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The Influence of Spatial Dimension on Task Completion in Human Reliability Analysis: A Pilot Study

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ABSTRACT

In the context of nuclear power plants, human reliability analysis (HRA) is an assessment approach focused on analyzing human error probability in complex systems, minimizing human errors, and increasing safety at nuclear power plants. Both time and location are major influencing factors when it comes to dynamic HRA, because they can easily determine operator success or failure. Despite this, research on these factors is still in its early stages. This pilot study aims to provide preliminary data on four major factors—terrain, distractions, mobility restrictions, and load—to determine the influence of these factors on walking time. Four scenarios were developed to figure out whether movement factors can affect task completion time. By using experimental data, we derived the average walking time and speed under each condition, time increase rate as compared to the regular condition, and the relation of height and speed in given scenarios. These data were linearly regressed to extrapolate time for uncollected data. We found that task performance time varied significantly depending on the determining factor. For example, the distraction scenario drastically increased walking time, while performance changes under factors such as the uneven road were less severe. This research can be used to determine the influence of the spatial dimension during operator walking time, which can help minimize time-related human errors and enhance safety at nuclear power plants.

Keywords: Human reliability analysis, Spatial factors, Task completion time, Walking

INTRODUCTION

Human reliability is a critical consideration in the design and operation of complex systems, and understanding the influence of human factors is essential for ensuring system safety and reliability (Sharit, 2012). Human reliability analysis (HRA) is a systematic approach used to assess and quantify the likelihood of human error in complex systems, particularly those involving safety-critical operations. HRA focuses on understanding and mitigating the potential for human errors that could lead to adverse consequences, such as accidents, failures, or operational errors (French et al., 2011). Conventional approaches in HRA emphasize the collection of qualitative insights from the operational context to quantitatively assess human error probabilities (HEPs) based on performance shaping factors (PSFs; Pan and Wu, 2020).

The evolving field of dynamic HRA introduces a temporal dimension and incorporates simulation techniques to model human performance (Boring, Joe, and Mandelli, 2015). In other words, dynamic HRA goes beyond the binary assessment of success or failure in completing tasks; it considers the time it takes to complete tasks in relation to the available time. For example, recent work on the development of the Human Unimodel for Nuclear Technology to Enhance Reliability (HUNTER), highlights the utility of dynamic HRA in a nuclear control room to capture the time-dependent nature of events, enabling the exploration of various scenarios and what-if analyses using Monte Carlo simulation methods (Boring et al., 2016). However, both static and dynamic HRA often overlook spatial and temporal considerations and their influence on task execution (Boring, 2023).

Spatial consideration is a fundamental aspect of human factors research, encompassing various elements such as workspace design, equipment placement, and layout optimization (Cvaja and Nair, 2012). In the context of HRA, spatial considerations are particularly relevant in complex operational environments where individuals interact with their surroundings to perform tasks. For example, within nuclear power plants, operators often face the need to travel from Location A to Location B, which can give rise to potential hazards. Consideration of transit and location is especially important for balance-of-plant HRA. The duration of this travel between the two locations during field operations can significantly impact the success or failure of an assigned task. Task completion within the time window is crucial for task success; otherwise, failure may occur (Park et al., 2022). This is illustrated in Figure 1. To model the true risk faced by operators in dynamic HRA, it is essential to account for spatial and temporal changes.

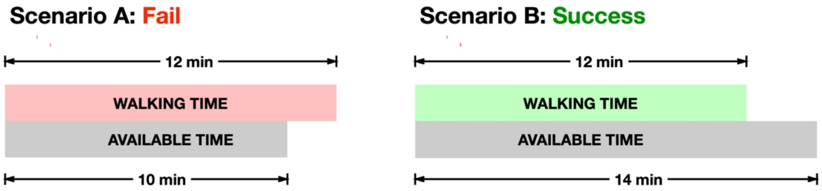

Figure 1: Example of task time windows in HRA scenario.

Recent research has highlighted the importance of incorporating spatial considerations into HRA (Boring, 2023), without which human risk modeling should be considered incomplete. In this study, we collected preliminary data by focusing on four specific aspects of spatial considerations when walking: terrain, distractions, mobility restrictions, and load. By examining these aspects within a spatial context, we seek to gain insights into how walking time varies under different conditions, how these conditions influence task completion time, and their implications for HRA. These insights can be used to model and predict walking time under different scenarios. The motivation behind this research is to enhance our understanding of the spatial effects on human performance and further advance the field of HRA in nuclear power plants. By investigating the interplay between spatial factors and task completion time, we can develop more accurate dynamic HRA models and provide valuable insights for HRA.

METHOD

Experimental Design

Three individuals working with Idaho National Laboratory participated in the pilot study. All participants were female. They had a mean age equal to 26.3 years, with a standard deviation (SD) of 9.6 years. Their mean height was 162.3 cm, with a SD of 7.3 cm.

Scenarios were selected to be representative of walking tasks for field operators in balance-of-plant activities at nuclear power plants. The participants walked a constant distance of 100 meters under different conditions to determine if the factors would influence their walking time. Four scenarios plus a control condition were considered to examine the impact of movement factors in spatial HRA. Due to the limited sample size, we used within-subject analysis and had each of the three participants walk three times to get an accurate idea of their average time. The conditions served as the between-subject variable of the experiment and included (see Figure 2):

- Control condition (pavement).
- Uneven terrain (grass/field).
- Distraction (texting on a cellphone).
- Mobility restriction (wearing personal protective clothing similar to radiological gear as simulated by wearing puffy winter clothes).
- Load (dragging a small generator as simulated by rolling a 25 lbs [11.3 kg] suitcase).

Fig. 2a: Control

Fig. 2b: Terrain

Fig. 2c: Distraction

Fig. 2d: Example 1, Mobility Restriction

Fig. 2e: Example 2, Mobility Restriction

Fig. 2f: Example 3, Mobility Restriction

Fig. 2g: Load

Figure 2: The paper authors demonstrating mobility conditions tested in the experiment.

Apparatus

The apparatus used to conduct the experiment included:

- The stopwatch app on a mobile phone to record time.
- Sidewalk chalk to mark the 100-meter distance.
- A standard tape measure to measure an accurate distance.
- A 25 lb. suitcase to simulate a small generator.
- A puffy winter coat and snow pants to simulate wearing protective gear.
- An iPhone to simulate interference/distraction.

Data Analysis

The collected data underwent descriptive and inferential statistical analyses. Initially, a descriptive analysis was conducted to assess the mean times taken by participants under different spatial conditions. The time increase rate (R) was calculated for each condition relative to the regular condition. Subsequently, a one-way Analysis of Variance (ANOVA) was employed to examine the variations across different participants. t-tests were conducted to compare between conditions.

RESULTS

Participants walked three times under each condition. Table 1 displays the average time taken by participants in each condition. Consequently, we normalized across the participants and obtained the mean time taken under different conditions, as shown in Figure 3. From Figure 3, we can observe that the mean time varies across different conditions. In the regular condition, participants took an average of 73.22 seconds to move from Location A to Location B; however, when faced with different spatial factors in the experimental conditions, the mean time increased. Under the uneven road condition, the mean time increased to 82.56 seconds, slightly higher than the regular condition. In the distraction condition, participants took an average of 118.33 seconds, showing a substantial impact on the time for spatial changes. The mobility restriction condition resulted in an average time of 88.67 seconds, indicating a mild increase in time needed compared to the control condition. Finally, the load condition had an average time of 91.89 seconds, with a moderate effect on the time compared to the regular condition.

Table 1. The mean walking time (in seconds) under different conditions for each participant.

Participant	Regular	Terrain	Distraction	Mobility Restriction	Load
1	76.67	88.67	127.00	93.33	102.33
2	68.67	77.00	117.00	82.33	85.33
3	74.33	82.00	111.00	90.33	88.00

To further understand the impact of each condition on the time required for spatial changes, we calculated the time increase rate (R) using Equation (1) for each participant, in which R is the time increase rate of each condition; T_C is the time spent in each condition; T_R is the time spent in regular condition.

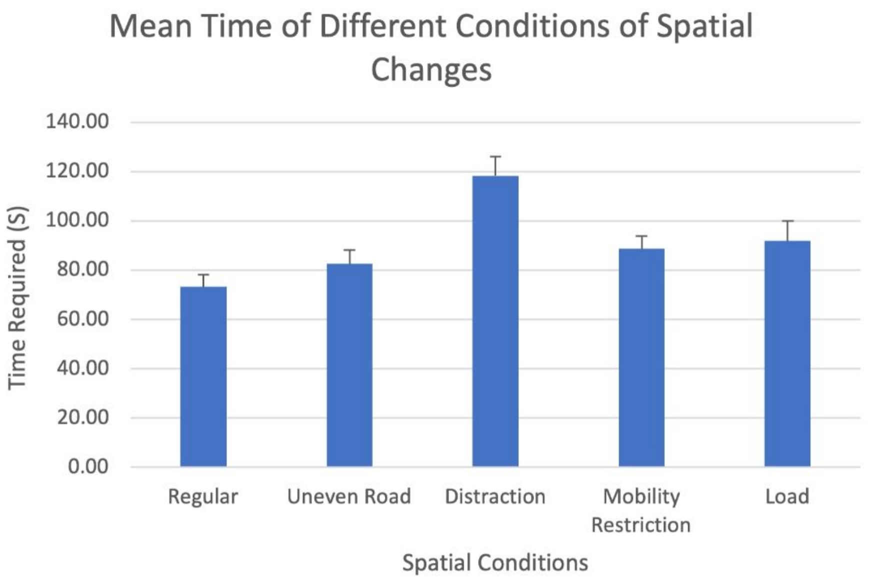

Figure 3: Mean walking time taken under different conditions.

$$R = \frac{T_C - T_R}{T_R} \times 100 \quad (1)$$

The results are presented in Figure 4. The time increase rate represents the percentage increase in time for each condition relative to the regular condition. For example, for Participant 1, walking under uneven road resulted in a 16% increase in time compared to the regular condition, while distraction led to a substantial 66% increase.

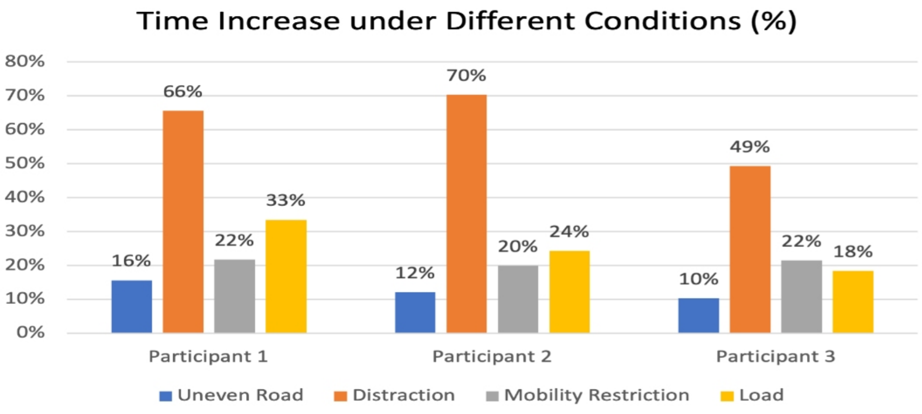

Figure 4: Time increase rate (%) for each condition relative to regular condition.

The time increase rates calculated from the data indicate that different spatial factors have varying effects on participants' task completion time, suggesting that different conditions significantly influence the time needed for spatial changes. However, it is crucial to acknowledge that participant variance exists. While Participants 1 and 2 demonstrated similar performance in reaction to spatial changes, with the order of influence being distraction > load > mobility restriction > uneven road, Participant 3 exhibited different performance under mobility restriction and load conditions. This variation raises concerns about the influence of participant differences on task completion time under different spatial conditions. To address this concern, a one-way ANOVA was conducted to assess the significance of time required under different conditions among participants, and the results are shown in Table 2. The *p*-value is larger than 0.05, so the results of the ANOVA did not lead to the rejection of the null hypothesis, indicating that there were no significant differences among participants in the time needed for spatial factor changes under different conditions.

Table 2. One-way ANOVA results of dataset.

Source	*SS*	*df*	*MS*	*F*	*p-value*	*F crit*
Between	356.8444	2	178.4222	0.606519	0.56114	3.884294
Within	3530.089	12	294.1741			
Total	3886.933	14				

Besides the ANOVA results, *t*-tests were conducted to compare between conditions. The regular condition served as the baseline or control condition. Further comparisons were made between the regular condition and uneven road, distractions, mobility restrictions, and load, respectively. In all cases, the *p*-values were found to be less than 0.05, indicating significant differences between the regular condition and all other conditions. Notably, the most significant difference was observed between the regular condition and distraction, with a *p*-value of 0.003. This result suggests that distraction has the greatest effect on the time required for spatial factor changes.

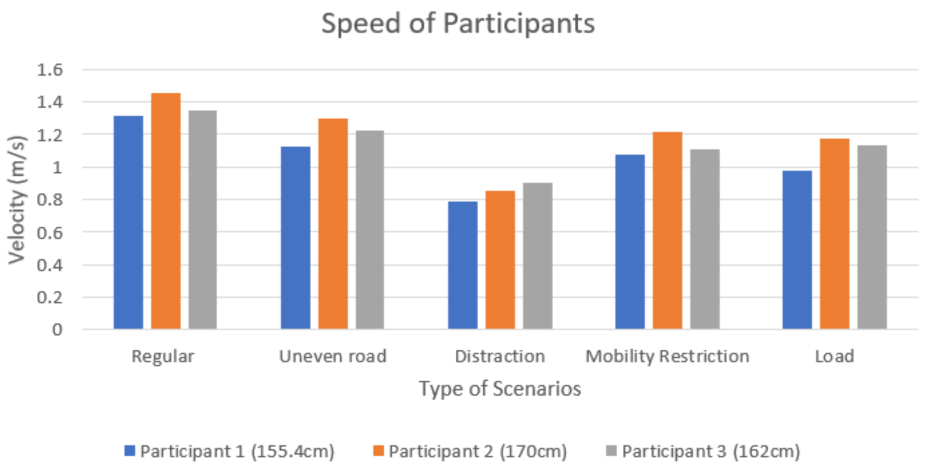

Figure 5: Speed of participants in scenarios: regular, uneven road, distraction, mobility restriction, and load.

Figure 5 represents the speed of participants under various conditions including the regular condition, uneven road, distraction, mobility restriction, and load. Each speed was calculated using the velocity formula:

$$velocity = \frac{distance}{time} \tag{2}$$

The result of speed tends to follow the height of participants. Participant 2, the tallest in the group, had the fastest speed in all instances except distraction. In contrast, Participant 1, who is the smallest member of the group, moved the slowest in all cases except distraction.

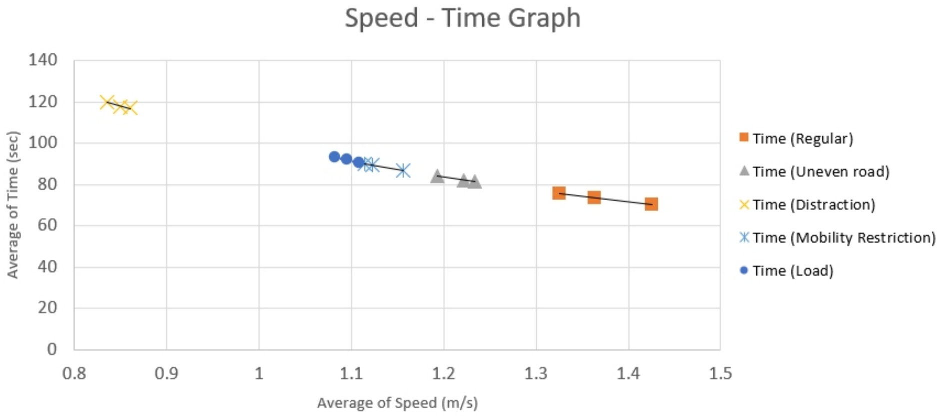

Figure 6: Sample points related to speed and time.

Due to this experiment being a pilot study with a limited number of participants, there are only three sample points from which to build an equation for the relationship between time and speed. Each point in Figure 6 is the average time for each trial, and 100 meters was used to calculate the average speed. Average speed, determined using Equation 2, was based on average time and given distance. Table 3 offers the linear regression equations gained through the sample points in each scenario. This equation helps to find unknown average times at various speeds, which were not obtained in this study. *R*-squared, a measure providing information about the goodness of fit, was computed to check the reliability of the regression line. It demonstrates that the linear equations accurately approximate the actual data because the values are located around 1.

Table 3. Regression equation for average time (t) as a function of average velocity (v).

	Regular	Uneven Road	Distraction	Mobility Restriction	Load
Regression Equation	$t = -53.605v + 146.73$	$t = -59.753v + 155.22$	$t = -125.69v + 224.97$	$t = -79.27v + 178.35$	$t = -88.177v + 188.48$
R-Squared	0.9999	0.9795	0.99	0.9997	0.9974

DISCUSSION

General Findings

This experiment aimed to investigate the influence of spatial factor changes on the time required for participants to move locations. Our analysis provides valuable insights into the variations in the time required for spatial changes under different conditions. These findings align with the motivation to incorporate spatial considerations into HRA methods, as highlighted in recent research (Boring, 2023). The results demonstrated that different spatial factors influence participants' task completion time. Walking under the uneven road condition showed a moderate increase in the time needed for spatial changes, while the distraction condition had a substantial impact, leading to a considerable time increase. Additionally, mobility restriction resulted in a slight increase, and the load condition had a minor effect on the time compared to the regular condition. The calculation of the time increase rate (R) further emphasized the varying effects of spatial factors on task completion time, and the presence of participant variability was noted. Participants 1 and 2 exhibited similar behaviors in response to spatial changes, while Participant 3 showed different responses under specific conditions. This introductory data is important because it shows us that a greater amount of time will need to be allotted for a specific task if the operator is distracted, wearing protective gear, or carrying a load. This observation reinforces the importance of considering individual differences and the spatial context when conducting HRA.

Limitations

Several limitations should be acknowledged in this study. First, the small sample size of only three participants limited the statistical power and generalizability of the findings. A larger and more diverse sample would have provided more robust results. A larger sample size is planned beyond this pilot study, but the results are already informative to modelling different mobility influences in dynamic HRA. Second, the experiment was conducted in a simulated environment, which may not fully represent real-world conditions, potentially affecting the ecological validity of the study. Nonetheless, the conditions simulated in this experiment are representative of actual balance-of-plant settings in nuclear power plants.

Application

The results of this study can be used to determine the duration of travel time when creating procedures and help analyze whether a task will be completed on time or not. Timing out of an operator task or procedure could be the difference between a reportable event and carrying on as normal. The overall safe operation of the plant is linked to the timely execution of activities, including those involving walking between locations.

CONCLUSION

This pilot study sheds light on the crucial role of spatial factors in HRA. The results demonstrate significant variations in task completion time across different spatial conditions. Despite some limitations in this study, including the small sample size, not fully representing real-world scenarios, and lack of considering other individual factors, the study's insights lay the groundwork for integrating spatial considerations into HRA, offering valuable contributions to safety optimization and HRA in nuclear power plants.

The incorporation of spatial considerations in HRA models can enhance their realism and applicability in complex operational environments. Understanding how spatial factors influence human performance allows for the development of guidelines, best practices, and effective countermeasures to optimize system design, workflow efficiency, and safety in critical operations. Further research could explore the interaction between individual characteristics and spatial factors to enhance our understanding of human performance in complex environments. Future research will also seek to address factors beyond biomechanical considerations that may affect mobility performance. For example, how do psychological factors like task complexity affect the speed of walking? One long-term goal of spatial HRA research is to catalog and model the systematic effects that may influence mobility rates and errors.

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