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THE RELATIONSHIP BETWEEN SPATIAL COGNITION AND HAZARD ANTICIPATION IN PREVENTION THROUGH DESIGN TASKS

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Abstract: Construction Hazard Prevention through Design (CHPtD) is an injury prevention method that is achieved by reviewing design information to identify and mitigate hazards before they are encountered in construction. It has been postulated in construction safety literature that three-dimensional computerized design information is superior to two-dimensional paper-based design as 3D visualizations will allow users to spatially orient themselves within the design yielding increased hazard anticipation as compared to 2D designs alone. Unfortunately, it is unknown spatial cognitive ability affects hazard anticipation skills in design. To test this, a series of experimental trials were conducted with a mixture of 81 construction designers, construction supervisors, and civil engineering students to determine if spatial cognitive capabilities associated with various formats of design information influence hazard anticipation performance during CHPtD tasks. Participants were provided mutually-exclusive arrangements of traditional two-dimensional construction drawings, three-dimensional computer visualizations, and a combination of the two and asked to identify all possible safety hazards associated with three discrete construction work activities. Prior to the task, participants completed card and cube rotation tests to assess pre-existing personal spatial cognitive capability. Pearson's correlation tests were used to measure the association among these variables. The results indicate that there is no association between spatial cognitive ability and hazard anticipation performance for the formats provided. The results conflict with the prevailing belief that 3D visualizations are superior to 2D visualizations in terms of promoting hazard anticipation.

1 INTRODUCTION

The construction industry has long been known for being dangerous. The high fatality and injury rates of construction industry must be examined more closely. To combat the dangers of construction work, researchers have strived to identify methods that reduce the occurrence and severity of safety accidents in the workplace. One prominent method is Construction Hazard Prevention through Design (CHPtD), which involves anticipating and mitigating hazards during project design phases before they arise in construction. Research has shown that the prevailing opinion is that CHPTD provides an opportunity to make changes that would have prevented serious injuries and fatalities (Behm 2005; Seo and Choi 2008; Driscoll et al. 2008; Ghaderi and Kasirossafar 2011; Lingard et al. 2012: Hallowell and Hansen 2016).

Some have theorized that three-dimensional (3D) design information, such as building information modeling (BIM) provides a more useful visual platform than two-dimensional (2D) because it enhances hazard anticipation and requires less mental effort to process. This is because it is assumed that 3D visualization technologies will allow individuals to better orient themselves within the design (Ku and Mills 2010; Bansal 2011; Kasirossafar and Shahbodaghlou 2012; Ganah & John 2015; Zhang et al. 2015). However, these assumptions remain untested. Understanding how construction designers' and supervisors' spatial cognitive capabilities affect hazard anticipation during design may identify the ideal design information formats or mixture of formats that promote hazard anticipation in design for safety reviews. Therefore, there is a rich opportunity to investigate the extent to which various formats of design information and spatial cognitive ability relate to hazard anticipation in design. This paper focuses on the intersection of participants spatial cognitive capabilities and their ability to anticipate hazards from construction designs.

2 LITERATURE REVIEW

2.1 Construction Hazard Prevention through Design

Construction Hazard Prevention through Design (CHPtD) is a safety management principle founded in eliminating hazards and controlling risks to workers as early as possible in the life cycle of a project. CHPtD may include any stage of design including design, redesign, and retrofit of new and existing facilities and structures. The central premise of CHPtD method lies in hazard elimination, as only those hazards anticipated during design can be eliminated or controlled with CHPtD solutions. In the past 20 years, CHPtD has seen an abundance of research, which has resulted in a large and dispersed body of literature. This body of knowledge has made valuable advances in construction safety research. However, considering limited empirical evidence CHPtD has been extolled as a superior safety management strategy. There has been little research to date regarding safety accidents and how design elements affect safety risk during construction activities. Although a lack of formal empirical data examining the efficacy of CHPtD processes exists, there is a need for a more robust understanding of the role of design information during CHPtD implementation. This is especially important, given that CHPtD processes rely on some level of developed design.

The CHPtD method has seen much research in the last decade. For example, research has been conducted which suggests linkage between design features and accident data (Driscoll 2008; Seo and Choi 2008; Ghaderi and Kasirossafar 2011) and research has developed technology applications to provide mechanisms for CHPtD implementation (Cooke et al. 2008; Zhang et al. 2015). Although, this research and technology applications have provided valuable knowledge and mechanisms for CHPtD implementation, little is known about their effectiveness. For example, no research to date has examined the cognitive processes of employing CHPtD and it is unknown if designers and construction practitioners possess the inherent skills to anticipate hazards during the CHPtD process. Additionally, it is unknown what visual cues existing in design information can be used for hazard anticipation and how design reviewers' spatial cognitive capabilities will affect their ability to anticipate hazards. For this reason, more investigation into the cognitive processes and visual search patterns of CHPtD implementation are needed.

2.2 Role of Design Information in CHPtD

The design process uses design information (i.e., plans, specifications, contract documents, etc.) to express the intent for the delivery of construction projects. The format of such information may include 2D computer aided drawings (2D CAD) (Goodrum et al. 2016); 3D building information models (3D BIM) (Zhang et al. 2015), material specifications (Dadi et al. 2014), and even virtual reality (Sacks et al. 2015). Although 3D design technologies have emerged as a practical option for some practitioners, traditional 2D drawings remain the pervasive method of conveying design information (Bowden et al. 2006; Goodrum and Miller 2015).

Researchers have proposed that various types of design information can be used for pre-construction safety planning. However, others have suggested that 2D design information does not permit simple conceptualization of future physical and environmental conditions, which may lead to the misunderstanding of project design information (Collier 1994; Young 1996; Chantawit et al. 2005; Zhang et al. 2015). Alternatively, it has been proposed that 3D visualizations of design information promote optimum hazard recognition because the information is believed to be easier to understand and interpret (Ku and Mills 2010;

Bansal 2011; Kasirossafar and Shahbodaghlou 2012; Ganah & John 2015; Zhang et al. 2015). These postulations inspired this research.

2.3 Principles of Spatial Cognition

Spatial cognition is defined as the ability to retain, manipulate, and generate precise visual images (Lohman 1979). An individual's spatial cognitive capabilities are considered to be a personal condition that precedes any activity and that is relatively stable. Construction designs, which are typically presented via 2D paper-based drawings (Collier 1994; Young 1996; Chantawit et al. 2005; Goodrum et al 2016), require workers to use spatial orientation to mentally manipulate the design information to generate an understanding of the construction design (Goodrum et al. 2016). The process of spatial orientation includes encoding, remembering, transforming, and matching design information and has been found to lead to omissions and ambiguities of information (Lohman 1979). Therefore, it has been suggested that design information should accommodate retention, manipulation, and generation of precise visual images that can be used to anticipate construction safety hazards (Lohman 1979).

2.4 Spatial Cognition Measurement

Several studies in the fields of mathematics and geometry show the positive relationships that exist between individual's spatial cognitive abilities and their problem-solving skills. Since the 1920's, research has been conducted attempting to improve and calculate a person's spatial cognitive abilities. For example, several studies have attempted to measure and improve subjects' spatial cognition using engineering and mechanical drawings (Saloman 1979); mechanical aptitude skill assessment (Seashore and McCollom 1932); and dynamic geometry software (Travis and lennon 1997).

Spatial cognition has also been found to play a significant role in construction craft productivity. Recent research by Goodrum et al. (2016) tested the influence of spatial cognition on model assembly tasks. They presented 54 participants with a mixture of design information formats (i.e., 2D isometric drawings, 3D visual displays, and a 3D physical scale model) and found that both design information format and spatial cognition significantly had an effect on participants abilities to assemble a replicate model (Goodrum et al. 2016). Additionally, Dadi et al. (2014) performed a similar study in which 77 participants constructed a physical model using a 2D drawing set, 3D computer model, and a 3D scale physical model. The results show that participants which used the 3D scale physical model outperformed others in completion times and direct work rates and resulted in lower mental workload levels (Dadi et al. 2014).

The Educational Testing Service developed two tests to measure spatial cognition associated with a task (Ekstrom 1976). The card rotation test measures the ability to interpret the transformation of a 2D shape. The test presents the subject with a 2D image, which is then manipulated by rotating or flipping. The participant is asked to compare the image against the modification and correctly identify if the image is rotated or flipped and rotated. Alternatively, 3D spatial cognition is measured using the cube rotation test. The participant is presented with two cubes of equal size and dimensions but with different labels on each face. The participant is asked to distinguish whether the first cube could be logically rotated to match the second cube. The participant's skill with this distinction represents their 3D spatial cognition. The card and cube rotation tests were used in this study as it has been validated by providing strong evidence to evaluate human's spatial abilities (Presson 1982; Wraga et al. 2000; Kozhevnikov and Hegarty 2001). The card and cube rotation tests are shown in Figure 1.

Figure 1: Example Card and Cube Rotation Test Excerpts

2.5 Research Objectives and Point of Departure

The objectives of this study were to explore the relationship between spatial cognition and hazard anticipation performance for three formats of construction design information. The three primary steps conducted to achieve this goal included the following: (1) assessing spatial cognition, (2) performing experimental hazard anticipation testing by manipulating the design format, and (3) examining the relationship of spatial cognition on hazard anticipation task performance for three formats of design information (3D BIM, 2D CAD, and a combination of the two). The corresponding null hypothesis is:

Ho1: Participant spatial cognition does not predict hazard anticipation task performance.

3 RESEARCH METHODS

The research objectives of this study were achieved in two distinct steps. The first was the development of 2D and 3D construction design information for construction tasks selected because previous field research has already identified hazards associated with each work activity. The second stage of the study involved conducting a series of quasi-experimental trials. The specific research protocol for each phase is provided in the sections below.

3.1 Selection of Work Activities

A set of independent trials modules were created to be used in the experiment based off past research by Hallowell and Hansen (2016). Hallowell and Hansen (2016) previously collected data and 2D plans from 5 construction projects, and they identified the hazards by observing actual construction work, pre-job safety meetings, post job interviews of work associated with 12 discrete construction work activities. They defined a construction activity as "*a discrete building element and the associated activities required for its installation*". All 12 activities were limited to commercial high-rise construction; component installation duration was limited to 1-5 hours each. Additionally, each component was discrete as components were self-contained in 2D plans and were independent of adjacent tasks (Hallowell and Hansen 2016). From the original 12, 3 were selected for inclusion in this study to ensure the results were externally generalizable to vertical commercial construction. Additionally, construction activities were selected to ensure diversity in construction methods, tools, materials and equipment, and contained minimal overlap between activities. Each work activity and their associate descriptions can be seen in Table 1 below.

Table 1: Work Activities and Descriptions

Work Activity	Activity Description
Skylight Installation	This work involves the construction of a skylight. The framing for the skylight and original roof has previously been demolished and opened up. A temporary cover was installed. Includes: removal of temporary cover and installation of new skylight. Does not include removal of debris or materials.
Soffit Drywall Installation	This work involves the construction of a drywall soffit. Includes: all preparatory work and setup, and installation of soffit and wall drywall.
Interior Wall Stud Framing	This work involves the construction of an interior wall. Includes: vertical members of metal stud framing.

3.2 Developing 2D and 3D Design Information

The 2D construction plans collected by Hallowell and Hansen (2016) were transformed into 3D BIM using Autodesk Revit software. The designs were developed to a level of detail #350. This was an acceptable level of detail where a constructability review would be performed as there is enough detail in the design to convey designer intent. Multiple screenshots of BIM environment were compiled into a portable document file (pdf) (See Figure 2). Screenshots were selected to ensure that all attributes of the 3D BIM environment were included. Screenshots were used to reduce the potential effects of any user interaction with the BIM system. Additionally, all attributes of the design were included in the 2D plans to ensure that research participants had a realistic experience while obtaining information from the 2D design documents. 2D CAD, 3D BIM, and a combination of 2D and 3D were the three modes of design stimuli developed.

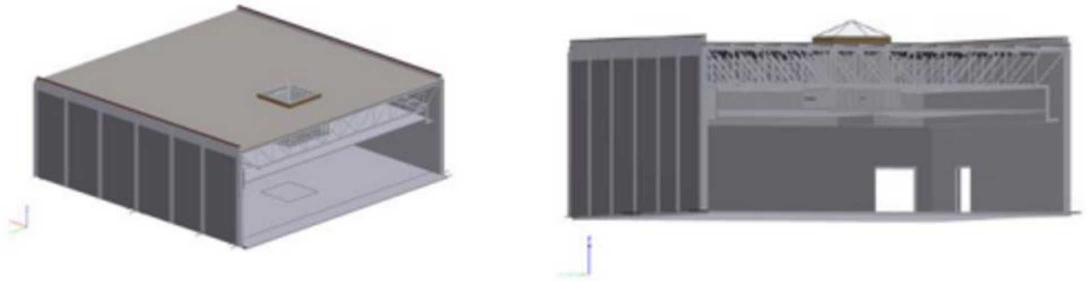

Figure 2: Example 3D Visualizations Detailed to #350 Level of Detail

3.3 Quasi-experimental Testing

For this study, 81 participants including construction designers, construction supervisors, and civil engineering students were recruited. Construction designers and construction supervisors were recruited as they are known to be important for CHPtD activities. Students were used as subjects only if they had formal training in construction design. A total of 27 participants from each population were selected to balance the sample and maintain adequate sample size for exploratory analysis. Within each population, 9 participants were randomly placed into three experimental and mutually-exclusive groups (A, B, and C). These experimental groups were organized to cross the formats of design information with the construction work activities. The three experimental groups (A, B, and C) and the ordering sequence (1, 2, and 3) are shown below in Figure 3 to demonstrate the counterbalanced and blocked experimental groups across participants. For example, a randomly selected construction supervisor within experimental group "A" would first receive the 3D BIM skylight installation activity, then the 2D CAD soffit drywall installation activity, and finally, a combination of 3D BIM and 2D CAD interior wall stud framing activity.

3X3 Experimental Research Design		**Design Information Format**		
		3D (BIM)	2D (CAD)	Combination
Work Activity	Skylight Installation	**A-1**	**C-3**	**B-2**
	Soffit Drywall Installation	**B-3**	**A-2**	**C-1**
	Interior Wall Stud Framing	**C-2**	**B-1**	**A-3**

Figure 3: 3X3 Counterbalanced Design

To help confirm participants understand the scope of the work activities, participants were provided a copy of the work activity descriptions (see Table 1) and appropriate design information according to the randomly assigned trial group. Participants were provided the 3D BIM via pdf displayed on a 17" laptop computer monitor, subjects used a mouse to navigate through the pdf. Additionally, participants were provided with a set of 24”X18” 2D paper drawings and a combination of 3D and 2D stimuli when appropriate. There was no time limit for participants to view the design information and anticipate hazards. Participants were asked to verbally narrate safety hazards as they were anticipated, and lead researcher documented hazards narrated by subjects.

For the purposes of this study, safety hazards were identified as “*a source of energy that, if released, and results in exposure, could cause injury or death.*” Participants were asked to disregard citing safety and health regulation infractions, and solely focus on identifying “*ways that workers could become injured, ill, or be killed in the work situation*”.

4 RESULTS

Data analysis occurred in three distinct phases: (1) measuring the hazard anticipation performance; (2) assessing participant’s spatial cognition; and (3) using a Pearson correlation to test the hypothesis. The following sections discuss the three-step analysis procedures

4.1 Measuring Hazard Anticipation Performance

The Hazard Anticipation Index (HA_{index}) was adapted from previous research by Albert et al. (2014a). The HA_{index} results in proportional data. It is a viable method to evaluate hazard anticipation performance levels of construction workers. Previously, Albert et al. (2014a) developed the HR_{index}, which was used to evaluate construction workers abilities to recognize physical hazards shown in construction photographs. The HA_{index} is similar as it results in proportion data which evaluates the percentage of correct hazard identifications. However, it is slightly different as the hazards are not visible in the construction design and therefore must be anticipated, rather than recognized. The numerator in the equation is the total number of hazards that participants correctly identified from each work activity. The denominator of the equation is the total number of specific hazards for each work activity (HA_{index}) [Eq. (1)].

$$[1]\ \text{HA}index = \frac{\text{Hazards Anticipated}}{\text{Hazards Total}}$$

Table 2: Hazard Anticipation Scores by Design Information Format and Construction Work Activity

Design Information Format	Construction Work Activity	Hazard Anticipation Performance
2D CAD	Skylight Installation	0.29
	Soffit Drywall Installation	0.49
	Interior Wall Stud Framing	0.35
		Average = 0.38
3D BIM	Skylight Installation	0.31
	Soffit Drywall Installation	0.41
	Interior Wall Stud Framing	0.38
		Average = 0.37
Combination	Skylight Installation	0.31
	Soffit Drywall Installation	0.44
	Interior Wall Stud Framing	0.32
		Average = 0.36

4.2 Assessing Spatial Cognition

Each participants’ overall spatial cognition score was calculated by generating the mean of the card rotation test scores and cube rotation test scores of each participant. This results in proportion data which is hereby considered the (μ_{SC}) [Eq. (2)]. The resulting μ_{SC} value for each participant was thus considered to be the participants pre-existing spatial cognitive capability.

$$[2]\ \mu_{SC} = \frac{\text{Card Rotation Test Score} + \text{Cube Rotation Test Score}}{2}$$

Table 3: Spatial Cognition Scores by Population Group

Construction Designer Participant	μ_{SC}	Construction Supervisor Participant	μ_{SC}	Engineering Student Participant	μ_{SC}
1	0.55	1	0.85	1	0.90
2	0.92	2	0.25	2	0.68
3	0.60	3	0.70	3	0.68
4	0.54	4	0.65	4	0.73
…	…	…	…	…	…
…	…	…	…	…	…
27	0.61	27	0.67	27	0.58
Average	0.65	Average	0.75	Average	0.71

4.3 Pearson Correlating for Hypothesis Testing

The null research hypothesis was that *spatial cognition does not predict hazard anticipation task performance.* To test this hypothesis, Pearson's correlation in R studio was used leveraging the interval nature of the HA_{index} and u_{sc} variables. The Pearson correlation test was performed for the total of all data points collected for the three formats of design information independent of construction work activity. This provided 81 observations for hypothesis testing for each format of design information, due to each participant observing three independent formats of design information. It was because of the counterbalancing of the research design that allowed for the aggregation of data by design information format as any confound resulting from a learning curve through subsequent trials was eliminated.

The results of the analysis show that there is no definitive correlation between the participant's spatial cognitive capabilities and hazard anticipation performance for the aggregate of the 81 total observations within each design information format. The Pearson correlation resulted in $r = -0.011$, $n = 81$, $p = 0.9185$ for the 2D CAD format, $r = -0.053$, $n = 81$, $p = 0.6322$ for the 3D BIM format of design information, and $r = -0.029$, $n = 81$, $p = 0.7922$ for the combination format of design information. These values are too low to be able to definitively state any association between spatial cognition and hazard anticipation performance. The resulting P-Value does not provide sufficient statistical significance to reject the null hypothesis. Thus, the practical conclusion is that a subject's spatial cognitive capabilities does not predict hazard anticipation performance 2D CAD, 3D BIM, or combination of the two.

Table 4: Pearson Correlation Results

Design Information Format	μ_{SC} vs. HA_{Index}
2D CAD	$r = -0.011$, n (Pairs) = 81, $p = 0.9185$
3D BIM	$r = -0.053$, n (Pairs) = 81, $p = 0.6322$
Combination	$r = -0.029$, n (Pairs) = 81, $p = 0.7922$

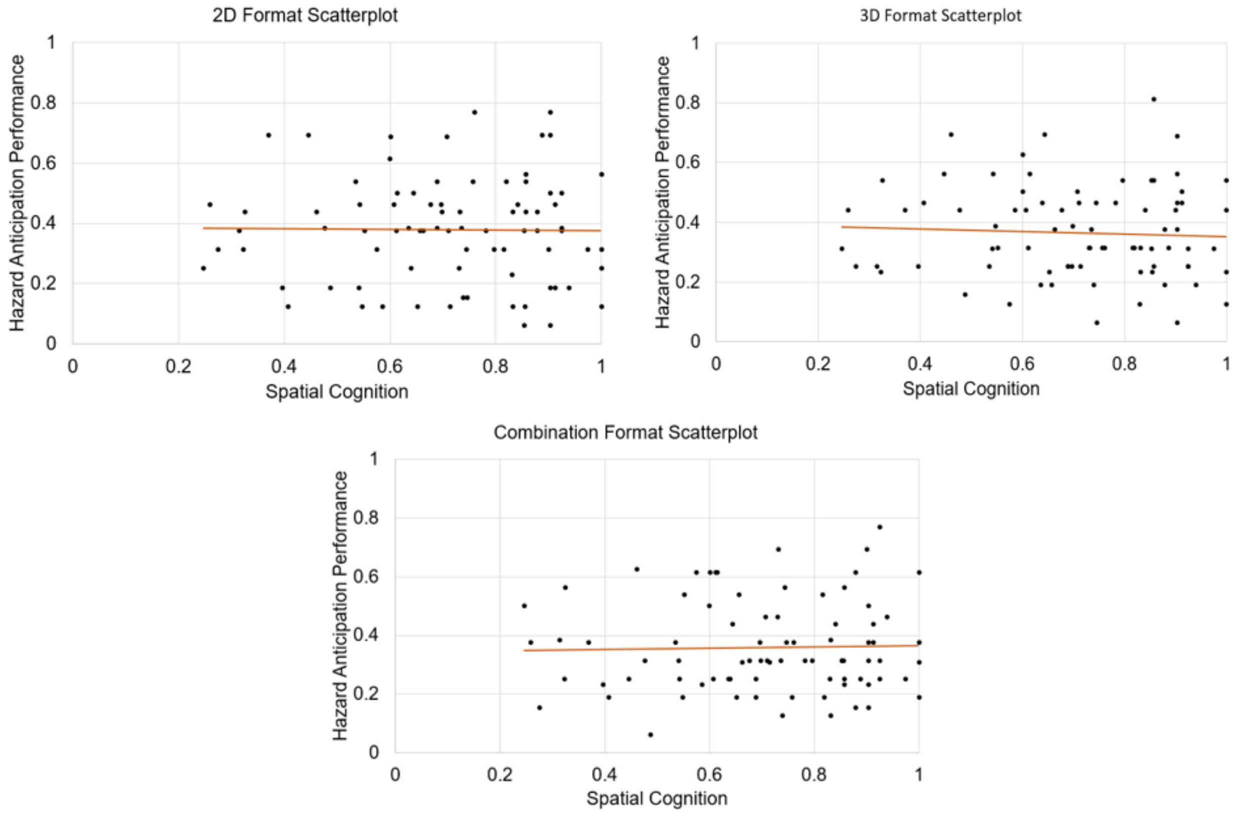

Figure 4: Scatterplots by Design Information Format

The correlation test results and scatterplot shown in figure 3 supports the lack of correlation between participant's spatial cognitive capabilities and the proportion of hazards anticipated for any of the formats of design information. All three Pearson correlation tests resulted in very weak correlations a weak correlation between μ_{SC} and HA$_{index}$ (all P-Values > 0.05). Further data collection to increase sample size may improve the statistical significance of correlation test results.

5 DISCUSSION AND CONCLUSIONS

Spatial cognition is defined as the ability to retain, manipulate, and generate precise visual images (Lohman 1979). Construction workers are required to use spatial orientation to use and understand 2D CAD construction blueprints. The spatial orientation process relies on encoding, transforming, remembering, and matching design information that has led to exclusions and vagueness of information. Therefore, it is suggested that design information should accommodate retention, manipulation, and generation of precise visual images that can be used to anticipate construction safety hazards (Lohman 1979).

Building information modeling (BIM) software is seen as essential in this regard as it can provide a 3D representation of traditional 2D drawings and has been suggested to improve the efficiency of hazard recognition tasks. This postulation is made suggesting that the 3D interface of BIM environments will allow users to easily orient themselves into the simulated work environment yielding increased hazard anticipation over 2D alone (Ku and Mills 2010; Bansal 2011; Kasirossafar and Shahbodaghlou 2012; Ganah & John 2015; Zhang et al. 2015). However, it is unknown if humans' spatial cognitive capabilities predict hazard recognition performance when employing various formats of design information for CHPtD tasks. No research to date has explored whether a person's spatial cognitive capabilities predict hazard recognition performance for various formats of design information. These knowledge gaps provided the inspiration for this research.

This is the first study to evaluate the relationship of participant's spatial cognitive capabilities and its effect on individuals' abilities to correctly anticipate hazardous conditions in construction. The findings of this study suggest subjects pre-existing spatial cognitive capabilities is not a predictor of hazard anticipation performance when using 2D computer-aided design drawings or 3D building information modeling software to facilitate prevention through design reviews. Pearson correlation test results support the lack of any correlation between participant's spatial cognitive capabilities and the proportion of hazards anticipated for any of the formats of design information. All Pearson correlation tests resulted in very weak correlations a weak correlation (all P-Values > 0.05).

Although the results suggest that spatial cognition does not influence an individual's abilities to anticipate hazards in construction environments during design, it has been found to play a significant role in construction craft productivity (Dadi et al. 2014; Goodrum et al. 2016). Researchers have found that 3D visualizations and 3D physical scale models improve the productivity time of model assembly tasks. This evidence contradicts the findings of this study which suggests spatial cognition does not influence hazard anticipation. More evidence is needed to determine if spatial cognitive capabilities influence conditional anticipation or if spatial cognition only predicts physical task completion. Future research is also needed to determine if the mental workload of hazard anticipation and the format of design information are related. Additionally, future research is needed to determine if the provision of design information reduces the mental workload of hazard anticipation tasks and determine if its provision improves overall hazard anticipation during design. Testing these gaps in knowledge will help to uncover methods in improving the efficacy of CHPtD tasks.

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