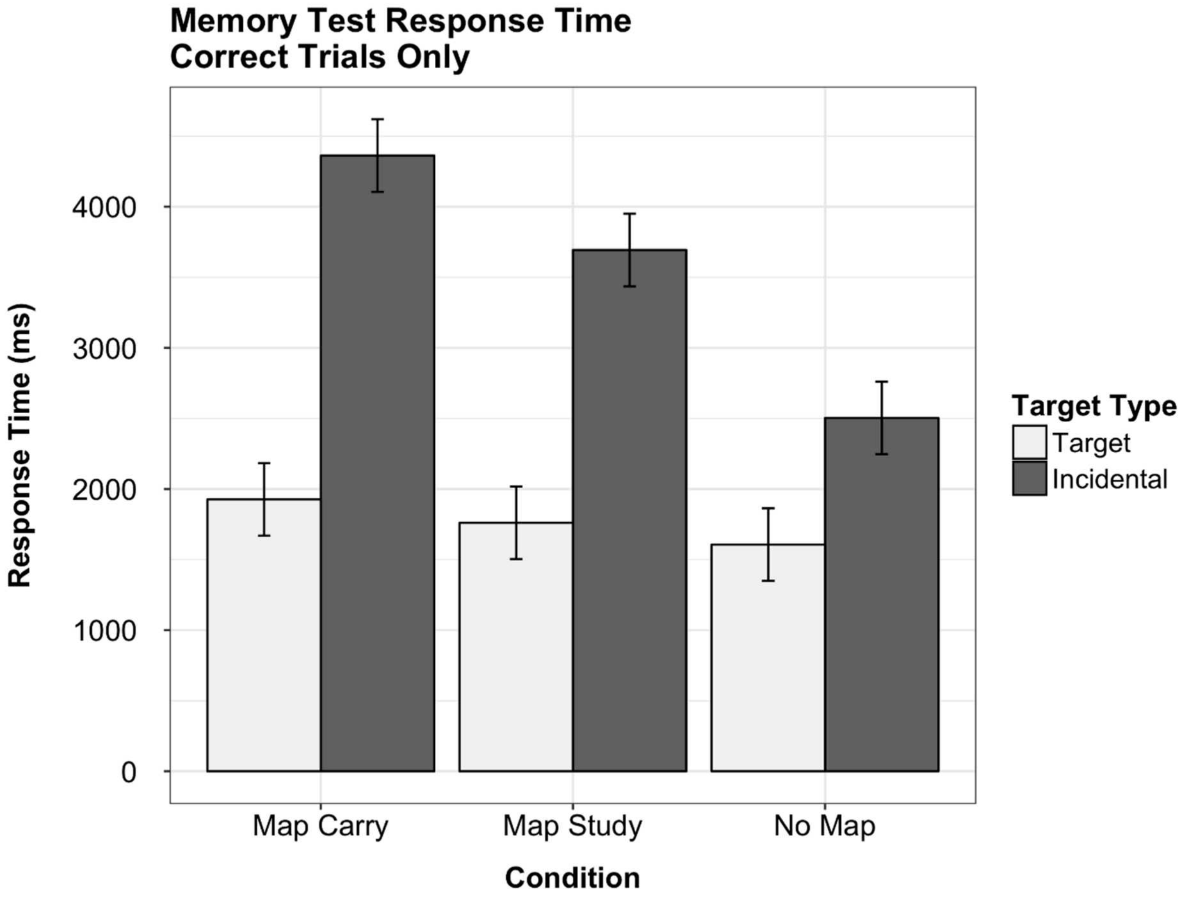

Figure 5 Memory Test Response Time for Correct Trials

4.5 Demographic Impacts

We also investigated the impact of gender on our results. When included as a covariate in the pointing task, gender had a significant effect. When including gender as a covariate on the shortcut task, we observed a marginal effect of gender, in which males took marginally shorter shortcuts than females. Gender also had a significant effect on memory task accuracy, specifically with males showing lower false positive identifications of landmarks than females. There was no effect of gender on map completion accuracy. These findings are consistent with other patterns of gender differences in the literature.

Our findings suggest that the provision of a map may eliminate or mitigate gender or SBSOD-based deficits in spatial learning. This confirms other studies in showing gender differences in spatial tasks that involve needing to know survey knowledge, like the pointing task, but not seeing gender differences in tasks that can rely on route knowledge, like the map completion task.

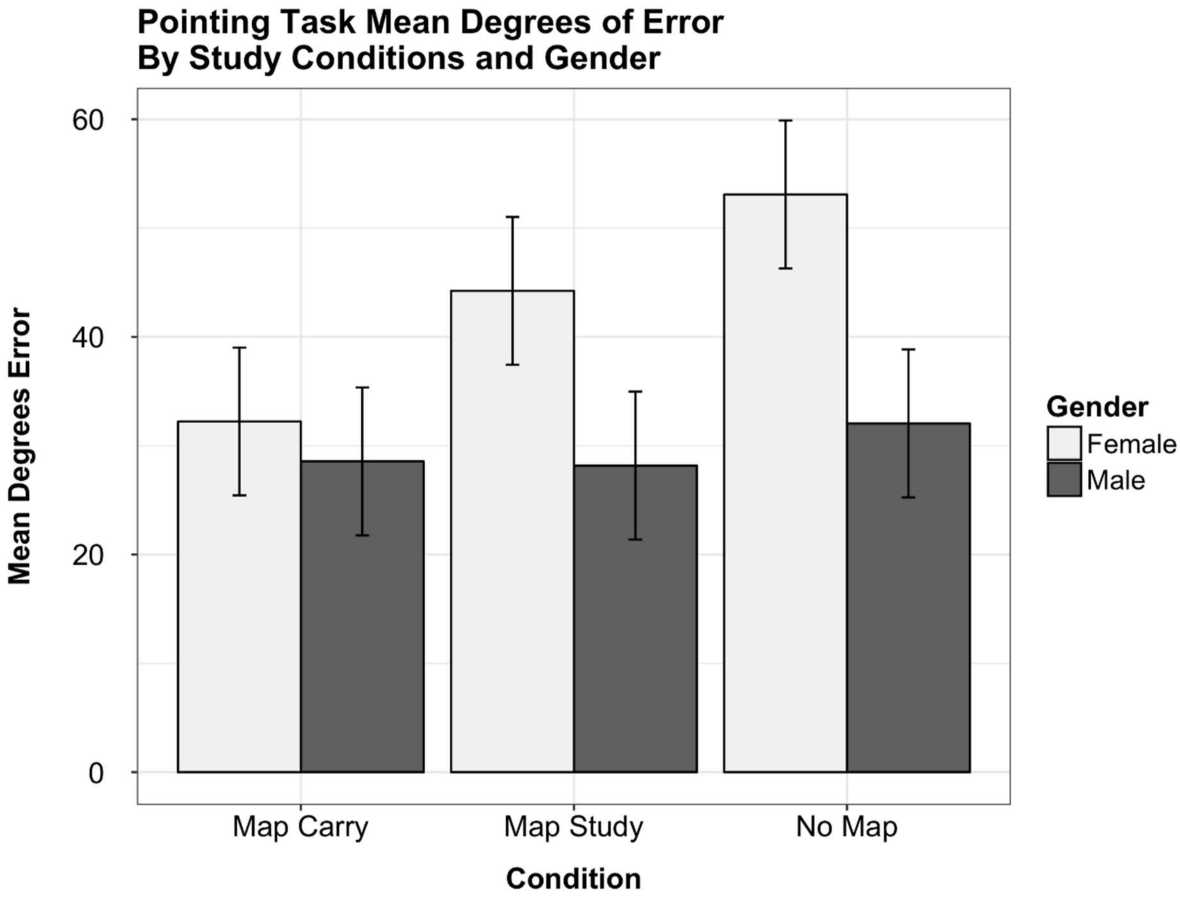

Figure 6 Gender Differences for Pointing Task by Map Condition

5. Discussion

Many of the tasks our participants completed were correlated with an individual's sense of direction. This self-assessed measure of individual difference, which also correlated with gender, shows that in general our participants were able to accurately predict their performance on these tasks, specifically the pointing task and map completion task. This may facilitate task self-selection among inspector teams working in the field.

Participants who had access to maps – either for map study or map carry – did perform better on the directional pointing task than participants who had not been exposed to a map of the facility prior to the test. This is important because the pointing task results represent the development of survey knowledge, or the ability to recognize straight-line directions between two locations. Survey knowledge could help support such inspector tasks as noticing when circuitous routes were used between two landmarks. The superior results of the map study and map carry groups on the pointing task indicate that there is a significant role for maps in supporting inspector survey and route knowledge of a facility, but that map study might be sufficient, especially in cases where portable maps are unavailable or infeasible to use.

For the landmark recognition task, the impact of map condition could indicate that participants not carrying physical maps focused on facility surroundings rather than the map during inactive periods of the facility tour, which allowed them to have higher landmark recognition accuracy and faster response times. Participant responses to the incidental landmarks represented general awareness of surroundings, and so we interpreted lower response times as representing better situational awareness. These results indicate that maps do and should play a role in inspection teams' ability to recount and locate their activities. Due to the impact of maps for reduced situational awareness, however, we recommend that inspectors either divide duties so that one member of the inspection team is responsible for the map while others focus on the facility environment, or that the team use the map only to study before a facility visit.

While we intend the findings of this research to inform international nuclear safeguards inspection activities, it is critical to remember that participants were not real inspectors, and it's possible that inspectors may have developed strategies over their years of experience that novices in our studies did not have. Furthermore, inspectors might return to same facility many times over career, and we did not capture interactions with facility familiarity here. We would also assume that expert knowledge in the nuclear fuel cycle may help direct attention during inspections (i.e., attention to incidental things along the route may be heightened in real inspectors if they show a deviation from the normal fuel cycle).

6. Future Work

The map used in the first part of this study is not broadly representative of map-type information available to inspectors, which may vary significantly by facility, site, or state. In a second iteration of wayfinding experiments currently being conducted at Sandia National Laboratories, we are testing two more map presentations to determine how the level of detail of the map impacts performance.

In this new research, we are running identical experiments as described above using a highly detailed CAD drawing of the facility and a three-dimensional representation created using the SketchUp software package (see

Figure *7*). Results will allow direct comparisons between maps with different levels of detail and orientations, to better understand which features directly support safeguards-relevant aspects of spatial knowledge.

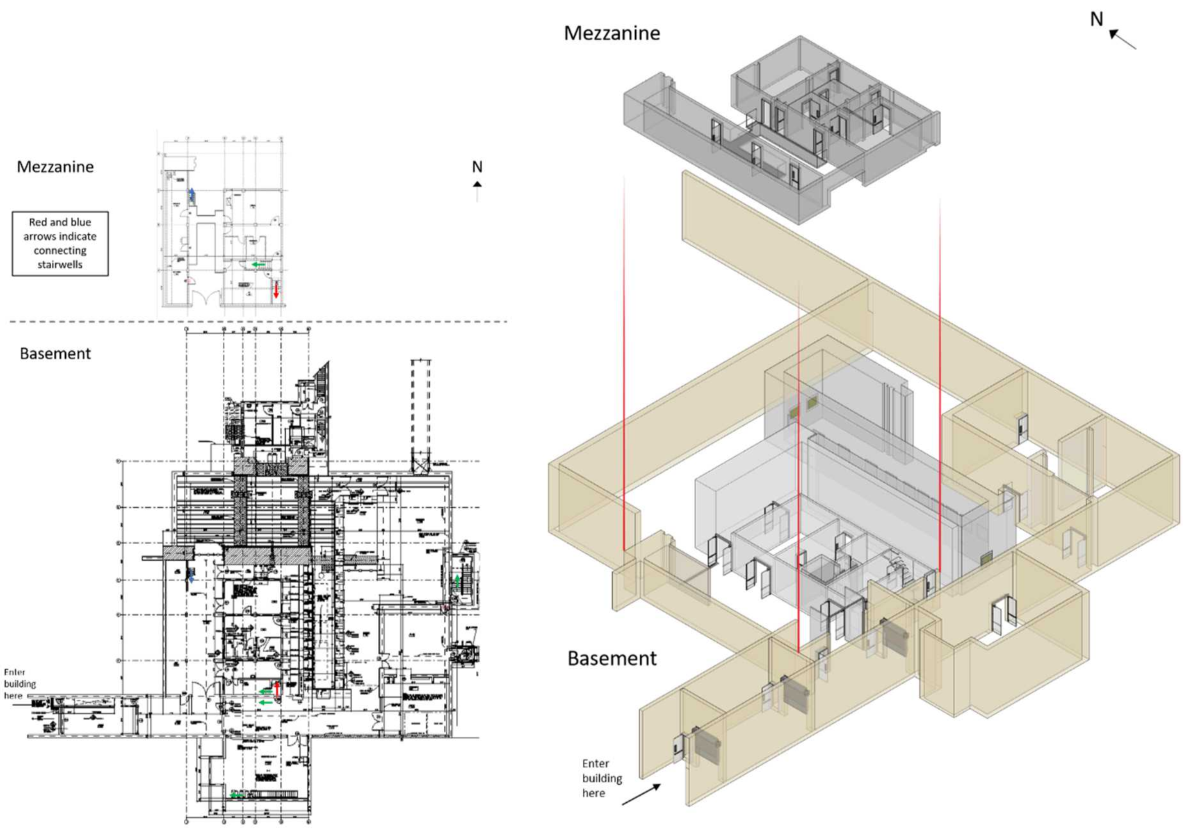

Figure 7 New Map Representations: Highly Detailed CAD (left) and 3D SketchUp (right)

7. Acknowledgements

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8. References

[1] Gastelum, Z.N., Matzen, L.E., Smartt, H.A., Horak, K.E., Moyer, E.M., St. Pierre, M.E.; *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*; *ESARDA Bulletin*; N. 54. June 2017.

[2] Gastelum, Z.N., Matzen, L.E., Smartt, H.A., Horak, K.E., Solodov, A.A., Moyer, E.M., St. Pierre, M.E.; *Testing Human Performance in Simulated In-Field Safeguards Information Environment; Proceedings of the Institute of Nuclear Materials Management Annual Meeting*; 2017.

[3] Gastelum, Z.N., Matzen, L.E., Stites, M.C., Smartt, H.A.; *Cognitive Science Evaluation of Safeguards Inspector List Comparison Activities using Human Performance Testing; Proceedings of the Institute of Nuclear Materials Management Annual Meeting*; 2018.

[4] Matzen, L.E., Stites, M.C., Smartt, H.A., Gastelum, Z.N.; *The Impact of Information Presentation on Visual Inspection Performance in the International Nuclear Safeguards Domain; Proceedings of Human Computer-Interaction International;* (forthcoming) 2019.

[5] Gastelum, Z.N., Matzen, L.E., Stites, M.C., Smartt, H.A.; *Human Performance Testing on Observation Capture Methods for International Nuclear Safeguards Inspections: Transferring Knowledge from the Field to Headquarters and Back; Proceedings of the Institute of Nuclear Materials Management Annual Meeting;* (forthcoming) 2019.

[6] Stites, M.C., Matzen, L.E., Smartt, H.A., Gastelum, Z.N.; *Effects of Note-Taking Method on Knowledge Transfer in Inspection Tasks; Proceedings of Human Computer-Interaction International*; (forthcoming) 2019.

[7] Wiener, J.M., Buchner, S.J., Holscher, C.; *Taxonomy of Human Wayfinding Tasks: A Knowledge-Based Approach; Spatial Cognition & Computation*; 9. 2009. 152-165.

[8] Chrastil, E.R., Warren, W.H.; *Active and Passive Contributions to Spatial Learning; Psychonomic Bulletin and Review*; 19. 2012. 1-23.

[9] Hegarty, M., Richardson, A.E., Montello, D.R., Lovelace, K., Subbiah, I.; *Development of a Self-Report Measure of Environmental Spatial Ability; Intelligence;* 30. 2002. 425-447.

[10] Steele, C.M., Aronson, J.; *Stereotype threat and the intellectual test performance of African Americans: Journal of Personality and Social Psychology*; 69. 1995. 797–811.

[11] Rand, K., Creem-Regehr, S.H., Thompson, W.B.; *Spatial Learning While Navigating With Severely Degraded Viewing: The Role of Attention and Mobility Monitoring; Journal of Experimental Psychology: Human Perception and Performance*; 41(3). 2015. 649-664.

[12] Labate, E., Pazzaglia, F., Hegarty. M.; *What Working Memory Subcomponents Are Needed in the Acquisition of Survey Knowledge? Evidence from Direction Estimation and Shortcut Tasks; Journal of Environmental Psychology*; 37. 2014. 73-79.

[13] Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., Lovelace, K.; *Spatial Abilities at Different Scales: Individual Differences in Aptitude-Test Performance and Spatial-Layout Learning; Intelligence;* 34. 2006. 151-176.