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THE EFFECTS OF SPATIAL COGNITION ON INDIVIDUAL WAYFINDING PERFORMANCE

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Abstract: An experiment was conducted to analyze the effects of different information formats and spatial cognition on individual wayfinding in unknown environments. Participants were asked to memorize either a set of 2D drawings or a three-dimensional (3D) model before navigating through a series of checkpoints in an unfamiliar environment. Individual wayfinding is dependent on an individual's use of route knowledge or survey knowledge. Route knowledge was assessed from the start of the route to Checkpoint A (i.e. the first checkpoint). Meanwhile, survey knowledge was assessed from Checkpoint A to Checkpoint B. Spatial cognition of participants was measured by administering the card rotation and cube comparison tests. The research found that 3D models have a beneficial impact on the success of individual wayfinding. Furthermore, the success rate of the participants with low spatial cognition improved significantly when using a 3D model rather than a set of 2D drawings. However, the information formats did not affect the success rates of participants with high spatial cognition. This research will aid in understanding the relationship of cognitive spatial abilities, task performance, and information displays on people with demanding and stressful jobs, such as first responders. Further research, with a larger sample size and longer route, is required to confirm the results concluded in the study. Additionally, research suggests that realistic rendering and color might have a beneficial effect on decreasing workload memory when navigating through a space.

1. INTRODUCTION

Individuals differ in their ability to visualize and process spatial information or "spatial cognition" (Hegarty and Waller 2005). The present research focuses on understanding how different factors influence individual wayfinding in unknown environments. Individuals have two kinds of wayfinding strategies: *route knowledge*, which consists of memorizing successive movement at each intersection of an environment before reaching a destination and *survey knowledge*, where the subject builds a mental visualization of the environment to orientate oneself (Tolman 1948, Tversky 2003). It has been observed that men tend to use *survey knowledge* while women use *route knowledge* (Taylor et al. 1999).

Nowadays, 2D plan sets are the main form of communication for spatial information of a building interior during its operations and occupancy (Grigsby 2000). Previous research studies have investigated the influence of different factors such as spatial cognition and engineering information format on construction workers' performance and found that 3D information effected their work positively (Bruce 2015, Dadi 2014, Goodrum et al. 2016, Lee et al. 2013, Sweany 2012). The present research reviews and analyzes previous studies to study the interdependency of information display, spatial cognition, and demographic background on individual wayfinding in unknown environments. Participants were required to find their way to two different checkpoints in a building unknown to them after analyzing either a 2D plan or a 3D model for sixty seconds. Participants' behavior was recorded to analyze their performance, in terms of distance and time traveled. Participants were then asked to complete a series of two spatial cognition tests, and their answers were matched to their recorded performance. The findings of this research are intended to improve route navigation during high stress events, such as the response of emergency responders or the evacuation of building occupants during extreme events (Blair et al. 2012, Blair and Schweit 2014) and construction workers in hazardous site conditions (Teizer et al., 2013) or even improving productivity on construction sites (Dadi 2014, Goodrum et al. 2016, Sweany 2012).

2. CONTEXT

Golledge (1999) defines wayfinding as the method of assessing and following a path from one place to another. Wayfinding is not to be confused with navigation, which is rather navigating from one place to another like a ship or aircraft (Webster 1995). Navigation does not fall within the scope of the present research and will not be studied. Individuals develop two kinds of strategies called *route* and *survey knowledge*. Route knowledge develops a series of landmark actions like those given by navigation software (e.g. GPS System: "turn right at the traffic light") (Tolman 1948, Tversky 2003). Survey knowledge is individuals mentally visualizing map-like representation of the environment (Tolman 1948, Tversky 2003).

Lawton (1994) developed a questionnaire to study the relationship existing between wayfinding strategies and gender. Lawton's (1994) research emphasized that women were likely to rely on a *route knowledge* strategy, where men maintained a sense of their position in relation with the environment using *survey knowledge*. Lawton also highlighted that women tend to develop an anxiety about environmental navigation unlike men (Lawton 1994). Taylor et al. (1999) studied the goal-specific influences on spatial perspective. The participants, in Taylor's 1999 study, had two ways to study an unknown environment, studying a plan or navigating through the environment. The results indicated a better performance (more accuracy) for survey tasks when studying a plan and the route tasks responses were more accurate when navigating through the environment (Taylor 1999). Therefore, wayfinding strategies are dependent on several factors and should be investigated carefully. Understanding how individuals create a cognitive map and the whole process of wayfinding could lead to findings that would help diminish the mental demand of wayfinding tasks allowing individuals to focus on other aspects of their job or environment.

Spatial cognition is an important factor in the wayfinding process and has been long studied by different researchers, such as neuroscientists focusing on the biological relationships between the brain and behavior (Stiles et al. 1988). Vecchi and Bottini (2006) studied the relationships between perception and imagery to understand how brain, behavior and cognition interact. This research does not discuss the neurologic aspects but focuses on behavioral aspects and the impact of spatial cognition on task performance. Lohman (1979) defines spatial ability as the generation, retention, and manipulation of abstract visual images to encode, remember, and transform spatial stimuli.

The influence of spatial cognition and engineering information on performance has been investigated in other contexts, such as the construction industry (Goodrum et al. 2016, Sweany 2012). Goodrum et al. (2016) indicated that information format, including 3D visual aids, help decrease workers' workload and therefore improve their productivity. Goodrum et al. (2016) stated that the performance of the lower spatial cognition workers matched the performance of the higher spatial cognition workers when provided with 3D visual enhancement. Sweany (2012) measured the cognitive demands of three types of information: 2D plan sets, 3D CAD, and 3D printed models on construction workers. Statistical analyses proved that subjects of both low and high spatial cognition performed best with 3D physical models. Additionally, both experience and training impact the performance of workers (Goodrum et al. 2016, Sweany 2012). A better performance was statistically proven for workers who were familiar with the type of information used (Goodrum et al. 2016, Sweany 2012). Formal training was close to having a statistical impact on workers' performance when using 2D plans (Dadi 2014, Goodrum et al. 2016, Sweany 2012).

3. RESEARCH HYPOTHESES

The objectives of this research are to explore the performance levels, wayfinding strategies, and cognitive workloads of participants using 2D and 3D information displays. Based on previous research studies (Goodrum et al. 2016, Sweany 2012), construction workers performed better with a 3D physical model than with 2D plan sets. Based on this prior experience, we will examine three hypotheses. First, our primary hypothesis is that individuals are more efficient in wayfinding when provided with 3D versus 2D information about their environment. A chi-square test will assess performance levels of participants on the ability of participants to reach the two checkpoints. ANOVA will assess other variables to determine any significance. Our second hypothesis will examine the correlation between the type of information display and the use of wayfinding strategies. Thus, our second hypothesis is that 3D information is more critical in wayfinding scenarios that rely on survey knowledge versus route knowledge. The researchers hypothesized that the route from the start of the waypoint experiment to checkpoint A will address route knowledge while the route from checkpoint A to checkpoint B will be prevalent in survey knowledge. The performance of each participant at each of the two checkpoints will investigate this wayfinding strategy hypothesis. Third, Goodrum et al.'s (2016) paper confirmed that 3D information displays improved the productivity among industrial pipefitters. This research attempts to prove that cognitive workload affects performance positively when incorporating 3D information displays, which leads to our third hypothesis that cognitive demand in a wayfinding experiment is lowered when the use of 3D versus 2D information is used. NASA-rTLX test scores will be used to study the effects of cognitive workload on the participant's performance.

4. METHODOLOGY

Our research attempts to understand the interdependency of information display, spatial cognition and individual demographics during a waypoint task requiring each participant to reach two checkpoints after studying a plan for sixty seconds. To study the influence of information displays, participants were given a 2D plan or a 3D model and their performance was recorded. The experiment has been conducted in the *University of Colorado at Boulder* with 48 students/staff ranging from 18 to 33 years old. While the wayfinding experiments involved university students in a university, each student was prescreened to assure that they were not familiar with the location and spatial environment of our experiment location.

The experiment consists of a time-framed analysis of human navigation performance using combinations of maps in the form of 2D plan sets or a 3D model. A highlighted path to reach two different checkpoints was shown on participants' plans. As each participant attempted to navigate both checkpoints, their success of reaching a waypoint, time, distance, and route selection was recorded by the researchers. The data from the experiments was used to test the proposed three hypotheses.

There are a few tests that quantify the spatial abilities of individuals. The Educational Testing Service (ETS) created two tests to assess the "ability to perceive spatial patterns or to maintain orientation with respect to objects in space" (Ekstrom et al. 1976).

These include the card rotation and cube comparison tests. The card rotation test assesses the subject's ability to see differences in a pair of 2D figures. The figures can be rotated, in which case the participant marks them as "same" or they can be flipped over and the subject marks them as "different". The cube comparison test compares two cubes. Participants mark the cubes as "same" if they match by rotation or "different." Sweany (2012) analyzed the cognitive demand of engineering information on construction workers. His research deduced that a card rotation test is best suited to study 2D information and a cube comparison test is best suited to study 3D information. The results of the two spatial cognition tests were used to assess individuals' spatial cognition and to also compare the results with the performance metrics to study the influence of individual spatial cognition on the participants' success. The card rotation test contains 40 questions and the cube comparison test contains 14 questions. The maximum scores are therefore respectively 40 out of 40 and 14 out of 14. When a participant answers a question incorrectly, the resulting score for that question is counted as negative. This explains why of the total test scores are negative.

Additionally, the National Aeronautics and Space Administration-Task Load Index (NASA-TLX) is probably the best-known tool to assess subjective workload (Hart and Staveland 1988). Workload is a term that represents the cost of accomplishing mission requirements for the human operator (Hart 2006). The concept is important if a task is not considered easy or quick to accomplish. Indeed, the test assesses the "difficulty" of a task in terms of different concepts or subscales that are well-defined. It is used in the present research to compare participants' workload during the experiment.

Two types of information formats were used in the experiment. The first was a traditional 2D plan. The set that was given to the students was the plan view of the ground and basement floor (below grade). The path highlighted for checkpoint A (on the basement) in red and checkpoint B (on the ground floor) in green are shown on Fig.1 (ground floor) and Fig.2 (basement). The first ten students used a laptop and the remained used a tablet computer to view the plans or model. The 3D model is shown in Fig. 3.

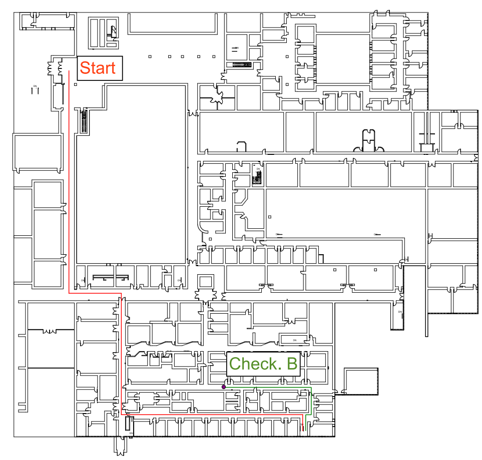

Figure 1: Ground Floor of the Building

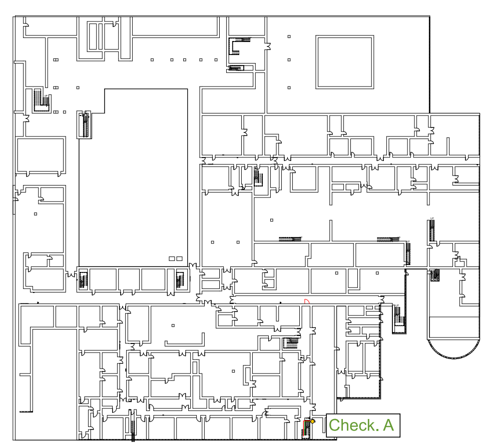

Figure 2: Basement Floor of the Building

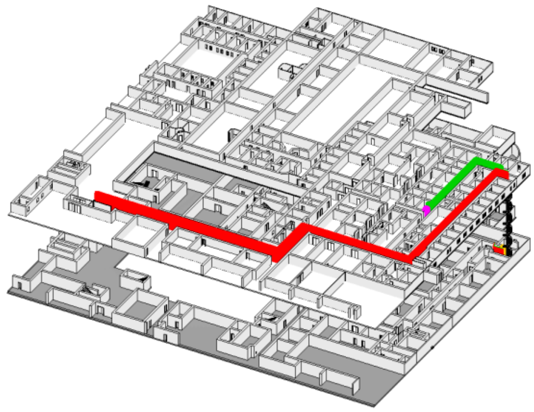

Figure 3: 3D Model of the Route from the Lobby to Checkpoint A in Red and Checkpoint A to Checkpoint B in Green

5. PROCEDURE

Each participant was briefed with an explanation of the experiment including a short tutorial on the 2D vs 3D displays. Each participant attempted the experiment once, with a sample of the participants completing the waypoint navigation using 2D plans and the remaining using the 3D model. Participants were given the opportunity to study the 2D plans for 60 seconds. The 3D model analysis included two different parts. Participants using the 3D model had 60 seconds to understand how to rotate and view the model and practice on a warm-up model. Then, each 3D participants had 60 seconds to analyze the 3D model for the experiment. The subjects were shown where they were initially located in the building and the four cardinal directions.

As soon as participants studied the plans, they began by proceeding from the starting point to checkpoint A and B. During the experiment, a coordinator filmed the path used by the participants. However, the coordinator was not allowed to say anything to the participants. At each checkpoint, they were asked to point out two directions: the starting point and direction to the south. If the students were unable to find the checkpoint, they were conducted back to the starting point and the wayfinding task part was ended. After completing the experiment, the subject and the coordinator came back to the starting point to complete a questionnaire, which included the NASA-RTLX Mental Workload Rating Scale, Card Rotation, and Cube Comparison tests.

During the experiment, the participants were filmed to monitor their performance. Different measures were used to assess the task, including the following:

- Duration of each part of the wayfinding task;
- Distance traveled for each part;
- Number of major deviations if the participant is going out off a radius of 30 feet around the right path. Each deviation is counted as one;
- Number of minor deviations if the participant is off the right path but still in a radius of 30 feet around the right path. The minor deviations are counted in term of steps; and
- At each checkpoint, the subject is asked to point out the direction of the south and the starting point. Those questions show if the subject can visualize himself/herself in the environment.

6. DATA ANALYSIS

Different performance metrics were statistically analyzed with two tests: the chi-squared test of independence and analysis of variance (ANOVA). In summary, the chi-squared test of independence exam if two populations X (e.g. low vs. high spatial cognition) are independent from each other based on their criteria Y (e.g. age, experience) that is binary or categorical. The ANOVA analysis was used to evaluate significance between checkpoints and information displays.

7. RESULT GROUP

The study included 38 participants. All participants were university students and had a mean age of 23.8 years and a median age of 22 years. The group was composed of males and females, 82% and 18% respectively. Most of the students were engineering students and had prior experience of working in industry. The participants' mean years of experience reading engineering drawings was 1.84 years.

Fig.4 displays the results of the two tests with a box plot. It conveniently shows the minimum, maximum, and the second and third quartile. For the cube comparison test, the median was 10.5, and the mean was 10.28. Participants scored high on both tests. The card rotation test scores had a median of 32.5 and a mean of 31.05. The fact that the medians are higher than the means indicates that some participants experienced very low scores making the distribution negatively skewed.

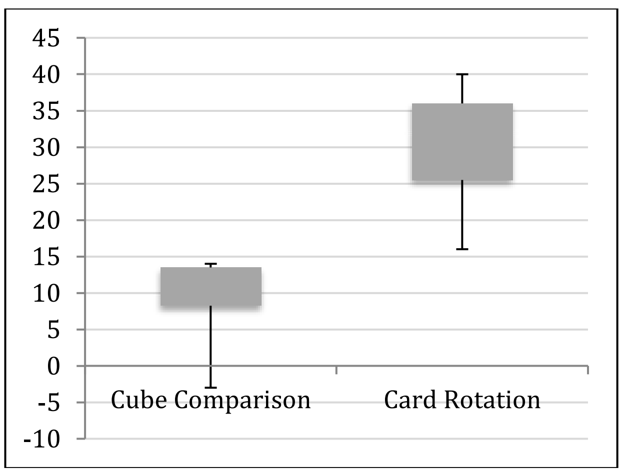

Figure 4: 3D Model of the Route from the Lobby to Checkpoint A in Red and Checkpoint A to Checkpoint B in Green

8. RESULTS ANALYSIS

The following results are used to answer the hypotheses stated previously. If the metric was significant, it is highlighted in green and if it was close to significance, it is highlighted in orange.

The format of the information display, in terms of the utilized 2D and 3D formats, was found to not influence the performance of participants in reaching Checkpoint A, as indicated in Table 1. Participants using the 2D and 3D information displays experienced the same completion ratios and a time requirement of two minutes in reaching Checkpoint A. However, Table 1 highlights a significant difference in the participants' completion ratio when using the 3D model from checkpoint A to checkpoint B. The route from the starting point and Checkpoint A relied more on route knowledge, which may be a contributing factor to explain why no difference was observed based on the format of information. Additionally, when monitoring the low spatial cognition subjects in Table 2, the difference in completion rate shows a significant influence of the 3D model when traveling from checkpoint A to checkpoint B. However, Table 3 indicates the 3D model significantly improved performance of participants with low spatial cognition but did not affect participants with high spatial cognition. All participants did benefit from the 3D model when traveling from checkpoint A to checkpoint B, as they relied on their survey knowledge.

Table 1: Influence of Information on Overall Performance

		Completion Rate	Time	Distance (feet)	Questions
Check. A	2D	73.6%	0:02:17	449.57	1.43
	3D	73.6%	0:02:11	466.64	1.57
	p-value	(1)	(0.691)	(0.558)	(0.596)
Check. B	2D	57.1%	0:00:53	136.25	1.67
	3D	92.8%	0:00:50	126.92	1.43
	p-value	(0.029)	(0.845)	(0.709)	(0.458)

Table 1 shows which information display was used to perform the best in each performance metric when comparing all participants.

Table 2: Influence of Information on Overall Performance for Low Spatial Cognition Subjects

		Completion Rate	Time	Distance (feet)	Questions
Check. A	2D	70%	0:02:24	460	1.29
	3D	62.5%	0:02:11	435	1.40
	p-value	(0.737)	(0.693)	(0.403)	(0.815)
Check. B	2D	42.9%	0:00:54	119.33	2
	3D	100%	0:01:05	154	1
	p-value	(0.038)	(0.708)	(0.579)	(0.145)

Table 2 shows which information display was used to perform the best in each performance metric when comparing low spatial cognition participants.

Table 3: Influence of Information on Overall Performance for High Spatial Cognition Subjects

		Completion Rate	Time	Distance (feet)	Questions
Check. A	2D	70.7%	0:02:10	439	1.57
	3D	81.8%	0:02:10	484	1.67
	p-value	(0.822)	(0.999)	(0.345)	(0.772)
Check. B	2D	71.4%	0:00:52	146.4	1.80
	3D	88.8%	0:00:41	110	1.63
	p-value	(0.375)	(0.185)	(0.065)	(0.546)

Table 3 shows which information display was used to perform the best in each performance metric when comparing high spatial cognition participants.

Based on the completion rate, the information displays seem to have no influence on the first checkpoint because participants were most likely employing route knowledge. On the other hand, the influence of 3D models was found significant for the second checkpoint. The researchers observed that the participants remembered the checkpoint B via its location more than the route, which suggests that participants who successfully reached checkpoint B relied on their survey knowledge rather than their route knowledge. However, this assumption needs to be verified more thoroughly.

As noted earlier, the participants required mental demand in completing the experiments was measured using the NASA rTLX index. Mental demand of the participants using the 3D versus the 2D information plans was lowered nearly (93%), marking it as statistically significant. The 2D plan yielded a score of 62.3 and 3D model yielded a score of 51.0. Most of the factor resulted in lower workloads when using a 3D computer model but further experiment would need to be conducted to produce more accurate results.

9. DISCUSSIONS

This research analyzed a sample size of 38 participants. The results were divided into high vs. low spatial cognition and 2D vs. 3D information formats. Spatial cognition divisions made the results difficult to analyze because previous literature did not recommend any objective criteria for assigning participants with low vs. high spatial cognition. Therefore, the sample was divided into two equal populations below and above the median. If the mean of the sample is high, participants below the median would be considered as low spatial cognition despite the higher mean of the population. A research with a larger sample on the topic could investigate a limit to define if a subject has a high or low spatial cognition compared to the average population.

The influence of 3D information formats could be investigated gradually to understand how 3D information and color influences participants. These findings suggest comparing different types of 3D models in further investigations. Information displays are not limited to 2D and 3D. Indeed, different manners to display more information exist. It's possible to bring photorealism by adding photo-views in 2D and 3D models. Virtual realism could also potentially improve individuals' wayfinding without having to be in the building. The coordinator also noted that some participants had better familiarity with technology and 3D modeling software. Therefore, in future studies, participants should be given unlimited time to practice navigating the 3D modeling interface to remove familiarity bias. Future experiments should also aim to have a consistent media format for participants' use because data will be more precise. Additionally, the experiment should also consider the use of color consistently in the models to limit bias.

The assumption that the second checkpoint was reached when using survey knowledge more than route knowledge must be further investigated. In this experiment, the location of checkpoint B was too close to checkpoint A to confirm the use of the survey knowledge. However, if checkpoint B was farther than the first one and the path to reach it included a detour, the behavior of the participants could be significant. Additionally, if participants could locate the checkpoint without using the highlighted path, it would mean they recreated a map of the place. On the other hand, if they would use the path to reach their destination, it would suggest route knowledge more than survey knowledge. The precision of the distance could also be improved if the coordinator of the experiment was wearing a pedometer and follow exactly the participant's movements (e.g. Fitbit or similar technology). Further research needs to be conducted if this research were to be applied to study the effects of emergency responders in stressful situations, where the experiment might add stressors to replicate real-world scenarios. The last suggestion is to increase the complexity of the experiment by lengthening the path or adding a third checkpoint to potentially gain more insight.

10. CONCLUSION

The importance of studying the factors influencing individual wayfinding is emphasized by the need of emergency response teams' efficiency in the growing number of extreme events in recent years (Blair and

Schweit 2013, 2014). Through different solutions, improving the information display is a direct and efficient way to help them.

Based on previous research studies on spatial cognition and engineering information formats, the research discovered new findings on individual wayfinding (Table 4). When analyzing overall performance, the results demonstrated inconclusive results about wayfinding strategies and spatial cognition levels. 3D information displays enhanced participants' performance in the second part of the experiment, suggesting that survey knowledge, which is linked to the mental representation of the surrounding, is improved using a 3D information display. This finding was found especially significant for low spatial cognition participants. The results indicated that 3D information displays induced a lower workload than 2D displays.

Table 4: Proven Hypotheses and Found Tendencies

#	Hypothesis	Results
1	Participants perform better when using 3D model	3D models improved the performance of participants in navigating from Checkpoint A to Checkpoint B, especially for low spatial cognition participants
2	The information display influences the wayfinding strategies	3D model tends to improve *survey knowledge*
3	Workload decreases when using 3D model	Tendencies toward lower workload when using 3D model

Individual ability is a strong factor in wayfinding task. It was not possible to assess training experience but it was possible to assess spatial cognition. Neither information display was significantly able to even the performance of low spatial cognition participants to the participants with high spatial cognition. This first research on the interdependency of factors on individual wayfinding does set the basis for further research studies on the topic. This area of research could specifically help a wayfinding task during emergency responses, but the findings concerning the interdependency of information display and spatial cognition could potentially be applied to several fields.

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