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INVESTIGATING THE PREDICTORS OF SPATIAL SKILLS ESSENTIAL FOR CONSTRUCTION SCIENCE STUDENT SUCCESS IN THE DIGITAL AGE

A DISSERTATION APPROVED FOR THE
DEPARTMENT OF EDUCATIONAL PSYCHOLOGY

BY

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This dissertation is dedicated to my dear parents, Mac and Phyllis McCuen, who I miss daily. The Christian values and work ethic you taught me as a child guides me each day. Your spirits have been with me throughout this journey.

I am blessed to have my soul mate Manuel ‘JR’ Garcia and my sister Terri (McCuen) Gaber in my life for continual support and encouragement. I am deeply grateful for you both.

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Abstract

This study investigated spatial ability, domain knowledge, and domain real-world experience as predictors of spatial skills. One hundred seventy-seven construction science students participated in the study. The study instrument included seven psychometric tests and two questionnaires. Descriptive statistics, correlation analysis, and path analysis were used for the study. Results from the study were inconclusive and did not provide answers to the research questions. Correlations between variables were weak, although some were significant. Additionally, results from the path analysis revealed a lack of direct effects between the hypothesized predictors and spatial skills. It is possible that measurement error may have influenced the study results due to heterogeneity of sample, mixed measurement scales, and lack of item reliability.

The current study did however present a new conceptualization of spatial skills as an amalgamation of predictors – spatial ability, domain knowledge, and domain real-world domain experience. Recommendations for future research are for factor analyses of the variables domain knowledge and spatial skills. There is also a need for greater reliability of items currently used to measure domain knowledge. Given the inconclusive results, further research is needed before instruction for spatial skills can be advanced.

Chapter 1: Introduction

Spatial problems are common in everyday life and many people face this type of problem on a daily basis. A spatial problem may be as mundane as packing a suitcase to ensure it accommodates several days of travel needs. Or, it may be a problem that involves navigating one's way through a maze of streets and buildings to arrive at the desired location based on lines and directions from a two-dimensional (2D) map. To successfully solve these problems one must employ his/her innate spatial abilities. In addition to solving spatial problems, spatial abilities are used for other daily activities such as playing ball, computer gaming, or driving a car. Spatial abilities that are germane to our everyday lives often provide the foundation for developing spatial skills in a particular area of routine activity or chosen profession. The terms and references associated with spatial abilities and spatial domains are often interchanged; therefore, a glossary of terms is provided in Appendix A as an aid for readers.

Skills have been described as the product of experiences, or bits of knowledge that are transferrable to different tasks and contexts (Lohman & Nichols, 1990). Prior research has shown that spatial abilities follow a model in which spatial skills gradually increase rather than being a sudden and abrupt development of skill focused training (Lohman & Nichols, 1990). Developing abilities into skills involves the translation of knowledge into action that is then manifested in one's task performance (Odusami, 2002). Estimates are that the most successful individuals in over 80 professional occupations are required to apply spatial abilities in their daily tasks (Hegarty & Waller, 2005). Over time those abilities will manifest into spatial skills critical to their occupation.

Spatial based occupations reliant on spatial abilities include various types of engineers, scientists, draftsmen, designers and medical doctors. As the demand for graduates from programs of spatial domains increases and it is expected to continue for many years to come. A 2010 study published by the Georgetown Center on Education and the Workforce (Carnevale, Smith, & Strohl, 2010) reported that occupations in medicine and in the science, technology, engineering, and math (STEM) related fields are expected to be the two fastest growing categories of jobs by 2018. The Georgetown study's STEM category also includes occupations such as computer and mathematical science, architecture, engineering, life sciences, physical sciences, and social sciences.

Building and construction science is a specialized area within the architecture and engineering domains. Building and construction science professionals, also known as constructors or construction managers, are occupations requiring post-secondary education and certification of domain knowledge. The United States Department of Labor released a report in 2014 predicting that 78,200 new construction science graduates will be needed between 2012 and 2022. The demand predicted is increasing faster than the national average of anticipated graduates (U.S. Department of Labor, 2014).

Construction science professionals work closely with architects and engineers during the design and construction of a project. Early in the preliminary design phase architects rely on construction professionals to review their conceptual drawings and models to determine the feasibility and constructability of the design. Once the design is complete the constructor becomes the one responsible for converting the two-dimensional (2D) drawings and three-dimensional (3D) models into reality as a facility in the built environment. At each point in the process, construction science requires one to combine their technical knowledge about materials, sequencing, and resources with their ability to visualize, orient, and rotate the drawing or models provided.

In addition to the high demand for well-educated construction professionals, the industry is experiencing an evolution from a paper based linear process of communication about a project design and details to a digital based iterative communication process (Smith & Tardif, 2009). The digital based process supports a more collaborative environment between architects, engineers, and construction managers and reduces many of the errors and omissions common in the traditional process. The digital environment in construction science facilitates interaction with 3D computer models and information to support the visualization of information about a building project. As a result, students in construction science programs are increasingly utilizing building information modeling (BIM) technology to (1) learn about building elements and their sequence of assembly, (2) understand alternative means and methods for assembly, and (3) solve problems that arise during the process of construction (Jin-Lee, 2012)

In addition to BIM, digital simulations, virtual reality, augmented reality, and laser scanning are examples of other technologies emerging for the 21st century design and construction of the built environment. Each of the technologies listed provide some form of three-dimensional (3D) spatial representation of buildings, supplemented with interactive levels of spatial and temporal information. The information available from each technology can be manipulated and extracted in various ways to solve complex ill-structured problems associated with the construction domain. As a consequence of the emerging technologies, it is increasingly important that construction students think spatially and have the ability to reason about spatial problems. Although questions exist about what types of spatial thinking are required by students when interacting with computer representations of data (Hegarty & Waller, 2005), research about visual analytics has shown that new technologies support spatial thinking (Thomas & Cook, 2005)

Thinking about a space and the relationship between objects occupying that space is one example of spatial thinking. As you can imagine, professionals in spatial based careers must think spatially to perform their daily tasks and solve problems within their domain. Spatial thinking is therefore the starting point for spatial based problem solving. If thinking is the active use of one's mind to form thoughts then spatial thinking is using the mind to form thoughts about space, objects in space, and the relationship between those objects. Spatial problems are not only prevalent in the construction domain, but they are also common in the domains of science, technology, engineering, and mathematics (STEM), geology, medicine, and meteorology (Uttal et al., 2013; Wai, Lubinski, & Benbow, 2009). An individual's ability to visualize objects and their spatial relationship is an ability that is highly correlated with success in both scientific and technical domains (Hegarty, 2010; McGee, 1979; National Research Council, 2006).

Critical to the success of construction professionals is the ability to translate spatial thinking into reasoning and solving spatial problems. During the design and construction of a project the Architecture, Engineering, and Construction (AEC) professionals are challenged with complex ill-structured problems both within their discipline and across the domain. The complexity and ill-structuredness of problems has increased in recent years as 21st century buildings become more complex due to advancements with building systems and building technology.

To meet the demand for AEC professionals, as well as other STEM occupations, it is important for students to receive a strong educational foundation that supports learning the essential skills necessary for success in these occupations. The current study will investigate a set of three variables believed to be predictors of spatial skills. The prediction model is based on a review of the spatial based and problem solving literature. The predictors are considered essential for success in all spatial domains (National Research Council, 2006); however, the current study will focus on students in the construction science domain.

Although the current study proposes a comprehensive model (as shown in Appendix B) for spatial-based problem solving as a framework for research, this study focuses exclusively on the first of three stages – spatial thinking. Each stage in the model represents one of the three constructs that influence an individual's level of spatial problem solving. The model was conceptualized based on literature from prior research in the areas of spatial ability, mental modeling, spatial reasoning, and problem solving. The model was developed based on the National Research Council's concept that spatial thinking approaches the idea of spatial problem solving by the coordination of space, representation, and reasoning (National Research Council, 2006, p. 27). The idea that spatial thinking merely 'approaches' spatial problem solving initiated questions about how and through what process spatial thinking is linked to spatial problem solving.

At the core of spatial thinking are spatial abilities. However, if spatial ability is simply a trait (National Research Council, 2006), then there must be additional components that contribute to spatial thinking and spatial problem solving. Consistent across the spatial ability, mental modeling, spatial reasoning, and problem solving literature is the importance of problem representations and its role in each cognitive processes (Dufresne, Gerace, Hardiman, & Mestre, 1992; Johnson-Laird, 1996, 2005; McCuen & Ge, 2013b; Newell & Simon, 1972; Schnotz & Bannert, 2003; Tversky, 2005) . Whether internal or external, problem representations is essential in spatial domains. As a result, problem representations and its role in the problem-solving process were the catalyst for the proposed spatial problem solving model.

It is assumed that each stage builds on the previous stage in the process. The stages in ascending order are 1) spatial thinking, 2) mental modeling, and 3) spatial reasoning. Spatial thinking is Stage 1 and the foundation; therefore, it is an imperative step that individuals have success at this stage if they are to have success in subsequent stages.

Spatial Problem Representations

Spatial problem representations provide support for the problem-solving process and may be in form of internal or external (Hsi, Linn, & Bell, 1997). Often both internal and external representations may be used in the problem-solving process. An internal representation is generated after one combines the information perceived in a scene with their knowledge about the context (Pani, Chariker, Dawson, & Johnson, 2005; Schnotz & Bannert, 2003). Organization of the spatial relationships between objects is required. It is important to understand that the resulting internal representation forms a mental image that requires more than just perception; the accuracy of one's organization and content of internal representations relies on internal knowledge about the world in which it was perceived. A mental image is a surface level depiction only and does not include detailed information about the objects perceived, such as material properties.

Scaled computer generated models, diagrams, images, and graphs are all examples of external representations used in the construction domain. External representations are considered cognitive tools that can provide support for the creation of a mental model and facilitate reasoning about the spatial problem by reducing the cognitive load during the spatial problem-solving process (Johnson-Laird, 1996; National Research Council, 2006; Tversky, 2005). A recent study (McCuen & Ge, 2013b) investigating construction science students' approach and cognitive processes related to spatial problem solving found that internal representations were more frequently utilized than external representations. The students attributed the lack of external representations to their lack of ability, knowledge, and real-world construction experience, indicating a lack of self-efficacy in their spatial representation abilities (McCuen & Ge 2013b).

The current study extends prior research about spatial skills through research that investigates spatial ability, domain knowledge, and real-world domain experience as predictors of spatial skills. Each of the constructs in this study are essential to the spatial problem-solving process. The first construct, spatial abilities contribute to the spatial problem-solving as they enable one to perceive spatial relationships, perform mental rotations, and visualize objects (National Research Council, 2006). Second is domain knowledge is built over time through practice and experience and contributes to solving spatial problems by adding one's knowledge about the concepts, rules, and principles of the domain (Jonassen, 1997; National Research Council, 2006). The third construct, real-world domain experience provides context and experience to the problem-solving process (Intons-Peterson & Roskos-Ewoldsen, 1989).

Problem Statement

Spatial intelligence is acknowledged as a distinct characteristic required for success in many professional and technical domains (Cronbach, 1970; Hegarty & Waller, 2005). Spatial intelligence combines spatial thinking, mental modeling, and spatial reasoning to solve complex spatial problems (National Research Council, 2006). It is important to understand the difference between a simple problem and complex problem. According to Funke (1991) simple problems have five characteristics: 1) all the information is known for the problem; 2) precise goals are defined; 3) variables are clearly defined; 4) problem properties are stable; and 5) there is a rich semantic articulation of the problem. Whereas, the six characteristics of a complex problem are much different: 1) intransparency of variables; 2) multiple goals; 3) complex situation of connections between variables; 4) high degree of connectivity between variables; 5) dynamic situational developments; 6) time-delayed effects of actions (Funke, 1991). Typically problems in the AEC domain are not only complex, but also ill-structured. Sometimes they have no single correct solution or process to solve it; but sometimes they may involve multiple solutions and paths, which require one to provide justifications for the solution one chooses (Jonassen, 1997; Kitchener, 1983).

Prior research (Hegarty, 2010) indicates that many individuals lack competence in the selection and utilization of internal and external representations for spatial problem solving tasks; however, there is a gap in the literature about improving competence in this area. On the other hand, there is an overwhelming amount of factor analytical research about spatial abilities (Cronbach, 1970; Uttal et al., 2013) from which there are conclusions about individual factors and associated contributions to one's ability. The literature points to spatial intelligence as the result of *spatial thinking, mental modeling, and spatial reasoning* without much detail about the variables and links between the three constructs. The first component in spatial intelligence, spatial thinking, is a cognitive process that combines one's spatial abilities, spatial skills, domain knowledge, and real-world domain experience (National Research Council, 2006). Mental modeling is a cognitive process through which a mental model is generated in the process of problem-solving. The mental model reflects the ontology of the domain in which the problem is situated and represents the real-world as the individual perceives the real-world (Johnson-Laird, 1998, 2005). Spatial reasoning is the third component of spatial intelligence and is reasoning that is a contextual domain specific cognitive process. Spatial reasoning may be considered a three step process involving the 1) extraction of spatial structures from representations; 2) transformation of representations; and 3) drawing inferences about the cause-and-effect relationships based on temporal sequences (National Research Council, 2006).

The literature is also missing substantive and rigorous inquiry about the variables associated with each construct that may contribute and influence one's ability to solve spatial based problems. Further research is needed in the area of spatial problem solving to 1) identify the variables for each construct, 2) investigate the influence of each construct, 3) analyze the results of rigorous research, and 4) apply research results to improve the design of instruction in construction and other STEM disciplines.

As the demand for more construction science professionals increases, so does the need for instruction about spatial problem solving. The use of technology for professional tasks as well as everyday tasks creates an environment in which individuals have more information to analyze and visualize than ever before requiring an increased level of spatial functioning (David, 2012). Historically construction professionals had to create and manipulate two-dimensional (2D) drawings using internal and external representations as aids in understanding the multiple views, planes, and slices of a building. To accomplish these spatial task, constructors relied heavily on their cognitive ability to mentally rotate a drawing from 2D to 3D and visualize the resulting representation. The image in Figure 1 is that of a floor plan view with the north annotation and standard section symbol. From this floor plan a constructor would have to create a representation to visualize the cross section shown in Figure 2.

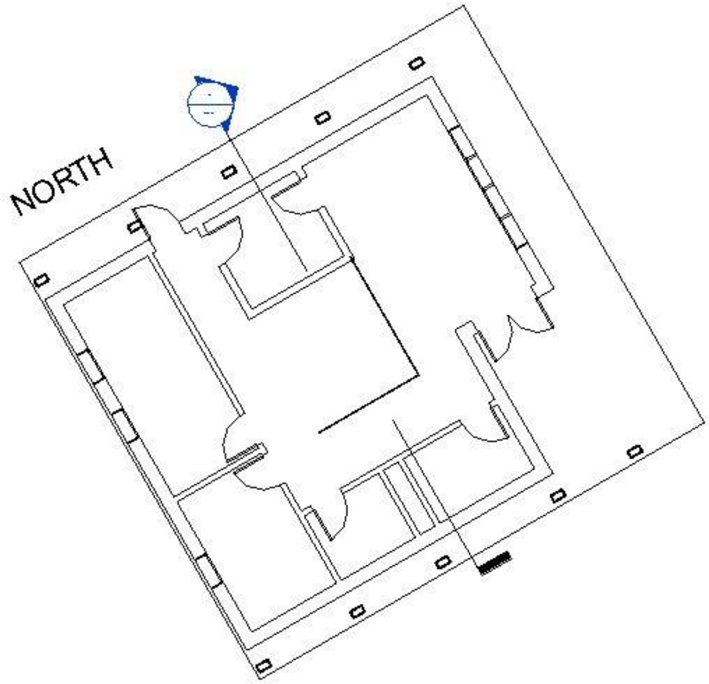


Figure 1. Two-dimensional plan view representation requiring mental rotation

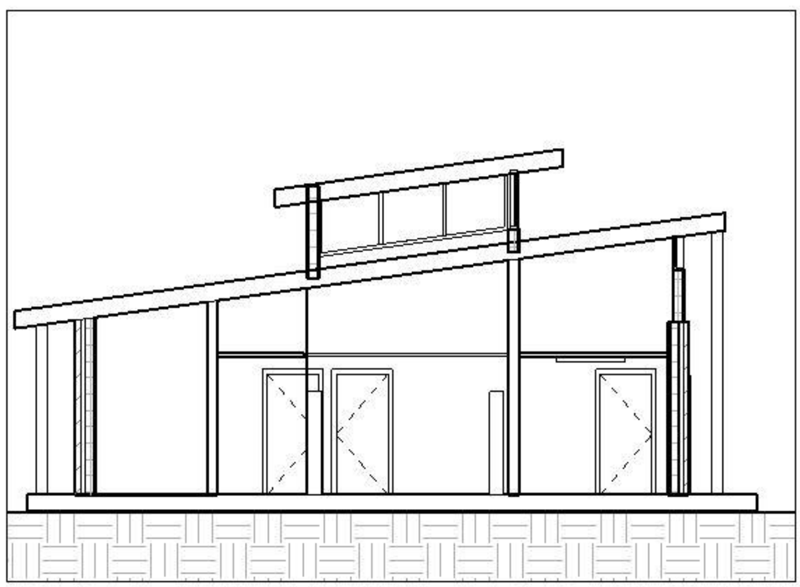


Figure 2. Two-dimensional section view representation requiring mental rotation

Although mental rotation remains a valuable spatial ability in construction science, spatial orientation and other visualization abilities are quickly gaining importance as spatial abilities. For example, Figure 3 shows a 3D computer generated model used to analyze multiple building elements and their locations. To use the model for its intended purpose, one must be able to orient himself spatially in the model. Once oriented, the viewer can then navigate through the model looking at spatial relationships, analyzing space use, and solving spatial problems. Spatial problems due to incorrect locations of model elements are complex problems because of the inherent space constraints associated with the elements' locations. Additionally, these problems are typically ill-structured and require one to reason about multiple solutions to the problem. This type of spatial problem can cause delays and cost overruns on a project if not solved in the 3D model.

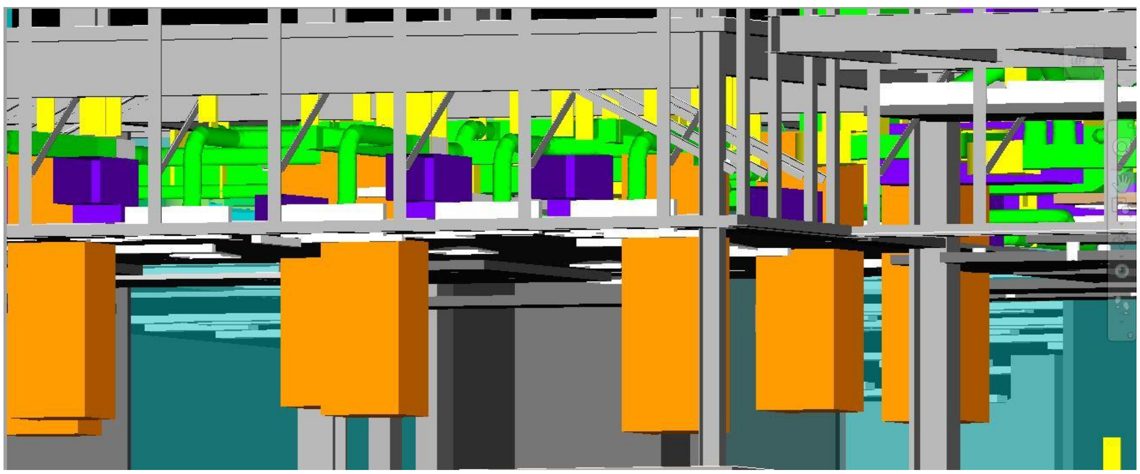


Figure 3. Three-dimensional representation requiring spatial orientation

An internal representation results in the formation of visual images, or visualizations, whereas an external representation results in a sketch or model of some type. Mental rotations and spatial orientation are considered easier to measure and less complicated than visualizations (I. M. Smith, 1964). For example, the classroom in Figure 4 is a project renovation with options being considered. The building owner has decided that the room's existing ceiling is no longer acceptable and would like renovations to accommodate new technology and sound attenuation needs. The problem is that the existing utilities must remain in place and the new ceiling assembly added within the original vertical and horizontal boundaries of the space. Additionally, the new ceiling assembly must be functional and visually appealing.

Figure 4. Picture image of room for renovation

Figure 5 is a computer generated external representation augmenting the existing space with the proposed renovations. In the past the external representation would have been a hand drawn sketch; however, thanks to technology one's internal visualizations can now be translated through computer software. Visualization technology does not replace the importance of one's own spatial ability to visualize and articulate that visualization through mental images.

Figure 5. Three-dimensional representation requiring visualization

Although Figures 1, 2, 3, and 5 were computer generated, a level of spatial skills is required to input and analyze the information from each representation. Computer representations of buildings and their environments using building information modeling (BIM), virtual reality (VR), and augmented reality (AR) are quickly emerging as the primary mode of representation in the 21st century construction industry and will further the need for spatial skills to analyze their content.

Investigating the entirety of the spatial based problem solving process proposed in the model available in Appendix B is beyond the scope of the current study; therefore, this research is designed to focus on investigating spatial skills, which is one of the spatial based problem solving components (National Research Council, 2006). Spatial skills are the result of combining one's spatial abilities, domain knowledge, and real-world domain experience in the act of spatial thinking. The expectation is that the conclusions from this research will be used to inform the design of instruction for the purpose of improving construction science students' spatial thinking.

The Role of Spatial Skills in Spatial Thinking

The ability to think about spatial relationships, manipulate objects in space, and visualize objects is essential to one's success in the domains of architecture, engineering, and construction (National Research Council, 2006; Newcombe, 2013; Youssef & Berry, 2012). For the purpose of the current study construction science and building science will be used interchangeably throughout when referring to the discipline responsible for transforming the intent of a building design into reality. Construction science is a post-secondary program of study for which students must complete coursework in the areas of design theory, analysis and design of construction systems, construction design, construction materials, site planning, along with basic building and site design. Upon graduation from college, students enter the workforce as construction professionals responsible for the execution of the designed building through the coordination of skilled trades who actually assemble the building. It is therefore important to design instruction using evidence from research investigating a combination of variables that interact and influence one's level of spatial skills. The current study uses a combination of existing psychometric tests and questionnaires to gather data about variables and the correlations between them.

Purpose of this Study

After a review of the spatial based literature three gaps were identified. It is important to address each of the three gaps to further research about spatial problem solving and inform instruction about spatial thinking and problem solving in spatial domains. The first gap is that there is no clear conclusion about how each of the processes, and sub-processes, in spatial thinking influence an individual's success in solving spatial problems. The second gap is that there is no clear conclusion about the relationship between mental models, internal representations, and external representations as events in the spatial problem solving process. The third gap in the literature is the lack of conclusive evidence about how representations, transformations, and spatial reasoning influence an individual's ability to solve ill-structured spatial problems.

The objective of the current study was to understand spatial skill as a set of skills developed in the context of a domain and dependent on the following relationship between: 1) spatial ability, 2) domain knowledge, 3) real-world domain experience, and 4) self-efficacy. In the current study spatial ability, domain knowledge, and real-world domain experience are treated as direct predictors of spatial skills. Self-efficacy was expected to mediate the relationships between each set of predictors and spatial skills. As previously discussed, a gap exists in the literature of spatial thinking about the relationship between spatial ability, domain knowledge, real-world domain experience, self-efficacy, and spatial skills. Therefore, the research questions guiding the current study were developed to investigate if a relationship exists between the spatial thinking constructs.

The current study focused on the following questions:

Question 1: Is spatial ability a greater predictor of spatial skills than domain knowledge and real-world domain experience?

Question 2: Is domain knowledge a greater predictor of spatial skills than spatial ability and real-world domain experience?

Question 3: Is real-world domain experience a greater predictor of spatial skills than spatial ability and domain knowledge?

Question 4: Does self-efficacy mediate the relationship between spatial ability and spatial skills?

Question 5: Does self-efficacy mediate the relationship between domain knowledge and spatial skills?

Question 6: Does self-efficacy mediate the relationship between real-world domain experience and spatial skills?

Question 7: Is spatial ability, domain knowledge, or real-world domain experience more useful in predicting spatial skills?

Significance of Study

It is expected that this study will contribute conceptually to the literature of spatial skills and spatial problem solving. In the literature of spatial skills there is no clear demarcation between spatial abilities and skills. Instead the terms are interchanged with little regard for the idea that skills are the result of experiences performing tasks in a context from which one's natural abilities then develop into skills (Lohman & Nichols, 1990). The current study attempted to establish a clear distinction between spatial abilities and spatial skills by investigating each construct using psychometric testing, which is designed to obtain a numerical estimate of an individual's performance at some point in time (Cronbach, 1970). Psychometric tests were also used to measure participants' performance related to domain knowledge.

The majority of construction science problems involve either the manipulation of an existing form in space or the visualization of a form in space within a situated context. The study is also expected to contribute to the literature based on the position that spatial abilities, domain knowledge, and real-world domain experience influence one's spatial skills. The literature includes evidence that declarative knowledge influences skills (Lohman & Nichols, 1990) and that experiences, other than training, influence the development of skills (Uttal et al., 2013). Research questions 1, 2, 3, and 7 were specifically written to guide the research design and analysis strategy during the investigation of constructs influencing spatial skills.

Finally, the study is expected to contribute to the literature of spatial problem solving as a complex model comprised of three stages – spatial thinking, mental modeling, and spatial reasoning. Although each stage is represented in the literature extensively, there is minimal reference to the possible relationships between the stages (National Research Council, 2006). Thus, the current study attempted to establish the processes and sub-processes influencing spatial skills and their place in spatial thinking. Each of the research questions for the study investigated relationships between constructs in an attempt to further the literature of spatial thinking and improve the design of instruction for spatial thinking.

Chapter 2: Literature Review

Success in the AEC industry and other technical spatial occupations requires that individuals be able to understand, draw, and comprehend technical drawings (Seel & Dörr, 1994). Technical drawings and models are the primary form of communicating between the AEC disciplines. Drawings and models are visual representations used to reason about alternatives in the planning and design phases as well as being used to solve problems during the construction and use phases of a facility. Technical drawings may be two-dimensional (2D) ‘flat’ drawings or they may be three-dimensional (3D) ‘model’ drawings. In addition to 2D drawings and 3D models there are two more dimensions that may be unknown to someone outside of the domain, but they are part of the everyday life of a construction professional. The two dimensions beyond 2D and 3D are 4D and 5D. The fourth dimension literally ‘builds’ the 2D or 3D representation of a building using a temporal sequencing of building elements in a paper or virtual mode of construction (Eastman, Teicholz, Sacks, & Liston, 2008). The fifth dimension takes information from the 4D representation and adds cost relationships interdependent with the 4D time (Eastman et al., 2008). The combination of multiple dimensions adds complexity to the already ill-structured nature of problems faced in the design and construction of a building.

Other domains such as science, technology, engineering, mathematics and medicine also rely on individual spatial abilities to understand and solve domain specific problems. Results from prior research (National Research Council, 2006) indicate that visualization and visual-spatial strategies are by the default domain-general problem solving approach used by novices. Additionally, certain disciplines may be dependent on spatial abilities because the discipline is grounded in real-world experiences that contain spatial objects and relationships (Hegarty, Crookes, Dara-Abrams, & Shipley, 2010; Hsi et al., 1997).

To provide support for the current study within the context of the proposed spatial problem solving process, four bodies of literature are included in this review: ill-structured problem solving, spatial thinking, mental models, and spatial reasoning. This synthesis provides an overview of each body of literature applied to the AEC domain for context and supplemented with a critical analysis of the literature based on evidence from a recent study (McCuen & Ge, 2013b). Participants in the referenced study were university students in their last semester of a construction undergraduate program from two consecutive calendar years. Gaps in the research are identified in this synthesis indicating a need for more research in the area of spatial thinking, mental modeling, and spatial reasoning for the purpose of ill-structured problem solving in spatial domains.

The existing literature reviewed addresses each construct in the process of ill-structured spatial problem solving, but it does not explain the links between spatial thinking, mental modeling, and spatial reasoning. Although this review is structured to provide a review of the literature by construct, it also indicates where those constructs may be interdependent within the process of ill-structured spatial problem solving. The chapter is organized by topic into four sections. The first section describes the types of problems and reviews the ill-structured problem solving. The second section is a review of the literature about spatial reasoning. In the third section a review of mental modeling is provided. The fourth section reviews the processes and sub-processes of spatial thinking including: spatial ability, spatial skill, domain knowledge, and real-world domain experience.

In addition to each of the processes in spatial problem solving, self-efficacy was integrated in the discussion due to its influence on personal accomplishments. Self-efficacy is a belief that interacts with one's skills and impacts their task performance (Bandura, 1993). The premise of this chapter is that spatial thinking, mental models, and spatial reasoning combine to form one's spatial intelligence as an interdependent iterative process essential to solving ill-structured problems in spatial domains. Self-efficacy is also included in the process of ill-structured spatial problem solving as a factor that influences the process at different times and at different magnitudes even within a single individual. Prior research has found that a construction science student's belief about his ability to accurately perform a task can create a barrier and negatively influence his task performance (McCuen & Ge, 2013a, 2013b)

Spatial Problem Solving

An individual's ability to solve problems has been described as a function of the nature of the problem, the way the problem is represented to and perceived by the problem solver, and individual differences that mediate the problem solving process (Jonassen, 2000). The nature of a problem refers to the type of problem presented to an individual. According to Jonassen (1997), problem types are defined as either puzzle, well-structured, or ill-structured. The problem type that this review will focus on is ill-structured, with a brief overview of puzzle and well-structured problems. Individual differences in solving problems will also be discussed.

The way a problem is represented impacts an individual's ability and therefore the problem representation provided to an individual should be based on the level of expertise that individual has about the domain or situation (Dufresne et al., 1992). Results from prior research (Dufresne et al., 1992) investigating the differences between the problem solving process used by an expert and that of a novice found that an expert's domain knowledge is highly organized and therefore experts have the ability to integrate domain specific principles, concepts, and procedures in a more efficient way than that of a novice. As a result, experts have the ability to recall domain knowledge and integrate it in a way that supports the creation of complex problem representations after a brief exposure to the problem (Dufresne et al., 1992). Having the ability to store, relate, and use domain knowledge to create schema impacts how problems are represented and solved.

One's perception of a without problem refers to their ability to filter through the given information and determine what is relevant to the situation (Jonassen, 2000). A major determinant of one's ability to solve problems is individual differences, which include: domain knowledge, structural knowledge, procedural knowledge, conceptual knowledge, domain-specific reasoning, cognitive styles, general problem-solving strategies, self-confidence, and motivation (Jonassen, 2000). Aligned with self-confidence and motivation is self-efficacy which is defined as an individual's conviction that he can successfully execute the behavior necessary to produce the desired outcomes (Bandura, 1977).

Individuals are challenged with different types of problems in both their work and everyday life. According to Jonassen (1997) problems fall on a continuum and are classified as: 1) puzzle, 2) well-structured, or 3) ill-structured. Puzzle problems require no prior knowledge and is domain-independent. Well-structured problems are the most commonly encountered problem in the classroom. Jonassen (1997, p. 68) lists seven characteristics of a well-structured problem: 1) presents all the elements of the problem; 2) is well-defined problem with a probable solution; 3) limited number of rules and principles applied and organized in prescriptive arrangement with well-defined, constrained parameters; 4) concepts and rules appear well-structured in a domain of knowledge that appears well-structured; 5) possess correct, convergent answers; 6) possess knowable, comprehensible solutions where relationships between decisions and choices of problem states is known or probabilistic; and 7) have a preferred, prescribed solution process. Jonassen (1997) stated that, "…the effects of well-structured problems in school contexts have limited relevance and transferability to solving problems that are situated in everyday contexts…" Therefore although this is the most common type of problem presented to learners in the classroom, well-structured problems are not the most common type of problems in the real world. The third type of problems, and most common in the design and construction of a building, are ill-structured problems, which are typically situated in, and emergent from, a specific context (Jonassen, 1997).

Subsequent sections in this review present spatial thinking, mental models, and spatial reasoning as the three stages in the proposed processes for ill-structured spatial based problem solving. Each section is titled in terms of its relationship to the proposed problem solving process model and includes a discussion with examples of how each stage influences problem solving for construction and the AEC domain. Figure 6 is an abbreviated depiction of each stage and the relationship between each stage in my proposed model of the ill-structured problem solving process.   A complete depiction of each stage with components, subcomponents, and information lines is included as Appendix B. The arrowed lines in Figure 6 indicate the flow of information between stages.

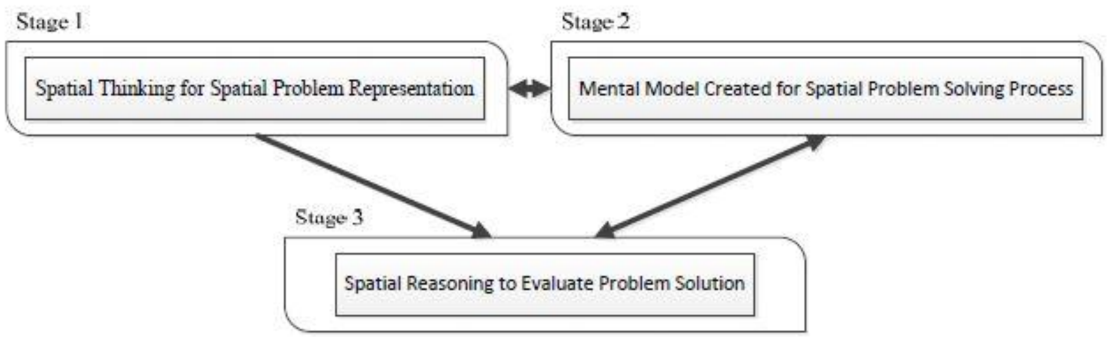


Figure 6. Proposed ill-structured spatial problem solving process

However, before starting the discussion about each stage the next section provides an overview of Jonassen' s (1997) seven iterative steps in the ill-structured problem solving processes related to the three stages proposed in Figure 6.

Ill-Structured Problems

An ill-structured problem is a real world problem for which there is no single correct solution to employ as a specific process to solve the problem (Kitchener, 1983). Jonassen (1997) elaborated on Kitchener's definition and described the attributes of ill-structured problems as appearing to be ill-defined because one or more of the problem elements are vague or unknown, with goals that are vaguely defined or unclear and have unstated constraints. Jonassen described ill-structured problems as problems that possess multiple solutions, solution paths, or no consensual agreement on the appropriate solution. They have multiple criteria for evaluating solutions, have less manipulable parameters, and have no prototypic cases. Ill-structured problems present uncertainty about which concepts, rules, and principles are necessary for the solution. They have relationships between concepts, rules, and principles that are inconsistent between cases and offer no general rules or principles for describing or predicting most of the cases. In fact, according to Jonassen (1997) ill-structured problems have no explicit means for determining appropriate action and they require that learners express personal opinions or beliefs about the problem while making judgments about the problem which they must also defend.

Ill-structured problem solving does not occur in a systematic process but rather in a seven step iterative process which will be discussed in some detail (Jonassen, 1997). Following is a description of the seven steps and how each step aligns with the proposed spatial problem solving model in Appendix B. According to Jonassen (1997), the first step is to articulate the problem space and contextual constraints which requires the problem solver determine what the nature of the problem is within the context from which the problem emerged. In the architecture, engineering, construction domain this may be presented as a design problem or as a project management problem depending on the discipline. For example, a constructor is given a building to construct and tasked with determining the most efficient means and methods to complete the project and ensure that the client is satisfied while the company makes a profit. The alternatives are endless for how this might be accomplished therefore the constructor must first determine the problem space. This step occurs in Stage 1 – Spatial Thinking for

Problem Representation – of the proposed ill-structured spatial problem solving process shown Figure 6.

The second, third, and fourth steps in the ill-structured spatial problem solving process occur in Stage 2 – Mental Model Created for Problem Solving – as indicated in Figure 1. According to Jonassen, Step Two requires the problem solver to identify and clarify alternative opinions, positions, and perspectives of stakeholders because ill-structured problems typically have divergent or alternative solutions to the problem. Step Three is the generation of all possible problem solutions and it is the step that relies on an individual's prior experiences to guide them in the selection of a solution they know is achievable. This is the step at which an individual builds their own mental model of the problem to help select a problem solution (Jonassen, 1997, p. 81).

Assessing the viability of alternative solutions by constructing arguments and articulating personal beliefs is the fourth step where the solver is constructing their own argument and personal position statement about the solution. The result of this step is a mental model that will support the solver's decision and justify the solution chosen from all the alternatives (Jonassen, 1997). Building on the example from the AEC domain presented above, Steps Two, Three, and Four occur in Stage 2, which is the point where the professional constructor processes the visual and textual information about a building into multiple mental representations of possible alternatives while striving to determine the most efficient means and methods for construction. In this stage an individual's spatial ability, domain knowledge, and real-world domain experience are required to process alternatives and propose a solution. For example, the sequence of building elements' assembly may vary and to determine the optimum sequence the constructor must consider this activity from multiple perspectives. Because sequencing may vary due to access, resource availability, or the need to ensure that the building elements are protected from damage after installation, all possible solutions must be considered. The sequencing of building elements is a cognitive task for which the constructor must create 4D mental models of the problem.

Stage 3 in the ill-structured spatial problem solving process is anticipated to be the point at which Step Five from Jonassen’ s (1997) process occurs. The model displayed in Figure 6 displays Stage 3 as a process influenced by inputs from Stage 1 and Stage 2, but there is also an iterative process between Stage 2 and Stage 3. This iterative process between stages aligns with Jonassen’s declaration that step five is not a separate post hoc reflective process but rather a metacognitive process that occurs throughout the previous four steps. It is a metacognitive process that requires the problem solver monitor the problem space and solution options.

The sixth step is to implement and monitor the solution selected and the seventh, and final step, is to adapt the solution (Jonassen, 1997). Step Six is typically accomplished in the AEC domain with either a physical mock-up of the solution or with a virtual mock-up of the solution. The virtual mock-up is facilitated by computer software for 4D modeling and is quickly replacing the physical mock-up as a tool that supports the sixth step. Monitoring the solution in Step Seven leads to a better integrated mental model of the problem space with the transfer of the solution to other domain problems based on implications from their solution.

As discussed in this section Jonassen’ s seventh step process for solving ill-structured problems can be aligned with the three stages in the proposed ill-structured spatial problem solving model. The differentiator between the two is the spatial aspects associated with spatial problems not specifically addressed by Jonassen (1997). The next three sections in this chapter provide a review of the literature associated with the spatial based stages in the ill-structured problem solving process along with a discussion about each stage, its components and subcomponents.

Spatial Reasoning for the Evaluation of Problem Solution

Hsi et al. (1997) reported that their prior research investigating spatial reasoning strategies used by individuals in spatial domains found three distinctive types: 1) a holistic approach, 2) analytic step by step approach, and 3) pattern-based approach. Using these three strategies the researchers (Hsi et al., 1997) asked professional engineers to solve engineering-specific spatial tasks and describe aloud the strategy used. The engineers' responses indicate that they used individual strategies and also combined strategies on the tasks. They reported that spatial reasoning is important and it contributes in many engineering activities, such as analyzing plans or creating a design (Hsi et al., 1997). The findings from the Hsi et al. study described the application and support for the use of spatial reasoning by experienced professional engineers in the AEC domain, but their findings did not address how engineering students used spatial reasoning. The participants in the current study were construction science students from the AEC domain and share with engineering students the need to solve spatial-based problems. The components and subcomponents of spatial reasoning are discussed in this section in an attempt to formulate a better understanding about the topic and to identify the fundamentals needed for novices to utilize this stage in their process of ill-structured spatial problem solving.

Fundamental to reasoning is going beyond the information given by a situation or problem (Bruner, 1973), although adding information to the information given does not necessarily equate to reasoning. Instead Tversky (2005), posits another way to go beyond the information given, that is, by transforming the information given in two separate ways: 1) represent the information internally or 2) represent the information externally. As discussed in the previous section, the creation of a mental model is one's internal representation of a problem and is essential for solving ill-structured problems. External representations for the AEC industry may be in the form of hand drawn sketches, computer generated 2D drawings, computer generated 3D models, or as some other virtual representation. Information may also be transformed through a process of transforming a representation from one type to another type (Tversky, 2005). In this section representations and transformations are discussed as two approaches used for spatial reasoning and as components of a metacognitive process for the evaluation of possible solutions for an ill-structured problem.

As indicated in the Appendix B process model, spatial reasoning is influenced by components from both Stage 1 – Spatial Thinking and Stage 2 – Mental Model Creation. The discussion turns now to expand on representations, transformations, and spatial reasoning and their contribution to the process.

Representations

Individuals use representations as aids to remember, understand, reason, and communicate about objects represented in space (National Research Council, 2006, p.

27). As discussed in the spatial abilities' section later in this chapter, representation may be internal in the form of a visualization or mental image. The actual process of how one creates an internal representation is unclear (Smith, 1964); however, research indicates that an internal representation is generated after one combines the information perceived in a scene with their knowledge about the context (Pani et al., 2005; Schnotz & Bannert, 2003). An internal representation forms a mental image that requires more than just perception; the accuracy of one's organization and content of internal representations relies on internal knowledge about the world in which it was perceived. A mental image is a surface level depiction only and differs from a mental model in that a mental image does not include detailed information about the objects perceived, such as material properties or other information not visible in the mental image (Johnson-Laird, 1996, 1998).

Representations may also be external and in the form of artifacts such as graphs, diagrams, images, or scaled models. When provided with a problem solving task, external representations are valuable in the acquisition and utilization of knowledge (Schnotz & Bannert, 2003). External representations have also been described as cognitive tools that facilitate reasoning by offloading memory and processing, along with aligning abstract reasoning with spatial comparisons and transformations (Tversky, 2005; Johnson-Laird, 1996). According to the NRC (2006) report, an individual's production of external representations of situations can aid with creating a mental model and provide a way to query one's own memory about the situation.

Results from a study by McCuen and Ge (2013b) with undergraduate students in the domain of architecture and construction revealed that a different sequence of events may actually occur when novices begin the process of solving a spatial problem. Participants in the study reported that they must first create a mental model of the situation before they could generate an external representation (McCuen & Ge, 2013b). Based on these results it is possible that the idea of a novice generating an external representation prior to creating a mental model is unlikely. More research is needed to determine the optimal sequence between mental models and external representations if the sequence influences the ability of a novice to solve ill-structured problems.

Transformations

Transformations can be thought of as mental operations on representations such that the transformations on representations resemble observable changes in things (Tversky, 2005). Modern day research about mental images and how individuals transform images to visualize objects from different views began with the seminal study of Shepard and Metzler's (1971) using nondescript block objects. Although the study was a psychometric test of spatial ability focused on a participant's ability to mentally rotate an object in space, transformations may also include transforming an object from one dimension to another dimension. Participants in the Shepard and Metzler (1971) study were asked to compare two objects to determine if the blocks were the same object from different points of views. Participants reported that they had to start comparing two views of the same object by first imagining one object as transformed, or rotated, to the same orientation as the other object before completing the task. As with representations, for the purpose of this study transformations are considered a part of one's spatial abilities used to support metacognitive analysis of a problem solution.

Both representations and transformation are discussed in the context of spatial reasoning in the section below.

Spatial Reasoning

In their early work about spatial reasoning, Byrne and Johnson-Laird (1989) performed two experiments investigating the use of rules or models for the purpose of drawing inferences about 2D layouts requiring one model or multiple models. The experiments did not include visual representations only verbal descriptions about objects in a spatial layout. The results revealed that it was easier for participants to draw a valid spatial inference when the verbal description corresponded to just a single layout that did not require the creation of multiple mental models (Byrne & Johnson-Laird, 1989).

Since this study research continued to expand for the purpose of better understanding about the components and subcomponents of spatial reasoning (Hsi et al., 1997; Knauff & Johnson-Laird, 2002; Shumway, 2013; Tversky, 2005). It has evolved and is now understood that spatial reasoning is a skill that is operationalized through the transformation of inputs as they are perceived from the environment (National Research Council, 2006). According to the National Research Council (2006) report, spatial reasoning is contextual, domain specific, and is a cognitive process that occurs in three steps:

1. Extract spatial structures using representations.
2. Perform spatial transformations as necessary for problem solving.
3. Draw functional inferences by establishing temporal sequences and cause-and-effect relationships.

Each of the three steps in spatial reasoning relies on an individual's ability to apply their spatial abilities, skills, and mental models to a problem in a domain specific context (National Research Council, 2006). For example, the first and second steps rely on spatial abilities and skills. The third step requires an individual to create a mental model to aid the reasoning process.

Mental Models Created for the Spatial Problem Solving Process

Two types of mental models are addressed in the literature. The first type is those generated to represent propositions or textual descriptions (Johnson-Laird, 2005). The second type of mental model is the type generated to aid with reasoning to solve spatial problems (Jahn, Knauff, & Johnson-Laird, 2007). This section focuses solely on the second type because it is the most relevant for this literature review. Mental models are defined as a mental representation of a problem, also known as the problem space (Newell & Simon, 1972), and consist of structural knowledge, procedural knowledge, reflective knowledge, images and metaphors of the system, and strategic knowledge (Jonassen & Henning, 1999). A mental model is situated in the domain for which the it was created and the parts of the mental model may be representative of a situation in either the real-world or in an imaginary world (Garnham, 1999). According to Johnson-Laird (2005), mental models are created by a person to represent the world as the world is perceived and mental models are the basis for thinking. Given that mental models are a cognitive process, they cannot be directly inspected by psychologists and the only evidence that mental models exist is indirect. Even though it is impossible to physically observe a mental model, this has not deterred researchers from their pursuit to understand the role of mental models in reasoning to solve spatial based problems.

For the purpose of this review, mental models are considered a primary stage in the process of ill-structured spatial problem solving. Due to the characteristic of ill-structured problems they may have alternative solutions, which will then require the generation of multiple mental models. Consequently these types of problems are considered more difficult and create more cognitive load on working memory (Johnson-Laird, 1996). The following discussion about mental models begins with the topic of mental images and how they compare and contrast with mental models. The primary focus is on the characteristics of mental models and how they are generated by individuals to solve spatial problems.

Mental and Visual Images

A mental image based on a visual scene is the result of perceptual processing in which objects and symbols are perceived and organized as an internal depictive surface representation (Schnotz & Bannert, 2003). Visual images and visual perceptions are based on the same cognitive processes therefore the conclusion has been made that visual images perception-proximal representations (Kosslyn, 1994). The perception process however represents properties of objects much more finely grained than does a visualization of an object (Langland-Hassan, 2011). Visual images may be used by an individual in their visualization of a situation, but they increase the demand for cognitive resources, which in turn, can impede their use for reasoning (Knauff & Johnson-Laird, 2002).

In experiments investigating the use of visuospatial information compared to the use of visual images, Knauff and Johnson-Laird (2002) discovered that the content of assertions matter. For example if the content of an assertion about spatial relationships is relevant to inference then reasoning proceeds smoothly however if the content of assertions generates visual images that are irrelevant to an inference then reasoning is impeded (Knauff & Johnson-Laird, 2002). Visualizations that include spatial relationships are more general in their representation of the spatial properties than are visual perceptions of an image and therefore are preferred as an aid for spatial reasoning.

Mental Models

Since the 1970s, the modern theory of mental models has developed to a point where it rests on three principles as presented by Johnson-Laird (Johnson-Laird, 2013a). The first principle being that each mental model represents what is common to a set of possibilities. The next principle is that mental models are iconic (Johnson-Laird, 2013a) and their structure corresponds to the structure of the object or situation that it represents (Johnson-Laird, 2005). The third principle is the principle of truth, which reduces the load that mental models put on working memory because they only represent what is true at the expense of what is false (Johnson-Laird, 2013a). Thus, the description of mental models can be summarized as follows:

- Mental models are iconic in that the parts of a mental model are interrelated in the same way that the parts of the object or visual scene perceived are interrelated (Johnson-Laird, 2013a; Langland-Hassan, 2011).

- Mental models underlie the experience of imagery (Johnson-Laird, 1998).
- Mental models may contain elements that cannot be visualized (Johnson-Laird, 1996, 1998).
- Mental models represent a possibility (Johnson-Laird, 2013b).

Along with his description of mental models Johnson-Laird (1998) further explained a mental model as 1) representing a set of individual objects in a visual scene by a set of mental tokens, 2) representing the properties of the individual objects by the properties of the tokens, 3) representing the relations among the individual objects by the relations among the tokens, 4) representing only certain aspects of the visual scene, and 5) representing several distinct sets of distinct possibilities for the current state of affairs. Based on the literature reviewed for this synthesis it is reasonable to conclude that the creation of mental models occurs in Stage 2 of the ill-structured problem solving process as shown in Appendix B.

Although mental models underlie mental imagery (Johnson-Laird, 1998), there are five distinct ways in which mental models differ from mental images. The first difference is that mental models are a sensory unspecific representation because the information used to create a mental model is typically obtained through various sensory modalities (Schnotz & Kürschner, 2008). Secondly, mental models are more schematic than visual images (Schnotz & Bannert, 2003; Tversky, 2005). Another difference is that mental models are 'runnable' for the purpose of determining function or causal inferences (Tversky, 2005). The fourth difference is that a mental model may represent several distinct set of possibilities for the situation (Johnson-Laird, 1998). The final difference is that mental models are more abstract and are elaborated on using an individual's real-world knowledge unlike a visual image (Schnotz & Bannert, 2003, p. 147).

The fact that an individual's real-world experience influences their mental model representation is consistent with findings from interviews in which study participants revealed that their lack of real-world domain experience impacted their ability to solve the building design problem given (McCuen & Ge, 2013b). Even with the three distinct differences described in the preceding section there is evidence that mental models and mental images are related, and that objects in an individual's representations can be concrete things or abstract concepts (National Research Council, 2006). According to Johnson-Laird (1998), mental models underlie mental images even though models may contain elements that are not visualizable and an individual's cognitive process of transforming spatial objects is dependent on the underlying model for that visual scene (Johnson-Laird, 1998).

Although Johnson-Laird (1998) draws the conclusion that mental models are likely the basis for how individuals reason about spatial relations between objects further research is needed about the relationship between mental models and spatial reasoning. I argue however that mental models are only one part of the basis for spatial reasoning and that spatial intelligence, or adapted spatial thinking (Hegarty, 2010), also influences spatial reasoning. According to Hegarty (2010), there are two important components of spatial intelligence are about representation use. The first component is about an individual's choice and use of internal representations, such as mental images and visualizations. The second spatial intelligence component is about an individual's choice and use of external representations, such as diagrams and computer generated 3D models. Other components of spatial intelligence include spatial navigation, relation between spatial objects, and spatial orientation (Hegarty, 2010). As with much of the other topical literature included in this review, the spatial reasoning literature is presented in a silo with few references to the other two stages in the process of ill-structured spatial problem solving. The next section reviews the spatial reasoning literature and its relevance to the AEC domain.

Spatial Thinking Supports Problem Representation

Intelligence is understood to be an individual's ability to think and learn (Cronbach, 1970). Hegarty (2010) defines spatial intelligence as adaptive spatial thinking that involves thinking about shapes, objects in space, and spatial processes using visualization techniques along with more analytic thinking processes. Based on Hegarty's (2010) definition, spatial thinking is conceptualized in this review as the compilation of four components applied to domain specific problems. The four components are spatial ability, spatial skill, domain knowledge, and real-world domain experience. Spatial abilities are based on cognitive processes that include perception, transformations, and visualization (Linn & Petersen, 1985; National Research Council, 2006; Velez, Silver, & Tremaine, 2005). Spatial skills are developed abilities learned within a specific domain (National Research Council, 2006). Domain knowledge and real-world domain experience add the context in which problems are to be solved and are discussed in the problem solving section above. Context is an important aspect for generating domain specific mental models to solve ill-structured problems (Johnson-Laird, 1998; Jonassen, 1997).

In this synthesis of literature spatial thinking is considered Stage 1 in the process of solving ill-structured spatial problems. The following subsections discuss each component and its subcomponents along with examples of spatial thinking in the context of the AEC domain.

Spatial Abilities

The first component to spatial thinking is spatial ability (Hegarty, 2010). Thurstone (1957) presented spatial ability as one of the seven primary mental abilities. Spatial abilities and spatial skills are characteristics unique to an individual and the two are closely related. In fact, it is often difficult to discern between spatial ability and spatial skill in the literature as authors often treat the two as interchangeable. There is a difference however between the two terms. The Merriam-Webster (Merriam-Webster, 2012) defines ability as a natural aptitude or acquired proficiency and skills as a developed ability. The National Research Council's (2006) definition for each term further supports the interdependence with their definition of abilities as innate and something that a person is born with, whereas skills are characteristics that a person develops from their innate abilities through practice and application. The concept of spatial abilities is based on the premise that a person's innate ability to perform mental operations on an object establishes that person's level of spatial abilities (Myers, 1958; National Research Council, 2006, p. 26). A person's spatial abilities are related to a set of spatial skills and are associated with the retrieval, retention, and transformation of visual information about a spatial context (Velez et al., 2005). Although related, spatial abilities and spatial skills are different. Spatial skills are developed in context whereas spatial ability is a general type of characteristic.

In a meta-analysis about spatial ability, Linn and Peterson (1985) defined spatial ability as a person's skill in representing, transforming, generating, and recalling symbolic, nonlinguistic information. Although the interdependence of the two characteristics is apparent in this definition, the authors included a list of four specific mental operations performed by individuals on spatial objects and information. The list of mental operations is as follows:

1. Represent spatial information which may be in the form of an internal mental image, an external sketch, or both.
2. Transform representations of objects for the purpose of spatial reasoning.
3. Generate spatial information from data based on perceived inputs and objects within the spatial reference.
4. Recall information based on the context and spatial domain.

In addition to the four requisite cognitive operations above spatial abilities can be thought of as actions on objects in space, and those actions occur on a continuum making the individual actions interdependent. According to the NRC (2006) the continuum of spatial abilities includes the following three actions that must be executed given a problem in a spatial context. The three actions are: 1) perceive spatial relationships between entities, 2) perform mental rotation on objects, and 3) visualize objects as a mental image. Each action is linked together as an element in a continuum for which all three must be present to constitute one's spatial abilities. The following sections provide a discussion with examples about each element of spatial ability.

The first element of spatial ability is spatial perception (National Research Council, 2006) and it is represented in Figure 2 as the first input to spatial abilities. Perception is a process that occurs in two steps. The first step is a pre-attentive process and is the step at which a person detects an input, discriminates between objects, configures the inputs, and establishes precedence between inputs (Winn, 1994). Given this definition it is reasonable to conclude that a person's pre-attentive process is the point in perception at which their innate spatial abilities would engage to process the spatial inputs. The second step in perception is an attentive top-down cognitive process that is influenced by pre-existing knowledge for the purpose of interpreting objects and their relations (Winn, 1994). The attentive process aligns directly with the definition of spatial skills, which is discussed in the next section of this chapter.

In summary, spatial perception is defined as the ability to know that an object is in a particular direction, at a particular distance, along with encoding spatial features and objects as they exist in the real world (National Research Council, 2006). The literature lists six aspects of spatial perception for which descriptions about how these aspects are utilized by the AEC domain when given a graphical representation, image, or real-time experience of a visual scene follow. Aspects one, two, and three require that an individual have the ability to distinguish figures from ground, recognize patterns, and evaluate size in a visual scene. These three aspects are important for individuals in all of AEC disciplines due to the standards of symbolism, nomenclature, and conventions of representation utilized by the domain to communicate during the design and construction of a building. Discerning texture, recognizing color, and determining other attributes of the represented elements are the remaining three aspects of spatial perception. In a graphical or modeled representation of a building prior to construction the texture of each material is represented by a unique symbol and color applied to represent a scheme.

After encoding the perceived spatial features, a person then creates an internal representation (Winn, 1994). The literature defines internal representations as a depiction of the object perceived in a scene combined with a person's perceptual organization of the spatial relations between objects in the scene (Pani et al., 2005). Internal representations resulting from perception are surface level only and contain no additional information about the properties of the perceived object (Schnotz & Bannert, 2003). For example, a person perceives the front of a house and encodes the house features such as, bottom of wall, roof shape, window locations, and color. The person then combines the features of the house with their internal knowledge about the world to create a visual image (Schnotz & Bannert, 2003). The house depicted in the mental image however only includes surface level perceptions and it is void of other properties about the spatial features, such as the wall thickness or the 3D geometry of the roof (Schnotz & Bannert, 2003). Although spatial perception does not include detailed information about the object, it does rely on a person's internal knowledge about the world to create a mental image.   A study (Velez et al., 2005) investigating factors that have an effect on the formation of mental images revealed two results particularly relevant to this review. The first result indicated that the point from which a person is viewing an object has an effect. The second is that the complexity of the object being perceived matters.

The second element on the continuum of spatial ability is transformation. Transformations are best described as manipulations performed on mental representations of spatial features of objects captured through spatial perception of the world (National Research Council, 2006). According to the NRC (2006) report, examples of transformations are: changing perspective, changing orientation, transforming shapes, changing size, moving wholes, reconfiguring parts, zooming in or out, enacting, and panning.

Transformation is a sub-process of spatial ability that is present as an individual characteristic and may be enacted when needed and as often as needed (National Research Council, 2006). In the process of solving a spatial problem transformations may be necessary at the beginning while identifying the problem and once again as part of an individual's evaluation after creating a mental model of the problem and solution. For example, if given graphical or modeled representations of a building from a single point of view an individual in the construction domain must be able to transform the external representations to a different point of view to gain more information about the building for logistics planning and sequencing of building elements. On most occasions this will require multiple transformations to identify a solution and evaluate the solution. Therefore transformations are included as a component in Stage 1 and Stage 3 of the ill-structured spatial problem solving process.

The most common transformation in the literature is mental rotation which is defined as a mental operation for the reorientation of a perceived object (Cohen & Kubovy, 1993). The task of mentally rotating an object is performed during the imagining process, or visualization, of what an object would look like from a different view or to determine if an object will fit within a certain space (National Research Council, 2006; Rock, Wheeler, & Tudor, 1989; Shepard & Metzler, 1971; Vandeberg & Kuse, 1979). Rotations may differ in complexity and be executed based on cognitive strategies unique to individuals. For example rotations may be performed as sets of points in which an object rotates around a fixed single axis or rotations may be a continuous change of an object's slant direction in a circle around an axis (Pani et al., 2005). Other studies (Rock et al., 1989) have investigated if rotations may be done by an individual imagining themselves moving around the perceived object.

Results from the early research of Shepard (1982) about mental rotation revealed that a person's skill in performing mental rotation correlates with their performance on complex spatial reasoning tasks.   The ability to mentally rotate a 2D object into a 3D object is an example of the type of mental rotation needed in spatial domains such as architecture, engineering, construction, and geosciences. Other studies since Shepard's first research about mental rotation (Shepard & Metzler, 1971) have investigated the question of whether someone can imagine how a perceived object will look from a viewpoint other than the original view, have had contradictory results about this ability (Rock et al., 1989).

Visualization is the third and perhaps the most commonly investigated and discussed element of spatial ability. In his review of the early literature about spatial abilities, McGee (McGee, 1979) discovered the most common definition of visualization as an imagining process in which other spatial abilities are relied upon to support visualization. Another definition of visualization is that it is an individual's ability to imagine how an object looks in a different view or moving in space (National

Research Council, 2006). More recently the phenomenon of visualization was described as form of sensorimotor reasoning comprised of an individual's beliefs about the way perceived visual scenes unfold (Langland-Hassan, 2011). Visualization is an analog imagery process that is useful for simple problems however results from an investigation of spatial thinking in mechanics, medicine, and chemistry revealed that professionals augment visualization with more analytic processes when faced with complex real world problems (Hegarty, 2010). Analytic processes for solving ill-structured problems are discussed in detail in the section about mental models later in this review.

A study designed to demonstrate the relationship between problem solving and spatial abilities focused on the relationship between participants' performance on spatial ability tests and solving domain specific problems (Kozhevnikov, Motes, & Hegarty, 2007). In their study Kozhevnikov et al. (2007) found a significant correlation between visualization, a component of spatial ability, and the overall accuracy of solutions to the domain specific problems. Based on their results, the researchers speculated that high spatial ability may enhance an individual's ability to understand domain specific concepts and principles (Kozhevnikov et al., 2007). What is unclear however is the role of spatial skills and its influence on spatial abilities. These results only further the need to investigate if spatial abilities alone contribute to solving spatial problems or if other components of spatial thinking contribute as well.

Additionally it is unclear in the spatial ability and problem solving literature exactly how one's efficacy about their spatial ability influences their spatial skill development and their application of skills in the problem solving process. For example, if an individual attributes their spatial ability as an acquirable skill that can be improved through increased domain knowledge and competencies then they are more likely to pursue the challenge of an ill-structured spatial problem. In contrast if one considers their spatial ability as an inherent capacity then they will more likely attribute their performance to their inherent intellectual ability and have a negative impact on their effort to pursue the challenge of an ill-structured spatial problem (Bandura, 1993).

Spatial Skills

As discussed in the section above about spatial abilities, many authors do not distinguish between spatial ability and spatial skill; however, they should not be treated as interchangeable but rather as interrelated. In fact, spatial ability is actually a component of an individual's spatial skills (National Research Council, 2006). The distinguishing characteristic between the two is that spatial abilities are general whereas spatial skills are the result of applying one's spatial abilities in a given context. The NRC (National Research Council, 2006) defines spatial skills as cognitive skills that are learned within a specific context and are supported by tools and technologies. As a result the cognitive skills learned are domain specific and expand on an individual's spatial abilities. This is an important distinction for educators to consider when designing instruction to teach spatial thinking.

Spatial skills are cognitive skills associated with an individual's ability to retrieve, retain, and transform visual information about a spatial context (Velez et al., 2005). As a result of the link between spatial skills and context it is reasonable to conclude that instruction should be designed with spatial elements and spatial problems germane to the domain of study. Based on the results from a 2006 study conclusions were made that when an individual learns about spatial aspects in a particular domain their spatial skills develop in terms of their 1) declarative knowledge about space, 2) perceptual knowledge about space, and 3) cognitive operations.

In summary, it remains unclear based on the literature as to how each component of spatial thinking – spatial abilities, spatial skills, domain knowledge, and real-world domain experience - influences an individual's ability to create representations for the purpose of solving spatial problems. Given the definition of spatial intelligence by Hegarty (2010), the literature supports spatial thinking as the means by which an individual creates a visualization of a situation, however visualization is only one subcomponent in spatial abilities and it is not enough to solve an ill-structured spatial problem. Visualization must be backed up by an independent representation of the problem in which abstract information about the situation is also included (Johnson-Laird, 1998). Combining a visualization with abstract information about the given situation is the foundation necessary to generate a spatial based mental model. Mental models and their application to solving ill-structured spatial problems are discussed in more detail later in this chapter.

Domain Knowledge

According to the National Research Council (2006), visualization is a spatial ability in which an individual creates a mental representation of a situation as an aid for use in solving domain specific problems. Domain knowledge is important and contributes to creating an accurate problem representation. Domain knowledge is something that is built over time through practice and experience (National Research Council, 2006). Students in spatial domains acquire knowledge from the classroom and practice problems, which is then supplanted with real-world domain experience. Knowledge about a domain includes specific propositional information, concepts, rules, and principles (Jonassen, 1997). According to Johnson-Laird (1998), individuals build mental models based on their understanding of concepts relevant to the situation which ultimately depends on their tacit domain specific conceptual knowledge. Mental models and their components are discussed in detail later in this review; however, suffice it to say at this point that if someone lacks domain specific conceptual knowledge they will be unable to generate a mental model of the situation. Because ill-structured problems are domain specific, knowledge and real-world domain experience play a major role in an individual's ability to successfully solve domain specific problems (D. Jonassen, 1997).

When tasked with solving an ill-structured spatial based problem in a recent study (McCuen & Ge, 2013a, 2013b) participants reported that drawing from the concepts and principles learned about the topic in the classroom aided in their ability to reason about the problem; however, they could not visualize alternative solutions because they had not seen the problem in a real-world context. Generalizing the reports by novice participants leads to the conclusion that domain knowledge and real world experience are essential in their creation of mental representations to use as an aid in the problem solving process.

Real-World Domain Experience

In an investigation about the possible effects of real-world domain experience on individual's ability to imagine the spatial relationship between two points, a study by Intons-Peterson and Roskos-Ewoldsen (1989) revealed that participants' real-world experience with the objects in the study had a significant impact on the study's outcomes. For example, a participant's familiarity with the weight or color of an object effected the mental images created of that object. In another study, researchers interviewed the participants about their internal and external representation techniques used to solve an ill-structured problem, which revealed a relationship between their ability to apply spatial skills and their previous real-world experience in the domain to solve the given problem (McCuen & Ge, 2013a, 2013b).

In a two-year study investigating how individual experiences and prior knowledge influence a construction science students' ability to visually represent problems internally and externally to solve spatial problems found that novices associate their ability directly to what they have experienced in the domain (McCuen & Ge, 2013a, 2013b). One participant, Mel, had two years of real-world experience reported regularly using external representations to communicate a problem and its solution to others. He described how his real-world experience had influenced his representations:

> I just draw on my experience. I was always someone who understood how systems and things went together. Ever since I was a little kid…you know when I would see something work out or how something goes together I would expand on that and understand how other things might go with it.." (McCuen & Ge, 2013b, p. 322).

Findings from interviews with novices in another study (McCuen & Ge, 2013b) also indicated that the majority of participants attributed their ability to generate some type of mental representation of the problem to their real-world experience in the domain. Evident from the reports by participants in these two studies is the importance of experience to solving ill-structured spatial problems. The fact that the participants' real-world experience impacted their ability to represent the problem aligns with the first step in the process to solve ill-structured problems. As discussed in the problem solving section of this review, the first step is articulation of the problem space and contextual constraints which is accomplished by the problem solver determination of what the nature of the problem is within the context from which the problem emerged (Jonassen, 1997).

Additionally, the findings contribute to a conclusion that self-efficacy about one's ability to solve the problem at hand is related to their personal accomplishments afforded through real-world domain experience.

Self-efficacy

In an exploratory qualitative study completed by McCuen and Ge (2013a, 2013b), construction science students revealed participants' beliefs about their ability to successfully perform spatial-based tasks was related to their domain knowledge and real-world domain experience. Participants with lesser amounts of real-world domain experience believed they lacked spatial ability because of it, and therefore did not perform well on the spatial tasks.

A meta-analysis of self-efficacy research (Multon, Brown, & Lent, 1991) revealed evidence of a relationship between one's self-efficacy beliefs and their academic performance and persistence. The study showed that a student's self-efficacy beliefs account for approximately 14% of the variance in academic performance and 12% of variance in academic persistence. According to Bandura (1977) an individual draws from their performance accomplishments in one area to transfer efficacy about their ability to perform successfully on similar tasks and similar situations.

The prior research (Merchant et al., 2012) about spatial ability and self-efficacy has revealed relationships and how the two variables influence student learning and performance related to problem solving tasks. In a study investigating relationships between perceptual and psychological processes in the spatial domain of chemistry, the relationship between chemistry learning, presence, self-efficacy, usability, and 3D virtual reality features were tested. Results revealed a significant positive relationship between spatial orientation, self-efficacy, and students' performance on chemistry learning test (Merchant et al., 2012). Another study also found a significant correlation between an engineering student's self-efficacy and their spatial ability based on a self-efficacy test developed and utilized to compare with the student's performance on a spatial ability test (Towle et al., 2005). Whereas Ackerman, Kanfer, and Goff (1995) research offered an integrated perspective with links between personality dimensions and performance criteria. Results revealed performance measures in tasks, including spatial abilities, were moderately to highly correlated with self-concept and self-estimates of ability which in turn had a direct effect on task self-efficacy (Phillip L. Ackerman et al., 1995).

Based on the prior research, self-efficacy is expected to influence spatial problem solving; however, the relationship between self-efficacy, real-world experience, and spatial skills is unclear.

Summary

Although research about the topics discussed in this review is gaining momentum, there is a lack of effort to integrate the topics as a process model for further research. A review of the literature revealed three gaps that exist both within topics and across topics. As a framework to guide research about the identified gaps, I have organized the topics by stages and propose the process model of ill-structured spatial problem solving shown in Appendix B.

The first gap is in Stage 1 where there is no clear conclusion about how each of the components, and subcomponents, in spatial thinking influence an individual's success in solving spatial problems. As mentioned at the beginning of this chapter spatial thinking is the foundation for ill-structured spatial problem solving which is essential for the success of construction science students. Given the importance of spatial thinking, the current study was dedicated to investigating the interactions among spatial ability, domain knowledge, real-world experience, self-efficacy, and spatial skill.

There is also gap with no clear conclusion about whether there is a strategy for sequencing the creation of mental models, internal representations, and external representations to improve outcomes from the spatial problem solving process. The third gap in the literature is the lack of conclusive evidence about how representations, transformations, and spatial reasoning influence an individual's ability to solve ill-structured spatial problems. The hope is that the second and third gaps were addressed and rigorous research pursued in an attempt to fill in both gaps.

The objective of the current study was to understand spatial skill as a set of skills developed in the context of a domain and dependent on the following relationship between: 1) spatial ability, 2) domain knowledge, 3) real-world domain experience, and 4) self-efficacy. In the current study spatial ability, domain knowledge, and real-world domain experience are treated as direct predictors of spatial skills. Self-efficacy is expected to intervene and mediate the relationships between each set of predictors and spatial skills. The literature reviewed in this chapter indicate that spatial skills represent the point in the ill-structured spatial problem solving process at which there is a lack of understanding about its input in the process and its relationship to a student's performance. Ultimately students must have relevant spatial skills to support them in their creation of mental models and spatial reasoning to solve complex ill-structured problems.

The first spatial skills' predictor is spatial ability which consists of visualization, spatial relations, and spatial orientation (Lohman, 1988). The use of psychometric tests to measure one's spatial ability and predict success in some categories of problem solving, technical occupations, math, engineering, and architecture courses gained popularity following the successful mass testing of World War I soldiers (Cronbach, 1970; I. M. Smith, 1964). The genesis of tests for spatial abilities can be traced back to the early work of Thurstone (1957) in which he had shown that there was a distinct difference between spatial ability and verbal ability and as such a distinction between verbal and spatial intelligence. His work also presented seven primary abilities as factors associated with visual thinking: (1) perceptual speed, (2) space visualization, (3) space rotation, (4) space relations, (5) speed of closure, (6) flexibility of closure, and (7) visual memory.

Numerous factor analytical studies have been done to investigate Thurstone's visual thinking factors. Prior studies (Cronbach, 1970; Shepard, 1982; Shepard & Metzler, 1971) have used small-scale paper and pencil tests that include graphical representations of a problem and multiple choices from which the test taker selects the correct solution. Each test is designed to measure one factor exclusively; however, there are multiple tests that measure the same factor. Preference has been for tests that correlate highly with the factor of interest. As a result of all the interest in individual differences in spatial ability, researchers expanded to investigate the factor structure of spatial ability, which revealed evidence that there are in fact several separable subcomponents of spatial ability (Lohman, 1988). The current study not only investigates the separate subcomponents of spatial ability, but it approaches spatial skill as a composition of separate subcomponents.

Domain knowledge is the second predictor and is described as the knowledge developed over time through one's practice integrating domain specific information, concepts, rules, and principles (Jonassen, 1997; National Research Council, 2006). Additionally one develops spatial declarative knowledge through domain activities that through practice and feedback (Lohman & Nichols, 1990). The current study investigated domain knowledge specifically in the categories of structural assembly and graphical representation. Both categories are fundamental to construction science and are categories for which students receive focused instruction.

The third predictor, real-world domain experience is achieved by completing domain specific tasks in the real-world context (McCuen & Ge, 2013b). The quantity and type of real-world experience within an AEC company are the two types of real-world experience investigated by this study.

Research Questions

The current study focused on the following questions:

Question 1: Is spatial ability a greater predictor of spatial skills than domain knowledge and real-world domain experience?

Question 2: Is domain knowledge a greater predictor of spatial skills than spatial ability and real-world domain experience?

Question 3: Is real-world domain experience a greater predictor of spatial skills than spatial ability and domain knowledge?

Question 4: Does self-efficacy mediate the relationship between spatial ability and spatial skills?

Question 5: Does self-efficacy mediate the relationship between domain knowledge and spatial skills?

Question 6: Does self-efficacy mediate the relationship between real-world domain experience and spatial skills?

Question 7: Is spatial ability, domain knowledge, or real-world domain experience more useful in predicting spatial skills?

A quantitative research methods study was designed to investigate the questions above and accept or reject the following hypotheses. To determine the appropriate sample size to test the hypotheses it was necessary that each hypothesis included the effect size expected as a result of testing the set of predictors. Effect size indicates the proportion of total variation in the dependent variable that is predicted from the set of independent variables, the quality of the predictor variables included in the study, and the quality of relevant predictor variables not included in the model (Cohen, 1988).

Hypothesis 1: The relationship between spatial ability and spatial skills is moderate with a medium effect compared to the relationship between spatial skills and domain knowledge or their spatial skills and real-world domain experience. A medium effect size is hypothesized based on the argument that skills are developed through practice in context and the study is designed to include context.

Hypothesis 2: The relationship between domain knowledge and spatial skills is moderate with a medium effect compared to the relationship between spatial skills and spatial ability or their real-world domain experience. A medium effect size is hypothesized based on the argument that skills are developed through practice in context and the study is designed to include context.

Hypothesis 3: The relationship between real-world domain experience and spatial skills is strong with a high effect compared to the relationship between spatial skills and a student's spatial ability or their domain knowledge. A high effect size is hypothesized based on the findings from a similar study (McCuen & Ge, 2013b) and the argument that real-world domain experience improves one's ability to create relevant mental models.

Hypothesis 4: Self-efficacy will be a partial mediating variable on the relationship between spatial ability and spatial skills.

Hypothesis 5: Self-efficacy will be a partial mediating variable on the relationship between domain knowledge and spatial skills.

Hypothesis 6: Self-efficacy will be a partial mediating variable on the relationship between real-world experience and spatial skills.

Chapter 3: Methodology

Participants

Students enrolled in accredited undergraduate construction science programs at three universities were recruited to participate in the study. Based on a priori power analysis and after considering rules of thumb concerning the minimum sample size needed for carrying out structural equation modeling (Kline, 2011), I sought to obtain a minimum sample size between 150 and 200 participants.

The typical age of students in undergraduate construction science programs ranges from 18-23 years of age; however, based on reported years of real-world domain experience it was noticed that some participants were older than this specified age range. A total of 177 undergraduate students participated in this study with 161 being male, and 16 female. The gender composition of participants is consistent with the gender composition in the industry (Sewalk & Nietfeld, 2013)

Context

The selection of universities from which to recruit students was based on the researcher's familiarity with the construction program, enrollment size, and approximate equal representation from the two types of accreditation for U.S. construction programs. It was also important to select universities with accredited programs that would provide some variety in course offerings. Moreover, the study instruments were administered in a variety of different topical courses in the construction curricula. However, the categories of topics in the study design aligned with the curriculum content standards required for accreditation by the American

Council for Construction Education (ACCE) and the Accreditation Board for Engineering and Technology (ABET).

The ACCE accreditation standards include five curriculum categories: 1) general education, 2) mathematics and science, 3) business and management, 4) construction science, and 5) construction. The ABET accreditation standard ("ABET," n.d.) requires effective development of curriculum to support student learning outcomes in three areas. The first area required by ABET is mathematics and the application of mathematics above the level of algebra and trigonometry, such as integral and differential calculus. The second area required is technical content and focus on applied aspects of science and engineering, including equipment and tools common to the discipline. The third required area of study required by ABET is physical and natural science that includes laboratory experiences appropriate to the discipline.

In both ACCE and ABET programs, the curriculum for underclassmen (i.e., freshmen and sophomores) focuses heavily on general education courses and the foundation courses necessary for the domain specific courses. Upperclassmen, juniors and seniors, have progressed into the domain specific coursework where they will apply the general education, math, science, and business course knowledge to domain specific concepts for the purpose of analysis and problem solving. Most construction education programs also require upperclassmen to complete an internship with a company in the building and construction industry. Given the distinction between the coursework and opportunity for real-world experience by upperclassmen compared to underclassmen, expectations are that both domain knowledge and real-world domain experience will have an effect on student's spatial skills.

Participants at the Mid-western state 1 university construction program were recruited from freshman level Computers in Construction course, an entry level course with instruction about spreadsheet and 3D software applications. Sophomore level participants were recruited from the Construction Documents and Quantity Surveying course, a course designed to teach print reading of 2D paper copies of building drawings. Junior students were recruited from the Project Controls Management course, which is designed for students to further understand construction controls using 2D building drawings and project information contained in descriptive text documents. Finally, senior level participants were enrolled in the program's Capstone for Construction course. In the Capstone course students utilize all forms of project documents – 2D, 3D, and text – to analyze and develop a feasible plan for the building's construction.

At the Mid-western state 2 university participants were recruited from three courses. The first course was a sophomore level Concrete Construction course in which students learn the material properties and methods for installation of concrete in different building system uses. Junior level students were recruited from the Construction Law course, a course designed to deliver instruction utilizing case studies to evaluate the impact of regulations and statutes on the industry. The third group of participants at the Mid-western state 2 university were enrolled in the Construction Capstone course. As with the Capstone course at the first university, content for this course required students utilize all forms of project documents for analysis and development of a plan to construct the building.

At the Western state university, sophomore, junior, and senior level participants were enrolled in the same Design-Build course. The course requires students to utilize project documents – 2D, 3D, and text – to prepare an interdisciplinary approach to the design and construction of the proposed building.

Procedures

The study procedures included the following four steps: (1) select instruments and validate research procedures, (2) contact course instructors for access to participant pools, (3) recruit participants, and (4) administer the study. The implementation procedures are diagrammed in Figure 7.

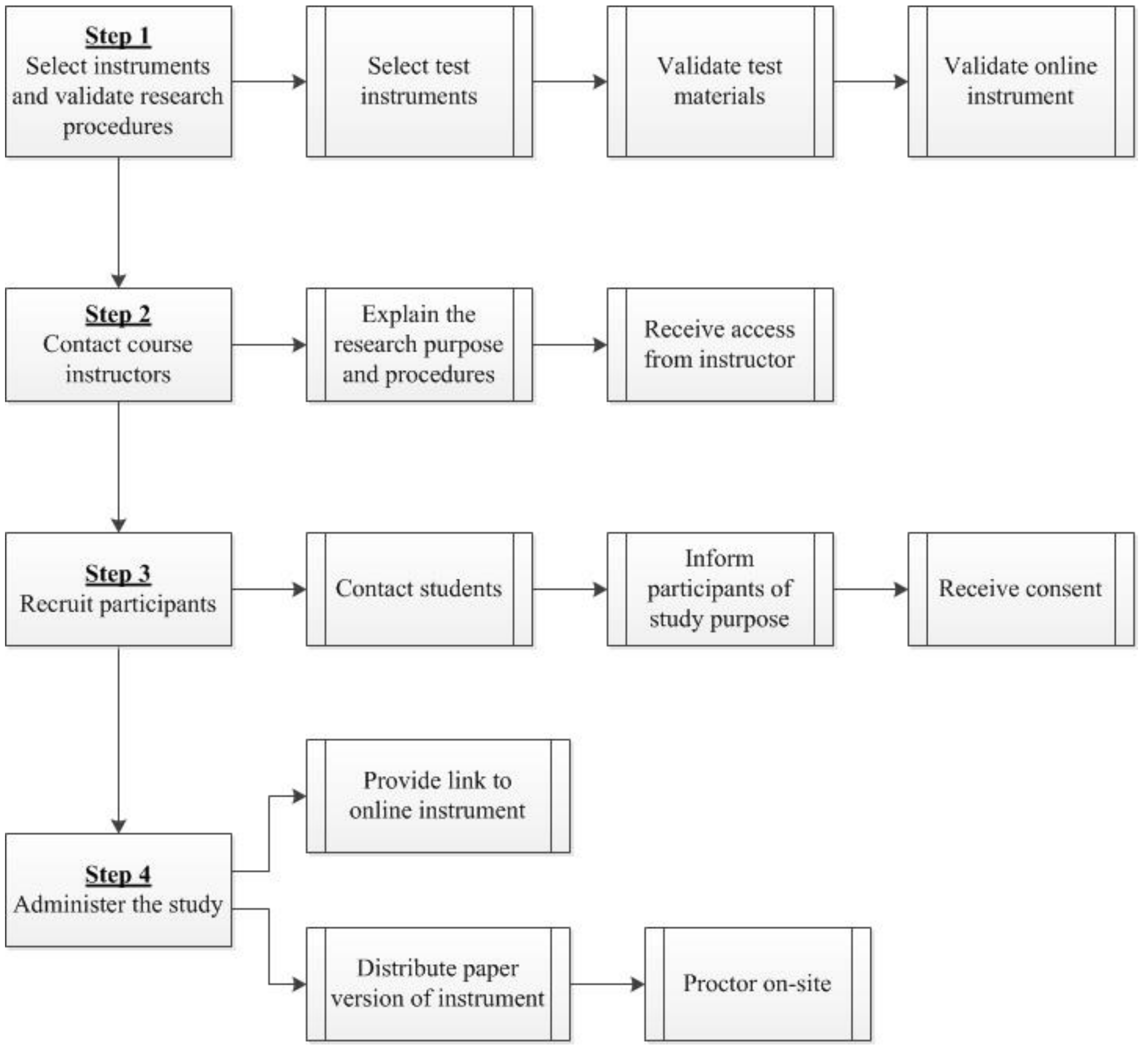


Figure 6. Study procedures

Step 1: Select instruments and validate research procedures

Instruments to test spatial ability were selected from the Educational Testing Services kit of factor referenced cognitive tests (http://www.ets.org/research/policy_research_reports/monographs/kit_of_factor_referenced_cognitive_tests). To validate the research procedures, a small group of building science students were recruited to complete the questionnaires and tests as a pilot. Masters level construction science students were recruited for the pilot. The primary purpose was to validate the research procedures and verify that the instrument's items and that the online tool would meet the study purpose and procedures. The first spatial visualization item on the spatial skills instrument was found to have an error in the answer options available. The item was immediately revised prior to administering it for the study.

Step 2: Contact course instructors

Instructors at three accredited construction/building science university programs in the U.S. were contacted and access requested to recruit students enrolled in their course during the spring 2015 semester. A brief overview of the study's purpose, tests, procedures, and an internet link to the instrument for their review was provided. Instructors were informed that if they agreed to participate they would be asked to dedicate in-class time for the principal investigator to recruit participants. Additionally, they were asked to integrate the study's participation in their course as a class activity with regular credit or extra credit given for participation to improve the rate of participation. Instructors at the Midwestern state 1 and Midwestern state 2 required participation in the study as an in-class activity. The Western state instructor offered extra credit for student participation. Instructors were also informed that they would be given a $25 gift card for providing access to recruit the students in their course.

A total of six instructors (five plus the principal investigator) allowed access to students in eight courses at three universities. All three universities were state public institutions. Two of the universities were in one mid-western state and the third was located in a western state. The instructors were asked to identify courses at each school that would provide a diverse group with a mixture of underclassmen and upperclassmen represented. Once the courses were identified, the principal investigator contacted the students for their participation.

Instructors at each site were asked to provide access to computers or require all participants to supply their personal computer with internet access to complete the online instrument. The Mid-western state 1 and the Western state universities met the computer and internet requirement; however, the instructors at the Mid-western state university did not require to students have laptop computers or have computer labs available at the course times. This site required a paper version of the study instrument and a proctor to administer the timed sections.

Step 3: Recruit participants

A brief overview of the study's purpose was provided to the students in the courses by the principal investigator seven days in advance of the date instructors agreed to the study being administered. The overview served to recruit students to participate and was done face-to-face or through Skype™. Participants were informed of the date on which the instrument would be administered in their course, and they were asked to bring their personal computer/laptop, paper, pencil, and calculator. Accommodations would be made if a participant forgot their laptop and they could borrow one or they would be given permission to complete the instrument using one of the school's desktops in the computer lab. Participants were informed that they would also be allowed to use a calculating device (cell phone, calculator, or computer); therefore, they would be expected to arrive with the device.

Additionally, students were informed that by participating in the study they would be eligible for a $25 gift card to be randomly drawn from the list of participants in each course. Students were informed that the lack of consent to participate in the study did not affect their eligibility for the gift card. All students in the courses at the mid-western schools were required to participate as an in-class activity; therefore, all were eligible for the drawing.

The name of each participant at the two mid-western sites in attendance on the study day were submitted by the instructors in a list format for the drawing. Participants at the western state site completed the online instrument as extra credit outside of class for which the instructor required a screen shot of the last page indicating completion. Participants submitted their screen shot to the course instructor who then submitted their names to the principal investigator for the drawing. The requirement for participants to submit a screen shot was the method chosen by the course instructor to verify participation for extra credit in the course. Students were informed that their participation made them eligible to be entered in the drawing for a $25 gift card to be drawn from names of participants in their course. Table 1 lists each site, student classification in the program, and the number of participants by classification.

Table 1

Participants

Site	Classification	Number of Participants
Mid-western state 1	Freshman	16
	Sophomore	21
	Junior	18
	Senior	10
Mid-western state 2	Freshman	0
	Sophomore	28
	Junior	30
	Senior	32
Western state	Freshman	0
	Sophomore	3
	Junior	4
	Senior	15

Step 4: Administer the study

Paper and pencils were provided for participants arriving to the study sites without these supplies. Participants were allowed to use any type of device for calculating purposes (cell phone, calculator, or computer). Calculators and computers were available for participants to borrow if needed at one of the mid-western universities and at the western state university.

At the designated start time of the class session at the mid-western schools students were notified to begin. At the mid-western site with computers participants were given the electronic address to access the online instrument in the Qualtrics™ survey tool. At the mid-western site using the paper version the instrument was distributed and participants were informed that the principal investigator would proctor the study due to the time limit set for each section.

The first page of the instrument provided participants with information once again about the study purpose and procedures. A consent form followed and participants were required to indicate their consent. Participants who did not consent were linked to the same questions in a different instrument to separate the data for reporting purposes. After consent the online participants started through the instrument, free to advance through sections at their own pace as long as it did not exceed the set time limit for each section. When a participant reached the time limit the instrument would automatically advance to the next section with the instructions and then begin the time clock. The principal investigator proctored the paper version of the instrument, timing each section and stopping any progress beyond the time limit. The entire class progressed through the instrument together. Participants that finished a section early were asked to sit quietly until the entire class completed the section and they advanced as a group. Participants not finished with a section when time expired were required to stop working and turn the page to the next section.

One gift card was awarded to a randomly selected participant in each course for a total of eight $25 gift cards. Additionally each of the five instructors was awarded a gift card for allowing access to their students. The intent for having gift cards associated with participation was to incentivize students and instructors to participate. It was expected that by incentivizing students to participate it would motivate them to perform their best. Offering gift cards to the instructors was expected to motivate them to agree to dedicate one hour of class time to the study, which for some was the length of an entire session.

Research Design

A structural equation model was created and path analysis was used to examine the relations between predictors and the criterion, with self-efficacy as a mediating variable between the predictors and criterion. In the design of this study, there are three predictors, or constructs (spatial ability, domain knowledge, real-world domain experience), one partial mediating variable (self-efficacy), and one dependent variable (spatial skills). The spatial ability predictor included three independent variables – spatial rotation, spatial orientation, and visualization. Modeling and visualization, bidding and estimating, and geomatics were the three independent variables for the domain knowledge predictor. The two independent variables for real-world domain experience were amount and type. A total of eight independent variables were included in this study. The partial mediating variable was self-efficacy and the dependent variable was spatial skills. The study was designed to investigate the relationships between (a) spatial ability and spatial skills; (b) domain knowledge and spatial skills; (c) real-world domain experience and spatial skills; along with (d) self-efficacy and spatial skills. The partial mediation model of the current study's design is shown in Figure 8.

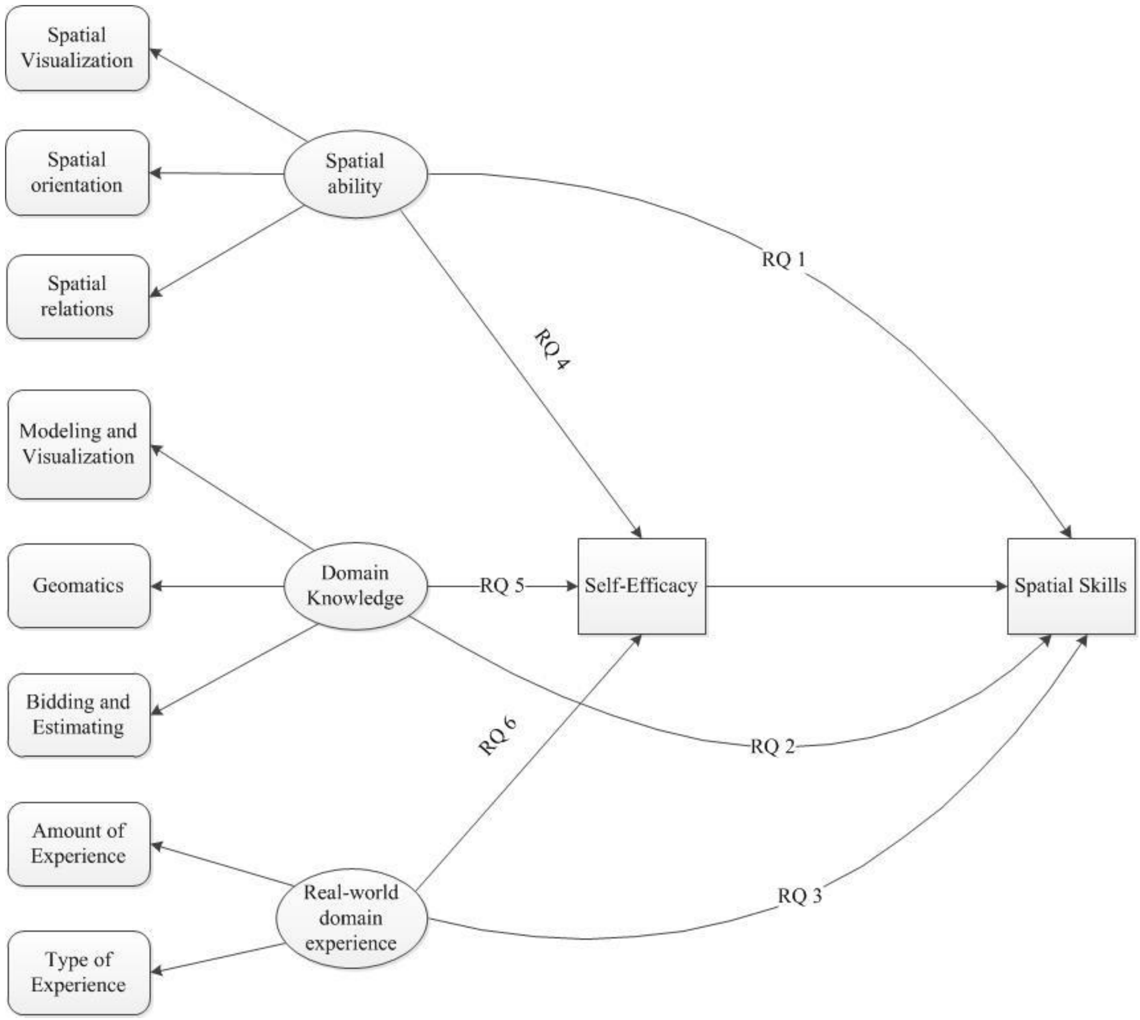


Figure 7. Partial mediation research model

Instruments

The tests of spatial ability, domain knowledge, and self-efficacy were administered to all participants. A brief questionnaire was used to gather information about the participants' real-world domain experience and general demographic information. Existing measures and instruments were used to determine a student's level of spatial ability, domain knowledge, and self-efficacy. A questionnaire and test for spatial skills measured real-world domain experience and spatial skills based on the measures described above. Scoring on the tests were classified qualitatively as low, average, or high. The quantitative score levels associated with each classification align with standard grading conventions used by many educators at U.S. institutions of higher education. A score of 80% or better was considered a high score. Scores between 60% - 79% were considered average scores. Finally, a score of 59% or less was classified as a low score.

Test items to measure domain specific spatial skills were created and required that participants apply their spatial ability, building science knowledge, and real-world domain experience to answer each item. Spatial skills items were contextualized graphical representations germane to the building domain. The current study was a non-experimental study designed to answer research questions 1 – 6 using identical questionnaires and tests for all the participants. The research questions, variables, research design, instruments, and analytical techniques are summarized in Table 2 below. The complete study instrument is available in Appendix C

Table 2

Study questions, variables, tests, and data analysis

Research Question	Variables	Tests
<u>Question 1:</u> Is spatial ability a greater predictor of spatial skills than domain knowledge and real-world domain experience?	IV1:Visualization IV2:Spatial relations IV3:Spatial orientation DV: Spatial skills	• Paper Folding test (IV1) • Card Rotation test (IV2) • Spatial Relations test (IV3) • Spatial Skills for Construction Science test (DV)

<u>Question 2:</u> Is domain knowledge a greater predictor of spatial skills than spatial ability and real-world domain knowledge?	IV1: Modeling and Visualization IV2:Bidding and Estimating IV3: Geomatics DV: Spatial skills	• Associate Constructor Level 1 – Construction Fundamental test – select items (IV1, IV2, IV3) • Spatial Skills for Construction Science test (DV)
<u>Question 3:</u> Is real world domain experience a greater predictor of spatial skills than spatial ability and domain knowledge?	IV1:Type of experience IV2: Duration of experience DV: Spatial skills	• Self-report questionnaire (IV1, IV2) • Spatial Skills for Construction Science test (DV)
<u>Question 4:</u> Does self-efficacy mediate the relationship between spatial ability and spatial skills?	IV1:Visualization IV2:Spatial relations IV3:Spatial orientation MV: Self-efficacy DV: Spatial skills	• Paper Folding test (IV1) • Card Rotation test (IV2) • Spatial Relations test (IV3) • Self-report Self-efficacy questionnaire (MV) • Spatial Skills for Construction Science test (DV)
<u>Question 5:</u> Does self-efficacy mediate the relationship between domain knowledge and spatial skills?	IV1: Modeling and Visualization IV2: Bidding and Estimating IV3: Geomatics MV: Self-efficacy DV: Spatial skills	• Associate Constructor Level 1 – Construction Fundamental test – select items (IV1, IV2, IV3) • Self-report Self-efficacy questionnaire (MV) • Spatial Skills for Construction Science test (DV)

<u>Question 6:</u> Does self-efficacy mediate the relationship between real-world domain experience and spatial skills?	IV1:Type of Experience IV2:Duration of experience	• Self – report Real-World Domain Experience questionnaire (IV1, IV2)
	MV: Self-efficacy	• Self-report Self-efficacy questionnaire (MV)
	DV: Spatial skills	• Spatial Skills for Construction Science test (DV)
<u>Question 7:</u> Is spatial ability, domain knowledge, or real-world domain experience more useful in predicting spatial skills?	IV1:Spatial ability	• Paper Folding test , Card Rotation test, Spatial Relations test (IV1)
	IV2:Domain knowledge	• Associate Constructor Level 1 – Construction Fundamental test (IV2)
	IV3: Real-world domain experience	• Self – report Real-World Domain Experience questionnaire (IV3)
	DV: Spatial skills	• Spatial Skills for Construction Science test (DV)

Table 3 provides an overview of the study instruments organized into five sections, including each questionnaire or test name, the time allotted to complete the section, and general purpose of the questionnaire or test. Summing up the amount of time dedicated to each section, it was estimated that a total time of 59 minutes was required for participants to complete the study instruments. The time allowed for each test in the online instrument was controlled by the computer software. Given that maximum time allowed for each test or questionnaire was set and that participants were prohibited from returning to a previous section, no one exceeded the 59-minute time frame.

Table 3

Survey/test, time sequence, and purposes for each

Section	Survey/Test Name	Time	Purpose
1	Self-efficacy instructions Pre-test self-efficacy questionnaire	1 minute 2 minutes	Collect data to measure participant's self-efficacy about spatial skills, spatial ability, domain knowledge, and real-world domain experience.
2	Spatial skills instructions Spatial skills test	1 minute 14 minutes	Collect data about participant's spatial skills.
3	Domain knowledge instructions • Domain knowledge modeling and visualization • Domain knowledge geomatics • Domain knowledge bidding and estimating	1 minute 3 minutes 8 minutes 6 minutes	Collect data about participant's domain knowledge using items to measure each of the three domain knowledge factors selected.
4	Spatial visualization instructions • Spatial visualization – Paper Folding Test Spatial orientation instructions • Spatial orientation – Cube Comparisons Test Spatial relations instructions	1 minute 6 minutes 1 minute 6 minutes 1 minute	Collect data about participant's spatial abilities using items to measure each of the three primary spatial abilities factors.

	• Spatial relations – Card Rotations Test	6 minutes	
5	Demographics and real-world domain experience questionnaire	2 minutes	Collect general demographic data and data about the participant’s amount and type of real-world domain experience
	Total time required to complete all instruments	**59 minutes**	

Self-efficacy Instrument

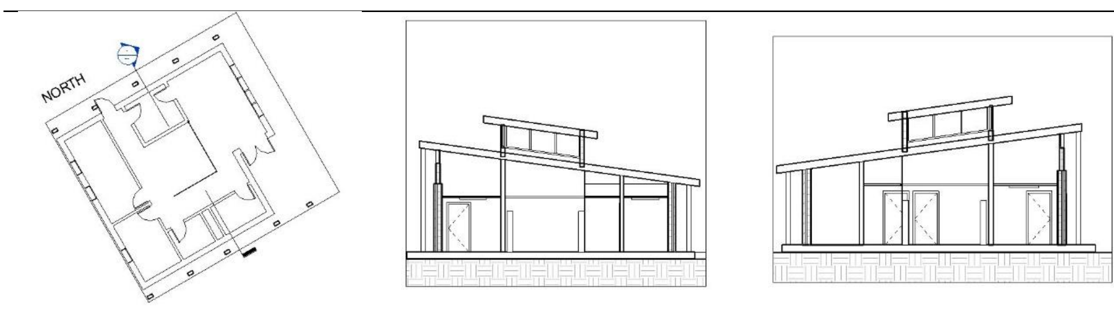
Section 1 of the current study’s instrument consisted of a 16 item self-efficacy Likert-type questionnaire about how confident they were in their ability to successfully solve a problem that requires spatial skills. The items in this section of the instrument were adapted from Bandura’s self-efficacy measures of efficacy expectations (Bandura, 1977) which have consistently shown reliability and validity between .70 and .89 (Multon et al., 1991).

Participants were asked a question such as *“How confident are you in your ability to rotate a building from a 2D plan view into a 3D view?”* A scale of 1 to 10 was intended to measure each participant’s confidence with 1 being “certain I cannot”, 5 was “moderately certain I can”, and 10 was “certain I can”. The items in section 1 were adapted from Bandura’s measures of self-efficacy (Bandura, 1977, 1993). Self-efficacy was measured prior to any of the tests in the hope that the results would be more likely to reflect a participant’s true confidence before worrying about how they had performed on the tests.

Spatial Skills Instrument

The second section of the instruments included nine items designed to measure spatial skills. Items in this section were designed specifically for the current study and paralleled the factors measured by the legacy tests in in Section 3, specifically spatial visualization, spatial orientation, and spatial rotation. Given the measure of spatial skills was developed for this study, no there is no prior information about the reliability or validity of this measure.

Although the items in this section were developed based on the items in Section 3, items in this section were contextualized and designed to reflect the construction science domain. A spatial visualization item from Section 2 is shown in Figure 9. An example of the question item was "*Given the floor plan with the section cut below, decide whether image A or image B represents the section view from the west looking east in the building. Select A if image A represents the section from the west looking east or select image B if image B represents the section view from the west looking east.* To be successful participants had to combine 1) spatial ability to visualize the correct 3D image from the given 2D image; 2) domain specific graphical knowledge, and 3) real-world domain experience about building elements to complete each task.



Floor Plan | Image A | Image B

Figure 8. Example of spatial skills item

Domain Knowledge Instrument

Section 3 tested participants' domain knowledge in three subsections with items extracted from three sections of a comprehensive eight hour certification exam for entry level construction graduates. The items were selected from the American Institute of Constructors (AIC) Associate Constructor (AC) or Level 1 exam. The Associate Constructor program is accredited by the American National Standards Institute (ANSI) under ANSI/ISO/IEC 17024 for Personnel Certification Bodies ("ANSI Accreditation Services," n.d.). Currently over 50 U.S. Construction Management Programs require students take the exam as part of their curriculum ("American Institute of Constructors," n.d.). The AC exam measures construction student knowledge in 10 categories. Table 4 displays the subject areas measured by the AC exam, the weight of each subject area relative to the exam score, and the number of exam questions used for the current study.

Table 4

Associated Constructor (AC) exam subjects

Subject area	Weight	Number of questions used
Communication skills	13%	0
Engineering concepts	5%	0
Management concepts	12%	0

Materials, methods, and project modeling and visualization	10%	3
Bidding and estimating	12%	4
Budgeting, costs, and cost control	12%	0
Planning, scheduling, and schedule control	12%	0
Construction safety	7%	0
Construction geomatics	2%	3
Project administration	15%	0

According to the AIC study guide the Level 1 exam objective is to measure the academic knowledge of entry-level construction professionals upon graduation. It also states that the exam includes some questions that require applied knowledge. However, the type and amount of real-world domain experience required to correctly answer the questions are basic and does not require extensive industry experience. Reliability and validity about the measures used for the AC exam are not published and when requested from AIC my request was denied. Measures were selected and utilized with AIC's permission for the current study. Reliability of measures was assumed based on the ANSI certification of the exam.

Subject areas for this study's instrument were selected deemed most relevant to spatial skills. The subject areas selected were: (1) materials, methods, and project modeling and visualization, (2) bidding and estimating, and (3) construction geomatics. Items were selected from each subject area based on the spatial representation content, and the point at which students would typically receive instruction about the item's content. As a result of the selection method used, domain knowledge items revealed a low internal consistency and should be changed for future studies.

The three subjects combine for 24% of the total items on the AC exam. With permission from the American Institute of Constructors, select items were used for the current study instrument. Each subject area and its relationship to the current study are discussed next.

The first subject area tested three items from the AC exam's testing materials, methods, and project modeling and visualization category. Items in this section were designed to measure students' ability to read and interpret the drawings and schedules of project materials and methods in architectural, civil, structural, and mechanical systems' plans. The knowledge measured in this particular subject area is essential for success in any building related discipline. The act of reading and interpreting drawings, and models, requires all three spatial ability factors. Participants were allowed three minutes to complete this section.

The construction geomatics subject, or field surveying of spatially referenced information, was the second subject area tested by the current study. Items in this subject area measured participants' ability to establish distances and elevations from established geospatial points, layout of a project based on geospatial points, and ability to interpret a topography map of the project site and surroundings. Four items were selected for the current study and participants were given eight minutes to complete the calculations and answer the questions. One item from the geomatics section was *"Given a rectangular structure that is 60'9" long by 42'6" wide, what is the diagonal* *measurement in feet and inches for squaring up the structure during layout?"*. Four multiple choice options were given to select from for the answer.

The final subject tested in this section was bidding and estimating, which focused on the entire bidding process to build a facility. Participants were given six minutes to interpret the drawings and complete the calculation necessary to answer the questions. Each question required a quick quantity takeoff of building materials and systems using project drawings or models. Items in this subsection were selected because they require all spatial ability factors to read, interpret, and calculate quantities for space represented by the drawings and models.

It was expected that participants would perform best answering the construction geomatics items given its grounding in fundamental mathematics and trigonometry. The items were designed as basic word problems with common building terminology referenced in the problem, thus limiting the domain specific knowledge required. The bidding and estimating items were expected to be the most difficult for the majority of participants below the senior level due to the complexity of the problem and understanding of bidding and estimating procedures typically introduced at the upper classmen level.

Spatial Ability Instrument

Section 4 of the instrument included three subsections, with two tests in each three subsections. The tests used in this section are all existing tests and seminal to research in the area of spatial ability. Additionally, the tests have been used numerous times to measure spatial visualization, spatial orientation, and spatial visualization. The long history of factor analytic studies of spatial ability tests provides an understanding of the measures tested (Carroll, 1993; Hegarty & Waller, 2005). Scientific study of spatial abilities began in the early 20th century and subsequently tests were created in the mid-20th century to measure different spatial abilities factors (Hegarty & Waller, 2005). Based on the literature of spatial abilities, existing measures for spatial relations, spatial orientation, and spatial visualization were selected (Cronbach, 1970; Hegarty & Waller, 2005; Lohman, 1988). The measure for spatial ability has consistently shown good reliability of between .70 and .80 on average (Guilford & Zimmerman, 1948; Lohman, 1988; Mayer & Massa, 2003). All items for the spatial ability measure are included with the entire instrument in Appendix C.

The first subsection tested spatial visualization using the Paper Folding Test ("Research: Kit of Factor-Referenced Cognitive Tests (1976 Edition)," n.d.), which included two tests with 20 items each, or 40 items total. Participants were allowed three minutes to complete each of the two sections. According to Lohman (1988) tests for spatial visualization contain the most difficult spatial tasks due to the sequencing of stimuli transformations and the complexity of stimuli used. The second test measured participants' spatial orientation using the Cube Comparisons Test ("Research: Kit of Factor-Referenced Cognitive Tests (1976 Edition)," n.d.). Lohman (1988) defined spatial orientation as the ability to imagine how a stimulus will appear from another perspective. It included two parts for which participants were allowed three minutes to answer 21 questions in each part, for a total of 42 items in six minutes. The third test was the Card Rotations Test ("Research: Kit of Factor-Referenced Cognitive Tests (1976 Edition)," n.d.), which required participants to perform speeded mental rotations of simple 2D items. Spatial relations were measured using 10 items in two parts, for a total of 20 items. Participants were allowed three minutes for each section of 10 items.

Selection of these tests was based on prior research (Hegarty & Waller, 2005) and the tests used to identify spatial ability factors in five studies considered primary works in this area of research. While the five studies include additional factors, measures, and tests, the three spatial tests selected for the current study were each used in all five studies. Ultimately the three factors identified by Lohman (1988) were used along with three of the five tests he used. The use of spatial tests for vocational prediction for occupations in spatial based domains is common, particularly in domains such as engineering and architecture (Cronbach, 1969)

Real-world Domain Experience Instrument

Section 5 included six multiple choice items about general demographic questions along with the amount and type of real-world domain experience. The items in Section 5 were questions about the participant's real-world domain experience, in particular the amount and type of experience. The complete instrument is available for review in Appendix C.

Data Analysis Strategy

My data analysis strategy involved computing Pearson's correlations in order to explore the zero-order relationships among my variables. Following, I planned to utilize path analysis to test the predictive relationships among my study variables according to my hypothesized model. Assuming my model might not exhibit a perfect fit to the data, I planned to re-specify the model based on both empirical and theoretical criteria and re-assess its fit to the data.

Kline (2011) described path analysis as a structural model for observed variables that represents hypotheses about effect priority. Correlation analysis and path analysis are utilized together as a procedure for structural equation modeling that supports the evaluation of relationships between a dependent variable and one or more independent variables. The flexibility afforded by computer programs supports structural equation modeling as one for forecasting the outcomes using psychological tests and ratings as predictors of an individual's success in an occupation or area of study (Cohen, 1988).

Data analysis for the current study required two separate processes due to 1) the different type of items and instruments in the study, and 2) because one collection site used a paper version of the instrument. The paper instrument added an extra step to convert the data in an electronic format. Figure 10 is a flow chart for the online instrument analysis process on the left and the paper instrument analysis process on the right. Both processes start with Step 1 which was the point at which the participants' submitted their responses to the questions. Within the process some sub-processes were required and are included in the discussion about each step. For the purpose of visual clarity the sub-processes are not indicated in the workflow diagram. Additionally, the workflow discussion is organized by instrument type therefore the entire online instrument process will be discussed first. A discussion about the process for the paper instrument data analysis will immediately follow.

The items on both instruments were identical and common to both processes was the need to score each test using a test key. The spatial skills test key was created by the principal investigator who also created the items. The domain knowledge tests key was based on the AC exam answers provided for the selected questions. Each of the spatial ability test keys was provided with the kit purchased from Educational Testing Services. The score for each test was then converted to a code representing the score specific to each particular test.

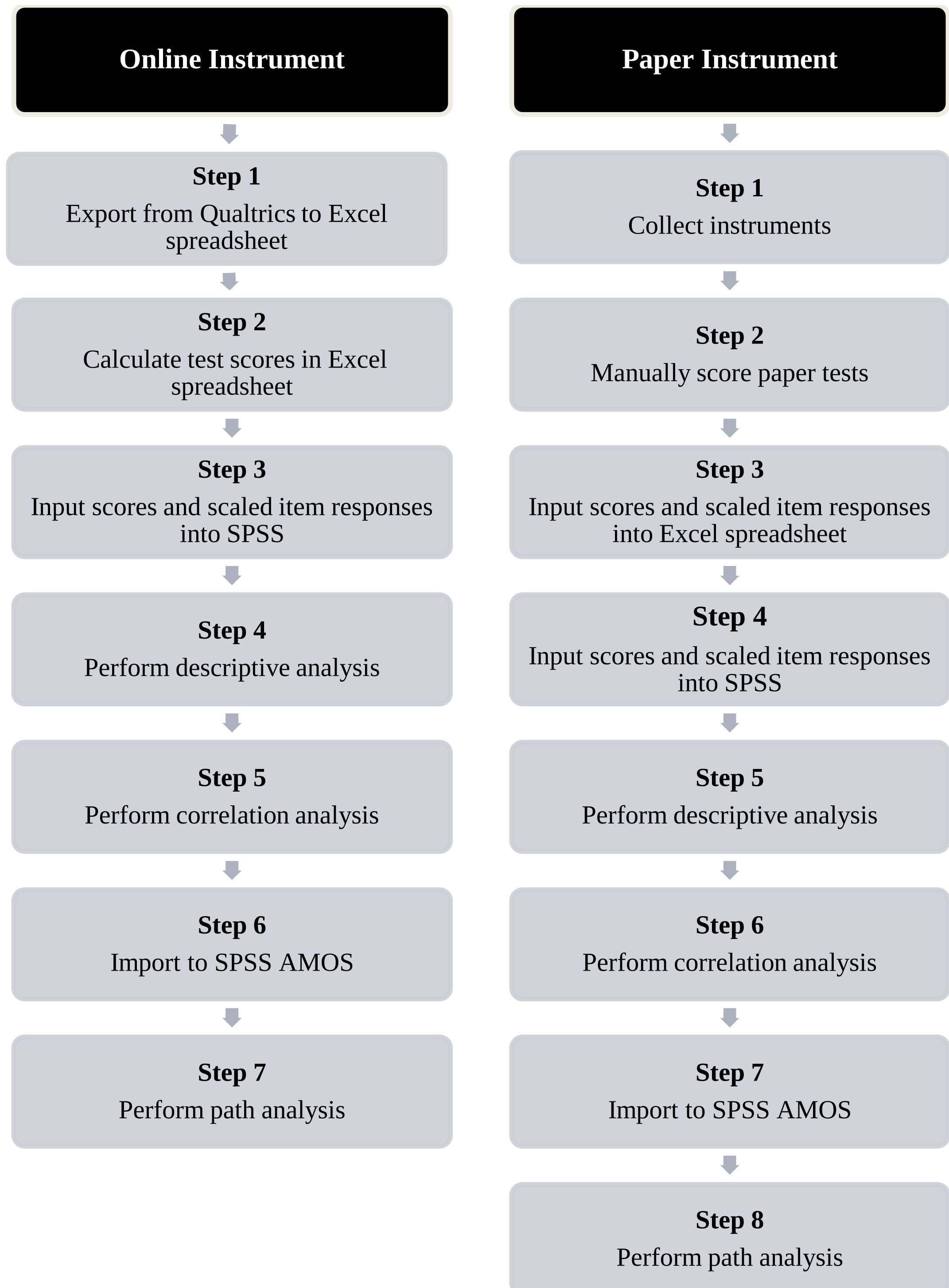


Figure 9. Administering the study for the group receiving online instruments and the group receiving the paper instrument.

Online Instruments and Paper Instruments

This section provides a general description about how the online and paper instruments were administered to the study's participants as shown in Figure 10, along with a brief description of the procedures for scoring and general data analysis. The instruments administered in each of the three settings contained identical items. However, the Qualtrics software was used to administer the online instrument. A digital timer is available as a standard feature of the software and the timer was used for each section in the online instrument. The paper version required that the researcher time each section using a stop watch. To accurately time each section, participants using the paper version were required to stop at the end of each section. As a result, participants completing the section early were required to wait for the researcher to call time for one test and then start time for the next test before the participant could advance. The difference in timing procedures between the online and paper version may have created some variance in the test results.

Qualtrics also stored the data and formatted it for export to a Microsoft Excel spreadsheet, whereas the paper version required manual input of the responses to a spreadsheet. The data was displayed by rows and columns in Excel. A row was displayed for each participant and a column displayed for each item by a primary and secondary number. An example from the Excel is shown in Table 5. The anonymous participant is identified as a unique Qualtrics generated code in the far left column. At the top the number Q115_1 represents the multiple choice options available for the answer.

Table 5

Example of response in Qualtrics

Participant	Q115_1	Q115_2	Q115_3	Q115_4	Q115_5	Q115_6	Q115_7	Q115_8
R_37wgH6P6VSQ5Znz	1	#NULL	1	#NULL	#NULL	1	1	#NULL

To better understand the relationship between the data displayed in Table 5 and the item, Figure 11 is a screen capture of question 115 with all available options for the answer shown. All test items with multiple choice answers were displayed in this manner and the data exported similar to the example in Table 5. Some multiple choice items allowed more than one choice while others allowed only one choice.

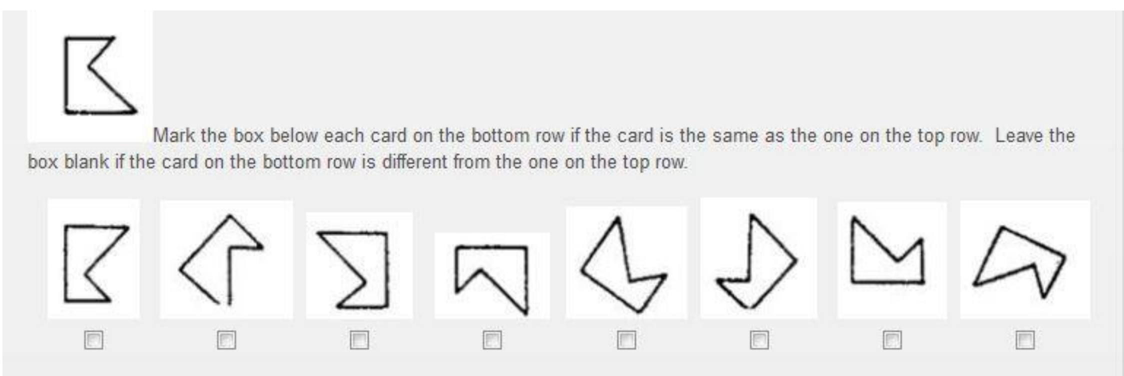


Figure 10. Example of spatial relations item

Each test was scored and input in the Excel spreadsheet as a percentage of correct answers. Scores for each test were then input into IBM SPSS Statistics 22, hereafter referred to as SPSS, file created for the current study. The responses to

Likert-type items were also input to the same SPSS file with the test scores. After scores and responses were all input to SPSS, descriptive statistics and correlation analysis were performed.

The results from the correlations were then input to SPSS AMOS and the original model was run and returned as just identified. As a result, the model was re-specified and two domain knowledge variables were trimmed leaving only the domain knowledge geomatics variable as a predictor of spatial skills. The model was re-specified to make the model consistent with the evidence which is a standard practice when using structural equation modeling (SEM) path analysis (Kline, 2011). Additionally, the value of α was set higher than the conventional value of .05 to avoid Type II error associated with false claims from not rejecting the null hypothesis in accept-support testing (Kline, 2011, p. 194). The higher α value of .10 was set prior to running the re-specified model. Consequently the second model's fit was improved.

Analysis software

Two computer software programs were used to analyze the data. First, descriptive statistics and Pearson correlations were generated using IBM SPSS Statistics 22 software. Listwise deletion was used to handle missing data in SPSS for the descriptive statistics and correlation analysis. The correlations were then used as input into a Structural Equation Model (SEM) in SPSS AMOS where path analysis was used to test the hypotheses and evaluate relationships among the variables in the model. Multiple stochastic regression imputation was used in AMOS to substitute a predicted value for any missing data.

Chapter 4 Results

The goal of this study was to investigate spatial skills as a set of skills developed in the context of a domain and dependent on the relationship between the following variables respectively: 1) spatial ability, 2) domain knowledge, 3) real-world domain experience, and 4) self-efficacy. Spatial ability, domain knowledge, and real-world domain experience were treated as direct predictors, or constructs, of spatial skills. The criterion, or dependent variable, in the model was spatial skills. Additionally, self-efficacy was expected to intervene and mediate the relationships between the three predictors and spatial skills. Figure 12 shows the initial hypothesized path model, which was created to test hypotheses and was based on the literature, prior research, and research questions focused on investigating the relationship between the model's predictors and its criterion. The arrows $\longrightarrow$ in the hypothesized model represent the direct effects from the study's hypotheses and implies that X is causally prior to Y (X affects Y), with the understanding that other causes of Y may exist (Kline, 2011)

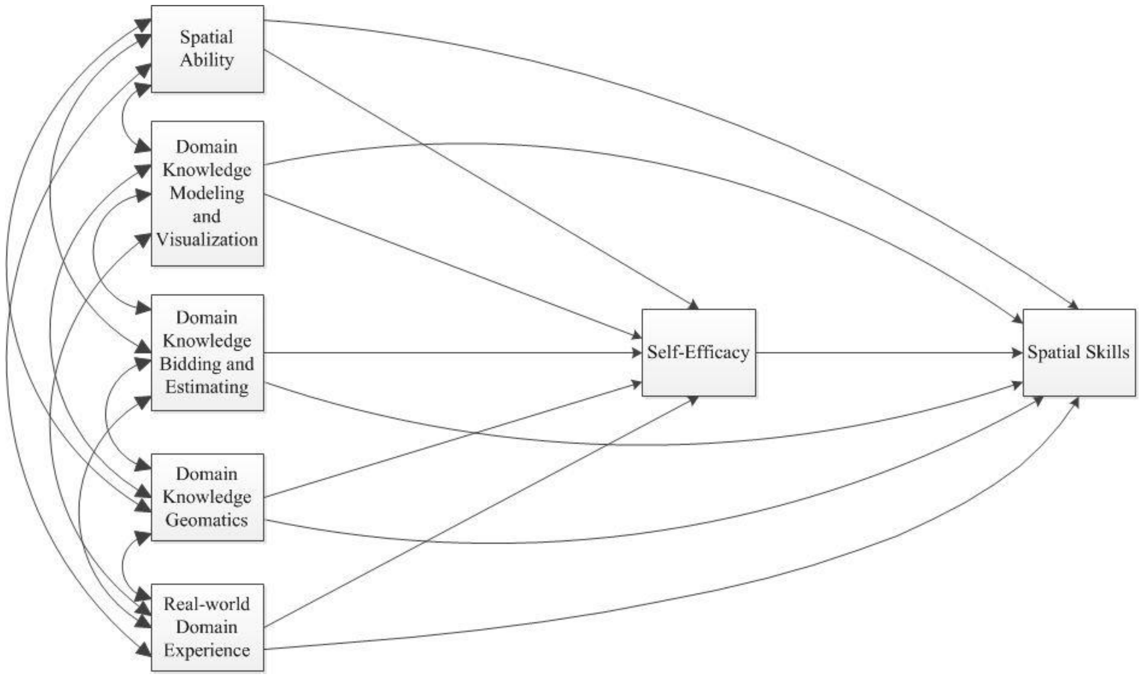


Figure 11. Initial hypothesized model

As mentioned in Chapter 3, data were collected from students at three accredited construction programs in the U.S. Two of the programs were located at mid-western state universities and one western state university. A total of 177 undergraduate students participated in the study. Results from the data analyses are reported in the following three sections. A detailed discussion about the descriptive statistics is provided in the first section. Correlations between variables are discussed in the next section. The last section discusses results from the path analysis.

Descriptive Statistics

To best evaluate the predictors of spatial skills the instrument designed for this study included seven tests and two questionnaires. As a result of the various sections in the instrument the scales used to measure the variables were different therefore a detailed discussion about the results is provided immediately following Table 6 below.

Table 6

Descriptive statistics

Measure	*M*	S.D.	Skewness	Kurtosis	Cronbach's α
Domain knowledge modeling and visualization	1.49	.93	-.16	-.86	.27
Domain knowledge geomatics	1.99	1.07	.12	-.49	.35
Domain knowledge bidding and estimating	1.06	.97	.51	-.77	.46
Spatial ability	7.54	2.55	-.35	-.04	.75
Spatial skills	6.83	1.45	-1.08	.1.96	.29
Real-world domain experience	4.30	3.49	.25	-1.39	**
Self-efficacy	7.29	1.35	-31	-.17	.96

A test was used to measure domain knowledge modeling and visualization that included three equally weighted questions based on a total possible 100 points. Participants' response to each question was either correct or incorrect and no partial credit was given. Scoring for answers was one correct answer equaled 33 points, two correct answers equaled 67 points, and three correct answers equaled 100 points. The scores then were coded as follows: 1 = 33 points, 2 = 67 points, and 3 = 100 points. The codes were then input into SPSS. If a grade was assigned to correspond with the means for domain knowledge modeling and visualization, it would reveal a score of 50% or a grade of F.

The test for domain knowledge geomatics included four equally weighted questions based on a total possible 100 points. Responses were marked as either correct or incorrect and then coded based on the number of correct answers where 1 = 25 points, 2 = 50 points, 3 = 75 points, and 4 = 100 points

Domain knowledge bidding and estimating was measured using a test with three equally weighted items for which the participants' answers were either correct or incorrect. Scores were based on the number of correct answers with 1 = 33, 2 = 67, and 3 = 100. The bidding and estimating test demands a higher level of domain knowledge and the results from this analysis reveal the lowest score of all the tests.

A total of three tests with two sections each were administered to measure spatial ability. The first test was spatial visualization with 10 questions in each of the two sections. The second spatial ability test was spatial orientation with 21 questions in each of the two sections. Spatial rotation was the third test and it included 10 questions in each of the two sections. Consistent with all test in this study, the participants' responses were scored as either correct or incorrect with all questions being equally weighted. To score the tests, the two sections in each test were combined and all questions weighted equally. Participants' answers were evaluated and the resulting scores based on the total number of questions marked correctly. Codes for the spatial visualization and spatial rotation scores were: 1 = 10, 2 = 20, 3 = 30, 4 = 40, 5 = 50, 6 = 60, 7 = 70, 8 = 80, 9 = 90, and 10 = 100. Scores for the spatial orientation test were calculated as 1 = 5, 2 = 10, 3 = 14, 4 = 19, 5 = 24, 6 = 29, 7 = 33, 8 = 38, 9 = 43, 10 = 48, 11 = 52, 12 = 57, 13 = 62, 14 = 67, 15 = 71, 16 = 76, 17 = 81, 18 = 86, 19 = 90, 20 = 95, and 21 = 100.

The scores from each section of each test were combined, resulting in a summed score for each test. The summed scores were then used to compute a total spatial ability using the Compute Variable function in SPSS. Possible scores for the new computed variable ranged from .50 to 12.83.

Nine equally weighted questions were included on the spatial skills test. As with the other tests in this study the participants' answer to each question was scored as either correct or incorrect. A participant's score reflected the number of points earned for the total number of questions answered correctly, therefore 1 = 11, 2 = 22, 3 = 33, 4 = 44, 5 = 56, 6 = 67, 7 = 78, 8 = 89, and 9 = 100. Compared to the means for the score on tests in the domain knowledge category and spatial ability category, the means of the spatial skills test represented the highest 'grade' at a mid C range.

The real-world domain experience was a self-report variable computed based on a participant's total real-world domain experience multiplied by the type of experience. Type of experience was classified as either part-time or full time and coded as 1 = part-time or 2 = full-time. Time for both categories was coded as: 1 = 1 -6 months; 2 = 7 – 12 months; 3 = 13 – 18 months; 4 = 19 – 24 months; and 5 = over 24 months of real-world domain experience.

Self-efficacy was measured using a questionnaire with 16 Likert-type items. Participants answered questions about their level of confidence performing spatial and domain knowledge based tasks. A scale of 1 to 10 was used for responses with 1 being 'Certain I cannot', 5 being 'Moderately certain I can', and 10 being 'Certain I can'. As shown in Table 6, the overall reliability estimates based on Cronbach's alpha for this questionnaire was $\alpha = .96$. This is expected given the items were adapted from Bandura's (1977, 1993) recommendations for self-efficacy measures.

Review of the participants' mean test scores revealed an overall poor performance. Although it is quite possible that the poor performance is due to a lack of knowledge and ability there are other possible explanations for this poor performance.

First reason may be due to the lack of encouragement for participants to earn the best score they could which is particularly important when ability test are administered (Cronbach, 1970). Participants were verbally instructed to perform their best, however due to the anonymity of the test no grade or other reward was given for performing well on the tests. The second reason for the poor performance may be that the participants may not have wanted to do well. A participant's desire to do well will affect their results on tests (Cronbach, 1970) and because all participants may not have the intrinsic motivation to perform well their performance may have reflected this characteristic. Participants may not have understood the test instructions due to their level of education or poorly written instructions. The only new set of instructions written for this instrument were the spatial skills test instructions; however, results indicate that this was the test on which participants performed the best, so the low performance may not be due to unclear instructions. The idea that spatial skills test instructions were poorly written may not be the only reason for poor performance. All the tests were timed and this may have contributed to their poor performance as well. Another reason for the overall poor performance may be a result of participants' lack of knowledge and ability.

Of the 177 participants in this study only 57 were classified as seniors in their respective construction science program. The domain knowledge and spatial skills tests were probably too advanced for the 16 freshmen, 52 sophomore, and 52 junior level students in the study. Expectations were that these lower level classes would perform at a lower level than the seniors due to the content of the curriculum. In particular, a lower level of performance by freshman and sophomore students because the Domain Knowledge Bidding and Estimating test, and the Geomatics test, include items that require knowledge of topics for which instruction is delivered in upper level course work for juniors and seniors. In the end the research design to include underclassmen may have been a flawed approach to assessing domain knowledge and its relationship to spatial ability for construction science students. Possible modifications to the research procedures might be to limit the participants to senior level or modify the test questions.

In addition to poor performance by participants, a review of the results in Table 6 reveals low reliability in the measures for all three of the domain knowledge tests and the spatial skills tests. The low reliability of measures may be due to one or all of the following reasons: 1) unclear or ambiguous questions; 2) participants guessing, misinterpreting questions, or fatigue; and 3) the test procedures may not have been standardized (Creswell, 2012). In this study all three reasons above are possible and the second and third reason above are highly probable. As discussed previously only 55 of the 177 participants in this study were senior level students therefore guessing answers for the domain knowledge and spatial skills questions by the other 122 participants is highly probable. Also, total time to complete the tests and associated questionnaires was approximately one hour; therefore, student fatigue is probable. Lastly, the test procedures were not standardized due to the lack of access to computers at one site with 92 participants. Expectations are that each of these factors contributed to the low reliability on the domain knowledge and spatial skills tests.

Correlations

The correlations among the variables are shown in Table 7. The data indicated that the only correlation for the variable domain knowledge modeling and visualization was with real-world domain experience and although positive, it was very weak (r =

.16, $p < .05$). The domain knowledge modeling and visualization variable did not correlate with any of the other variables in this study and was eventually trimmed from the hypothesized model in the path analysis of the data. Of the three domain knowledge tests, the modeling and visualization test contained the most basic and fundamental content and was expected to at least have some level of correlation with the other two domain knowledge tests.

The variable domain knowledge geomatics had a significant weak correlation ($r = .25$, $p < .01$) with domain knowledge bidding and estimating; self-efficacy ($r = .17$, $p < .05$); and spatial skills ($r = .21$, $p < .01$). Domain knowledge bidding and estimating had a significant weak correlation with self-efficacy ($r = .23$, $p < .01$) and real-world domain experience ($r = .22$, $p < .01$). Self-efficacy had a significant weak correlation with real-world domain experience ($r = .24$, $p < .01$) and spatial ability ($r = .18$, $p < .05$). The correlation between real-world experience and spatial ability ($r = .33$, $p < .01$), although still considered weak, it was the largest correlation between all of the variables. Intuitively this was expected but no conclusions can be drawn other than there is some low level evidence of a significant relationship between real-world domain experience and spatial ability. The variable spatial ability also had a significant weak correlation with spatial skills ($r = .27$, $p < .01$).

Table 7

Correlations of variables

	1	2	3	4	5	6	7
Domain knowledge-modeling and visualization	---						
Domain knowledge-geomatics	.10	---					
Domain knowledge bidding & estimating	.14	.25**	---				
Self-efficacy	.07	.17*	.23**	---			
Real-world domain experience	.16*	-.02	.22**	.24**	---		
Spatial ability	-.03	.09	.14	.18*	.33**	---	
Spatial skills	-.00	.21**	.03	.14	.06	.27**	----

Note, Predictor 1 = Domain Knowledge Modeling and Visualization; Predictor 2 = Domain Knowledge Geomatics; Predictor 3 = Domain Knowledge Bidding & Estimating; Predictor 4 = Self-efficacy; Predictor 5 = Real-world Domain Experience; Predictor 6 = Spatial Ability; Criterion = Spatial Skills
*p<.05, **p<.01

Overall the correlation analysis results indicate some significant, although weak, relationships between the variables in this study. Of particular interest are the significant correlations between the 1) domain knowledge geomatics predictor and the criterion spatial skills, and 2) the predictor spatial ability and the criterion spatial skills.

Path Analysis

Output from the correlations, along with the model shown in Figure 12, was then input into SPSS® Amos where maximum likelihood estimation was used to test the model and generate subsequent models. Multiple imputation was performed using stochastic regression for any missing data. It was determined that the hypothesized model was just identified with zero degrees of freedom; therefore, global fit statistics could not be computed. As a result, the non-significant paths (p >.10) between variables was trimmed to determine the most parsimonious representation of the data. The paths trimmed from the hypothesized model were 1) domain knowledge modeling and visualization to self-efficacy, 2) domain knowledge geomatics to self-efficacy, 3) self-efficacy to spatial skills, 4) domain knowledge modeling and visualization to spatial skills, 5) domain knowledge estimating and bidding to spatial skills, and 6) real-world domain experience to spatial skills. The trimmed model was then rerun in Amos.

The resulting model is a recursive parsimonious model with four degrees of freedom that includes six observed variables and two unobserved variables as shown in Figure 13. The parsimony normed fit index (PNFI) for this model was .256 achieved by trimming the hypothesized mode and rerun the data. The unobserved exogenous variables are the disturbance, or error (residual) term, and represents the unexplained variance in self-efficacy and spatial skills. The error terms represent other possible influences on self-efficacy and spatial skills that are not explained in the specified model. The error terms are designated with the symbols e1 and e2 in the model. Given the modest sample size of 177 for this study, p <. 10 was adopted for the resulting model. The significant (p <. 10) path coefficients between the retained variables are shown in Figure 13. The resulting model shown illustrates the relationships between the hypothesized predictors and criterion as well as the effect size each predictor has on the criterions.

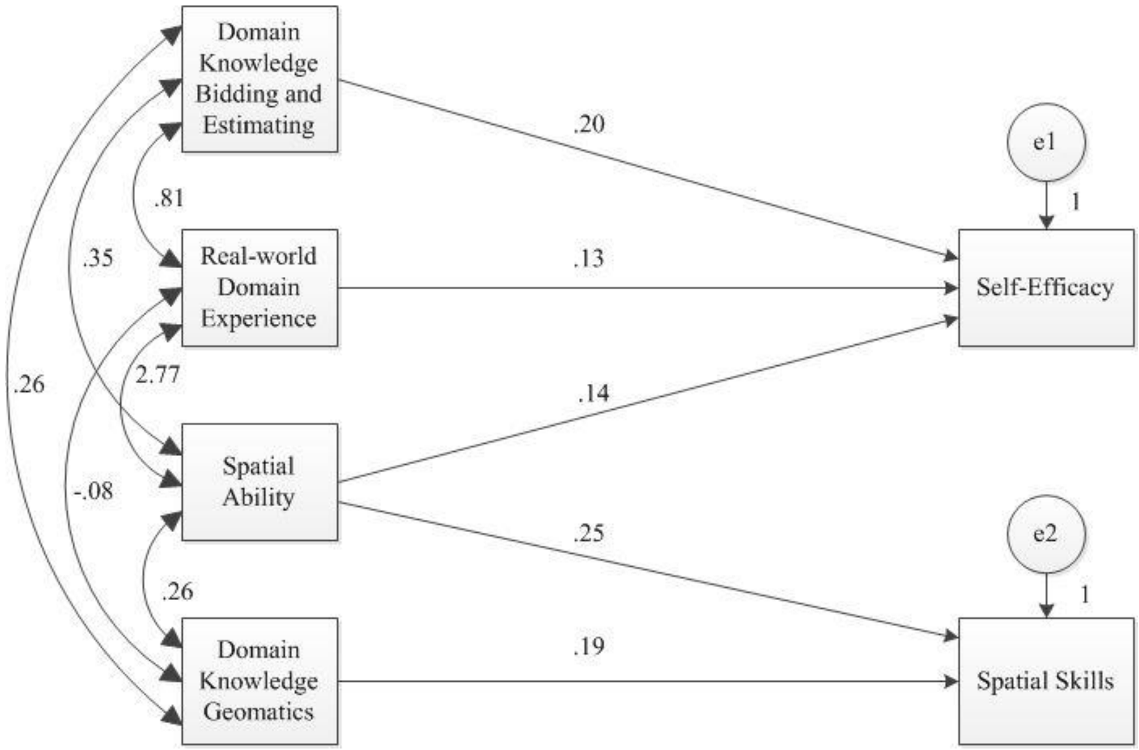


Figure 12. Resulting study model

The resulting exogenous variables are 1) domain knowledge bidding and estimating, 2) real-world domain experience, 3) spatial ability, and 4) domain knowledge geomatics. The hypothesized model included only one endogenous variable, spatial skills. Analysis of the data and subsequent trimming of the original model resulted in two endogenous variables for the final model, self-efficacy and spatial skills. The fact that the analysis resulted in self-efficacy as an endogenous variable was not hypothesized, it is an interesting result that is consistent with the findings from interviews with construction sciences in prior research (McCuen & Ge, 2013b).

The resulting model fit was good as indicated by the fit indices shown in Table 8 below. Interpretation of the fit indices was done with an understanding that no set of fit statistics is definitive and they come with a distinct set of limitations as described by Kline (2011). The first limitation is due to the value of fit statistics is an overall fit; therefore, some parts of the model may actually be a poor fit because the fit statistics consolidates many discrepancies into a single measure. The second limitation is in the fact that a single fit statistic may show a good fit reflects only one aspect of fit and must be viewed accordingly. The third limitation is that inspecting the values of fit statistics tells little about where the model may depart from the data because the direct relationship between values of fit and degree or type of misspecification is minimal. The fourth limitation is that limitation the predictive power of a model is not reflected in the fit statistics, but rather is relatively independent characteristics of a model. The fifth limitation is perhaps the most important in that a good fit does not necessarily mean the results are meaningful (Kline, 2011, p. 193). Model fit cannot be determined by a single index; therefore, five fit indices are reported in Table 8.

Table 8

Fit indices of resulting model

Model	*df*	χ^2	p	GFI	CFI	RMSEA	RMR
Resulting Model	4	3.409	.492	.966	1.00	.00	.07

The first model fit index shown in the table is the model chi-square (χ^2) statistic, which although it is considered to be the basic test for model fit, it may be more appropriate to call it a measure of badness-of-fit (Kline, 2011; Shumaker & Lomax, 2010). The goal is for a non-significant χ^2, and, with the resulting model's p = .492, this goal was achieved. Overall χ^2 = 3.409 (p = .492) indicates that the model is consistent with the covariance data, more specifically that the sample variance-covariance and the theoretical variance-covariance matrices are consistent. The next fit indexes reported are the goodness of fit (GFI) and comparative fit index (CFI). Although the two indexes measure fit, the GFI is an absolute fit index and the CFI an incremental fit index. The GFI estimates the amount of covariance in the sample data matrix explained by the model.

The CFI is explained as an index that measures the relative improvement in fit of the resulting model over the independence model (Shumaker & Lomax, 2010). The CFI has been criticized in the literature, because the baseline model is used as the independence model. The baseline model assumes that there are zero covariance among observed variables which is highly improbable (Kline, 2011). A value of 1.0 indicates the best fit for both indexes. As shown in Table 8 the resulting model's indexes are GFI = .994 and CFI = 1.0, both of which fall within the range of good fit for the resulting model.

The RMSEA, or root mean square error of approximation, is a parsimony-adjusted index that is follows a noncentral chi-square distribution, and it is scaled as a badness-of-fit index for which a value of zero indicates the best fit. The RMSEA value for this study was 0 and therefore considered to be a fit. The last index shown in Table 8 is the root-mean-square residual (RMR), and it is based on covariance residuals. The acceptable level for the value of this index differs with some understanding that the value should be about zero for acceptable model fit (Kline, 2011) and others stating that there is no defined acceptable level (Shumaker & Lomax, 2010). The problem is that the RMR is computed with unstandardized variables and as result its range depends on the scales of the variables. When the scales of observed variables differ, interpretation of the RMR value can be difficult. The RMR for the resulting model in this study was .07, which may be considered less than a good fit however the scales for the observed values in this study did differ. Given the variation in scales used, the RMR value should be interpreted with caution.

As discussed in this section, after trimming the hypothesized model the resulting model fit was good. The resulting model's Chi-square and fit indices support this conclusion. No further conclusions can be drawn when there is a good fit to a model other than what is stated in this section. Given the amount of errors in the data for this study, no conclusions can be drawn from the analysis (Shumaker & Lomax, 2010). Even with minimal measurement error, a good fitting model should not be interpreted as the only model of the relationship among the variables. Other models may exist that have yet to be identified. Additionally, the direct effect of a predictor on a criterion should not be interpreted as predictor *X* causing criterion *Y* (Kline, 2011; Shumaker & Lomax, 2010).

Summary of Results

A review of the correlation coefficients and SEM path analysis revealed that there were some relationships among variables. The significant correlations between variables were all weak; however, the results indicated that the relationships were positive. Of particular interest were the correlations between 1) domain knowledge geomatics predictor and the criterion spatial skills (r = .21, p < .01,) and 2) the predictor spatial ability and the criterion spatial skills (r = .27, p < .01).

Results from the path analysis also indicate a positive weak relationship between some variables. Spatial ability had a significant direct effect of .14 on self-efficacy; real-world domain experience had a significant direct effect of .13 on self-efficacy; and the significant direct effect of domain knowledge bidding and estimating on self-efficacy was .20. Spatial ability had a .25 direct effect on spatial skills, and the direct effect of domain knowledge on spatial skills was .19. Self-efficacy emerged; however, as a second dependent variable, with no effect on the hypothesized dependent variable spatial skills. Table 2 displays the research questions of this study, variables, and analyses used for the current study.

Due to the low correlations, weak relationships between variables, and large amount of measurement errors, the current study results are inconclusive and thus the research questions cannot be answered and the hypotheses cannot be confirmed. Results from the current study are poor to marginal and initiate questions about the research design, selected measures, and the data analysis strategy used to investigate predictors of spatial skills in the domain of construction science. The discussion in Chapter 5 addresses the results and different factors that may have influenced the results.

Chapter 5 Discussion and Conclusions

The objective of the current study was to understand spatial skill as a set of skills developed in the context of a domain and interrelated with: 1) spatial ability, 2) domain knowledge, 3) real-world domain experience, and 4) self-efficacy. Although the term spatial skill is interchanged frequently with spatial ability in the literature, the current study adopted the NRC (2006) definition of spatial skills as being cognitive skills that are learned within a specific context and are supported by strategies to combine data into visualizations, tools to create visualizations, and technologies such as computer-aided visualizations. As a result, the cognitive skills learned are domain specific and expand on an individual's spatial abilities. In the current study spatial ability, domain knowledge, and real-world domain experience were examined as direct predictors of spatial skills. Self-efficacy was expected to mediate the relationships between each set of predictors and spatial skills.

After a critical review of the literature and prior research, it was evident that to understand how individuals solve spatial problems there must first be an understanding about spatial thinking. The current study focused on the lack of conclusion about how each process, and sub-process, of spatial thinking influence an individual's success in solving spatial problems. The comprehensive model shown in Appendix B represents a proposed process and the current study focused on Stage 1. In Stage 1 spatial ability, domain knowledge, and real-world experience combine and form one's spatial skills.

The current study investigated spatial ability, domain knowledge, real-world domain experience, and self-efficacy as predictors of an individual's spatial skill.

Overview of the Results

One hundred and seventy-seven undergraduate construction science students from three U.S. universities participated in the current study. The participants included 16 freshmen, 52 sophomores, 52 juniors, and 57 seniors. Of the 177 participants, 161 were male and 16 were female. The study instrument tested participants' spatial skills, spatial visualization, mental rotation, spatial orientation, modeling and visualization, geomatics, bidding and estimating. The instrument included a questionnaire about the participants' self-efficacy about applying their spatial ability, domain knowledge, and real-world experience to solve spatial problems. A questionnaire was also included for participants' to indicate the amount and type of real-world experience they had in the construction domain. Overall performance on the tests was poor, except the spatial skills test on which the students' performance was considered average by conventional U.S. academic scoring practices. The poor performance on the spatial visualization Paper Folding Test was similar to the results when previously administered to a different group of participants. The previous study results revealed an average score of 54% for freshmen and 68% for senior students, both of which are considered poor performance scores on a scale of 1 – 100 points (McCuen & Eseryel, 2012)

Within the spatial ability research there is a belief that all individuals have some level of innate spatial ability (Smith, 1964); therefore, the expectation was that all participants in this study would have utilized their innate spatial ability to perform everyday spatial based activities. It seemed reasonable to expect that participants would have applied some general spatial abilities for navigation to a location or participation in sports that require one to judge distance and location. It was also expected that participants classified as juniors or seniors would perform better than the freshmen and sophomores who have limited domain knowledge and less real-world domain experience.

Reliability and Correlation

Because the results from the correlations and reliability analyses of the current study are marginal, the results of the path analysis about the relationship among spatial ability, domain knowledge, real-world domain experience, and self-efficacy are inconclusive. Therefore, the discussion in this chapter addresses both analyses and possible reasons for the outcomes. A test's reliability is critical and a low score reliability will be detrimental subsequent analyses (Kline, 2011). Poor reliability reduces the power of tests and attenuates the effect size below the true population value and ultimately attenuates the observed correlation between two variables (Kline, 2011) influencing the results of an entire study; therefore effort is dedicated in this section to understand how the research design, study instrument, and sample influenced, or limited, this study's results. The discussion begins with a look at the reliability of the tests and questions administered for this study. Immediately following is a discussion about the correlation analyses between variables in the study. It is suspected that several factors might influence a participant's performance and consequently the reliability and correlation of tests and questionnaires.

Reliability of measures

Factors influencing test reliability are: test length, clarity of questions, standardized test administration procedures, sample homogeneity, and the participants mental and physical being (Creswell, 2012; Cronbach, 1970; de. Gruijter, & van der Kamp, 2008; Kline, 2011)

A review of the study's procedures and tests may explain some of the results related to the list of influences on performance. The reliability coefficients for both the test of spatial ability (α = .75) and the self-efficacy questionnaire (α = .96) were high. High reliability of the tests measuring spatial ability can be credited to the fact that all three tests were well established general tests that are frequently used to measure an individual's general spatial ability. All three of the spatial ability tests have been available since the mid-20th century and consequently validated with multiple confirmatory factor analyses confirming the reliability of factors and their measurement (Lohman, 1988). The same is true for the self-efficacy items that were an adaptation of items based on factors validated since conceptualized by Bandura (Bandura, 1977, 1993). Reliability coefficients for the other four tests however were low to moderate and are discussed next.

Each of the three tests for domain knowledge used in the current study instrument contained excerpts from the full length tests, which had many more items within each. The current study domain knowledge modeling and visualization test (α = .27) only had three items whereas the full length test contains 30 items. The domain knowledge geomatics (α = .35) tested participants using four of six items from the full length test. The third domain knowledge test (α = .46) assessed participants' bidding and estimating knowledge using three questions from the 36 item full length test.

Selecting only a few items from each of the domain knowledge tests may be one probable reason for the low reliability scores because there was no delineation between items and difficulty their range of difficulty. According to classical test theory longer tests are more reliable (Embretson, 2000). More items for each measure could have increased the tests reliability for the domain knowledge measures. The variation in test administration procedures may also have influenced test performance between the 90 participants tested with the paper instrument and the 87 that took the online tests. Although the two instruments were identical, the paper test required a human proctor to time the sections while the online instrument displayed a timer at the top of the screen in each section. Another possible reason for the low reliability may be attributed to the heterogeneity of participants in terms of major study classification. Because the questions used to measure domain knowledge were from a standardized test for a certification exam of construction students at the senior or post graduate level, many of the items on the tests were probably too advanced for the typical underclassmen. Finally, the 59 minutes required to complete the study's instrument could have caused fatigue and distress, especially for the underclassmen who may have been frustrated by the level of item difficulty.

Spatial skills were measured using a test for which the items were created and were never administered to a heterogeneous sample like the current study sample. The items were verified prior to the study; however, the group members were Master's level students and were expected to have the contextual spatial knowledge. The resulting Cronbach's alpha was low at .29, and similar to the domain knowledge reliability may have been due to the low number of items, the variation in test administration procedures, and the heterogeneous group of participants.

Correlation between measures

Factors influencing correlation coefficients are: correction for attenuation, level of measurement, restriction of range in data values, missing data, nonlinearity, outliers, confidence intervals, effect size, significance, sample size, and power all can play a role (de. Gruijter & van der Kamp, 2008; Shumaker & Lomax, 2010). The correlation analyses for the observed scores in the current study revealed five significant weak correlations between pairs of predictors:

- Domain knowledge bidding and estimating correlated with domain knowledge geomatics (r = .25, p < .01).
- Domain knowledge bidding and estimating correlated with self-efficacy (r = .23, p < .01).
- Domain knowledge bidding and estimating correlated with real-world domain experience (r = .22, p <. 01).
- Real-world domain experience correlated with self-efficacy (r = .24, p < .01).
- Real-world domain experience correlated with spatial ability (r = .33, p < .01).

Additionally, the correlations between two of the predictors and the criterion were weak, but significant.

- Domain knowledge geomatics correlated with spatial skills (r = .21, p < .01).
- Spatial ability correlated with spatial skills (r = .27, p < .01).

Given that three of the results listed above are the Pearson correlation coefficient between psychometric tests, they were corrected for attenuation to yield a true score correlation. Attenuation is simply the unreliable measurement error in scores; however results from correcting for attenuation is not accepted in all research and thus should be interpreted with caution. Correction for the measurement error in the three test scores was performed based on the psychometric theory assumption that observed data contain measurement error and a Pearson correlation coefficient computed with the observed score will have a different value than one computed with the true score (Cronbach, 1969; de. Gruijter, & van der Kamp, 2008; Shumaker & Lomax, 2010). To correct for measurement error, the correlation (r) between the observed scores on X (r_{xx}) and Y (r_{yy}), the Cronbach alpha coefficient for X scores, and the Cronbach alpha coefficient for Y scores were used and resulted for the new computation. Pearson correlation coefficient, corrected for attenuation (r*)

$$r*_{xy} = \frac{r_{xy}}{\sqrt{r_{xx} r_{yy}}}$$

Once corrected for attenuation the correlations improved from weak to moderate as shown below:

- Domain knowledge bidding and estimating correlated with domain knowledge geomatics (r = .63, $p < .01$).
- Domain knowledge geomatics correlated with spatial skills (r = .67, $p < .01$).
- Spatial ability correlated with spatial skills (r = .57, $p < .01$).

There were four significant weak correlations which were not corrected for attenuation because scores for the associated instruments were calculated using either a non-test or mixed measurement scale. For example, real-world had a significant weak correlation with self-efficacy; however, both were categorical measurements therefore neither were psychometric tests. The assumption of measurement error only applies to psychometric tests (de. Gruijter, & van der Kamp, 2008).

The current study used different scales across tests and questionnaires. Categorical scales were used to measure self-efficacy and real-world domain experience, while nominal scales were used for test scores. Given that the type of scale used and the range of a variables values affects the statistical analysis (Shumaker & Lomax, 2010), the variation in the level of measurement between questionnaires and tests compromised correlation coefficients. The use of the same scale across variables would certainly help with interpretation of results. Additionally, the correlations for mixed scale items could not be adjusted to correct for measurement error.

While causal relationships cannot be drawn from correlations, it is evident that some associations exist between variables in this study. Once corrected for attenuation the strongest correlation was between domain knowledge geomatics and spatial skills ($r = .67$, $p < .01$). This is not surprising because both are domain specific. Geomatics is used to test participants' knowledge about field surveying of spatially referenced information. Items measured participants' ability to establish distances and elevations from established geospatial points, layout of a project based on geospatial points, and ability to interpret a topography map of the project site and surroundings. The items required calculations using trigonometry, applying mathematical skills to construction context.

Domain knowledge bidding and estimating correlation with domain knowledge geomatics was the second strongest once corrected for attenuation with Cronbach's alpha at .63. The two variables analyzed were hypothesized as predictors of spatial skills and when adjusted revealed a moderate association. Also improving when corrected for attenuation, was the correlation between spatial ability and spatial skills ($r = .57$, $p < .01$), which aligns with the expectation that spatial ability predicts spatial skills.

Four correlations were left uncorrected. They were: 1) domain knowledge bidding and estimating with self-efficacy; 2) domain knowledge bidding and estimating with real-world domain experience; 3) real-world domain experience with self-efficacy and; 4) real-world domain experience with spatial ability. Of the remaining four correlations left uncorrected for attenuation, the strongest correlation is between real-world experience and spatial ability (r = .33, p < .01). This result is consistent with reports (McCuen & Ge, 2013a, 2013b) from student interviews in a study over two consecutive years that investigated senior level building science students' spatial abilities. Findings from the interviews revealed that the majority of students associate spatial ability with real-world experience and their performance testing spatial abilities directly attributable to their amount and type of real-world domain experience.

Path Analysis

The path analysis results provided partial support for two of the study's hypotheses. Partial support was found for spatial ability as having a direct effect on spatial skills. There was also partial support for domain knowledge geomatics as having a weak effect on spatial skills. Although weak as a direct effect, these are the same two associations discussed in the previous correlation section for which the correlations improved with correction for attenuation. Real-world experience significantly correlated with spatial skills (r = .67, p < .01), but it had no direct effect on spatial skills in the path analysis, which indicates the need to reconsider the real-world experience variable. Given that the observed correlation matrix used for the path analysis included correlations not corrected for attenuation, a reasonable conclusion is that the subsequent path analysis results were negatively affected.

Limitations of this Study

Even with its limitations there are indicators that relationships exists between the spatial skills criterion and the three predictors of spatial ability, domain knowledge, and real-world experience. As pointed out in the chapter's preceding sections, several areas exist in which the research design could be improved for future research. The lack of significant findings from the study can be attributed to the imperfect design which led to low reliability and subsequent weak correlations and direct effects.

As discussed earlier in this chapter, I believe the research design greatly influenced the results of the study. For example, although the sample was limited to a single population of construction science students, they varied greatly in their classification as a student in the major. It is expected that as students advance through the curricula their domain knowledge increases; however, the variation of participants' domain knowledge within the sample may have influenced the reliability. Test length influences reliability as students may become fatigue or frustrated due to the time and cognitive load. Additionally, the inconsistency in testing procedures may have also influenced the reliability (Shumaker & Lomax, 2010). The online instrument included a timer which was prominently displayed on the screen. The displayed timer was counting down the time remaining for the section, whereas students completing the paper version of the instrument did not have the constant reminder of the time remaining and may have failed to pace themselves to allow for completing the test. Finally, the differing levels of measurement may have also contributed also to the low reliability of the test results.

Implications for Future Research

The study design must be revisited and improved to ensure reliable data first and establish a solid foundation for subsequent analyses (Kline, 2011). As mentioned in the previous section, the first step should be to confirm the factors for domain knowledge and spatial skills are actually factors of the respective constructs. The domain knowledge factors assumed for the current study were modeling and visualization, geomatics, and bidding and estimating. The three factors tested are safe to assume as domain knowledge given their use on the ANSI certified AC exam; however, real-world experience may also be a factor of domain knowledge. There is no known research supporting real-world domain experience as a factor of domain knowledge, however there was weak correlation between the two variables and the results raise the question for further investigation. An analysis of the domain knowledge variable should be performed to determine if real-world domain experience is a factor of domain knowledge. Prior to the factor analysis, a task analysis to map domain knowledge tasks to the concepts, principles, and procedures associated with each domain knowledge task should be completed first.

The items for the spatial skills test were created based on the three factors tested by the spatial ability tests – spatial visualization, spatial orientation, and spatial rotation – contextualized to a domain specific 3D representation. It seemed reasonable to conclude that the factors would be valid; however, a factor analysis should be completed to verify the items actually measure spatial skills. Additionally, the test length should be re-examined to avoid test fatigue (Shumaker & Lomax, 2010).

Once the factors are confirmed and the tests re-examined, the sample should be narrowed within the population of construction science students from all classification levels to senior level students only. Doing so will provide a more homogeneous sample that better fits the highest level of knowledge expected for the tests. It is expected that homogeneity will lead to overall improved performance within the sample.

In regards to the study's instrument, ways to improve it would be to change the levels of measurement to a nominal scale for all tests and eliminate the self-efficacy questionnaire. Secondly, the overall instrument length should be reduced by eliminating the spatial relations test. Results from Carroll's (1993) analysis of more than 90 data sets revealed a lack of consistent evidence for the separation of the spatial relations factor from the spatial visualization factor. In fact, only 7 of the 94 data sets he examined showed evidence for separation of the two. Eliminating this test would reduce the time to complete the study instrument by seven minutes. Additionally, the lack of evidence for self-efficacy as a mediating variable warrants removal of the questionnaire and would reduce completion time by two minutes. Combined time savings by eliminating the two parts would be nine minutes.

The fact that there were inconsistent procedures for administering the current study's instrument was unexpected. For future studies the online instrument will be used exclusively. The variability in procedures is an opportunity for variance in instructions, timing, and possible errors in scoring tests.

Visualization formation is another subject for future research that was not investigated by the current study, but has surfaced through the literature review (Smith, 1964) and previous studies (McCuen & Ge, 2013a, 2013b) associated with the current study. The ability to manipulate rigid forms, mechanically or mentally, is a proven ability of visualization. Three-dimensional visualizations formation is a necessary skill for students in the architecture, engineering, and construction disciplines. However, follow-up interviews in a previous study sought to understand how senior level construction science students form a 3D visualization when given a 2D drawing. Participants were tested, scored, and interviewed about their approach and process. The findings revealed that several approaches were used, including procedural based and spatial form manipulation (McCuen & Ge 2013a). Although the study was based on participants' mental manipulation of rigid forms and similar to studies from the literature, the rigid forms were domain specific thus extending a participant's general spatial ability to include elements of domain knowledge. Visualizing a design or problem solution requires the ability to form a visualization that is situated but without a baseline form to start the process. This type of visualization is classified as dynamic or environmental, compared to static visualizations measured by paper and pencil tests (Hegarty & Waller, 2005; Smith, 1964).

Implications for Instructional Design

Visuospatial ability was identified as an important skill for success for scientific and technical occupations since the early 1900s when testing first started and used mechanical manipulation of objects (Hegarty & Waller, 2005; I. M. Smith, 1964). Mid-20th century saw testing for spatial ability evolve from mechanical manipulation to paper and pencil testing. Twenty-first century students studying in the major areas of STEM are more accustomed to digital representations of forms that can be manipulated using commercial off-the shelf (COTS) software. So while the investigation of spatial ability needs to continue, a stronger understanding of its implications for STEM education should be the focus.

Results from the current study were weak to moderate and therefore cannot be interpreted as support for any particular approach to instructional design. The results did show moderate relationships between some variables once corrected for attenuation however they should be used with caution and are not generalizable. However, results do support redesigning the instrument for further investigation. A recent meta-analysis by Uttal et al.(2013) found evidence that spatial skills are highly malleable and training for spatial skills to be effective, durable, and transferrable indicating the need for instructional design for spatial skills.

Conclusion

There is little agreement in the spatial literature about the factors and processes involved with spatial ability. The literature however does emphasize the importance of spatial ability for problem solving in spatial domains (Carter, Larussa, & Bodner, 1987; Smith, 1964; National Research Council, 2006; Wai et al., 2009). Spatial skill is a term that is present in the literature; however, it is used interchangeably with spatial ability and its use seems random. There is no evidence that the two constructs are synonymous; however, they are frequently treated as such.

Spatial research is typically designed to test spatial ability using psychometric tests that are void of domain specific symbols or references. The absence of domain references appears to contradict the literature references to skill as an individual attribute that is developed out of ability. To interchange spatial ability and spatial skill as equivalent seems presumptuous; therefore, the current study investigated spatial ability, domain knowledge, and real-world experience as predictors of spatial skill. Although results of the study did not support the hypotheses, the study took the first step to identify and investigate predictors of spatial skills. Results from the study found only partial support for spatial ability as having a direct (weak) effect on spatial skills, in addition to partial support for domain knowledge geomatics as having a weak effect on spatial skills.

The current study contributes to the advancement of spatial thinking and spatial problem solving in two ways. First, this study provides a new conceptualization of spatial skills as an amalgamation of three predictors – spatial ability, domain knowledge, and real-world experience. Second, the study highlighted gaps in the spatial skill literature accentuated by the lack of evidence about the combination of the individual characteristics required as inputs in a process that transitions from abstract general spatial ability considered innate, to applied spatial ability in domain specific contexts. Additional studies are needed to investigate factors that contribute to spatial skills and advance the research about spatial problem solving in domain specific contexts.

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Appendix A: Glossary of Terms

Construction Science – Domain that requires that professionals understand the design and spatial attributes of a building project prior to its transformation from concept to reality.

Domain knowledge – Knowledge built over time through practice and experience based on specific information, concepts, rules, and principles germane to the domain.

External representations – Depictions of objects in space such as graphs, diagrams, images, or scaled models.

Ill-structured problems - Problems that possess multiple solutions, solution paths, or no consensual agreement on the appropriate solution. They have multiple criteria for evaluating solutions, have less manipulable parameters, and have no prototypic cases.

Internal representation – Result of perception with surface level information only about the properties of the perceived object. Also referred to as a mental image or visual image.

Mental image - See internal representation.

Mental model – The representation of a problem in which the parts of the model reflects the ontology of the domain in which it is situated, representing the world as the world is perceived.

Mental rotation – Most common type of transformation performed on a perceived object.

Spatial ability – Innate capability or general characteristic about objects and the relations between objects in space.

Spatial intelligence - Adaptive spatial thinking that involves thinking about shapes, objects in space, and spatial processes using visualization techniques along with more analytic thinking processes

Spatial perception – A two-step process involving the input and configuration of objects, and the interpretation of objects based on pre-existing knowledge.

Spatial reasoning – A contextual, domain specific, cognitive process that occurs through: 1) the extraction of spatial structures using representations; 2) transformation of representations; 3) functional inferences drawn based on temporal sequences and cause-and-effect relationships.

Spatial skills – Developed spatial abilities within a context through practice and application.

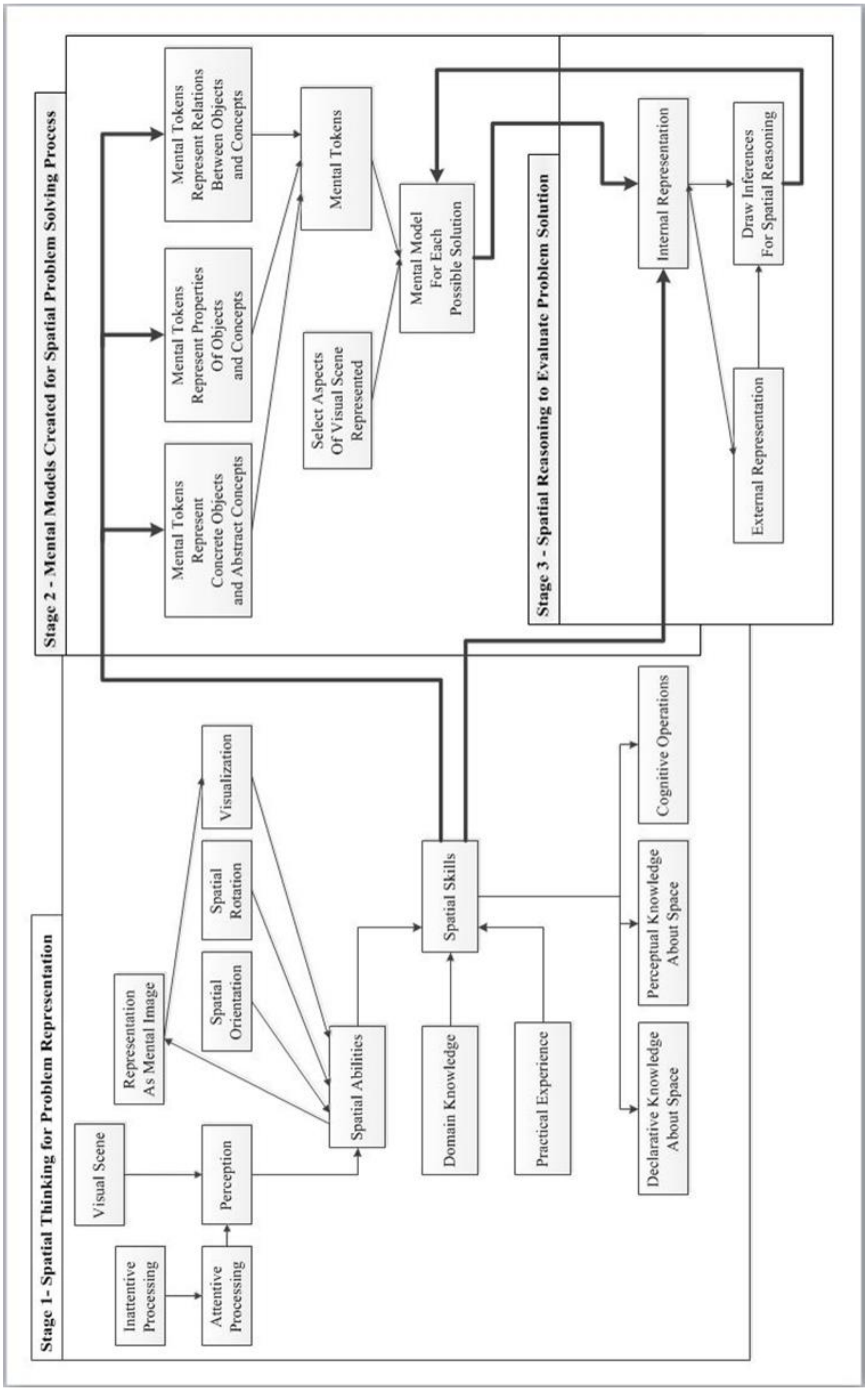
Spatial thinking – Conceptualized as the compilation of spatial ability, spatial skill, domain knowledge, and real-world domain experience, applied to domain specific problems.

Transformations – Manipulations performed on internal representations of spatial features of objects.

Visual image – see internal representation.

Visualization – An imagining process of how an object looks in a different view or moving in space.

Appendix B: Ill-Structured Spatial Problem Solving Process



Appendix C: Study Instruments

You are being asked to volunteer for this research study. This study is being conducted at the University of Oklahoma, Oklahoma State University, and Fresno State University. You were selected as a possible participant because you are an undergraduate student in the construction program at one of the universities listed.
Please read this form and ask any questions that you may have before agreeing to take part in this study.

Purpose of the Research Study: **The purpose of this study is to investigate spatial skills as a set of skills dependent on the relationship between spatial ability, construction knowledge, and real-world construction experience.**

Number of Participants: **About 150 people will take part in this study.**

Procedures: **If you agree to be in this study, you will be asked to complete an online survey comprised of 4 tests and 2 questionnaires.**

Length of Participation: The survey will take approximately 1 hour to complete.

Risks of being in the study are: **There are no known risks associated with participation in this study.**

Benefits of being in the study are: **There are no known benefits associated with participation in this study**

Compensation: You will not be reimbursed for your time and participation in this study however you will be eligible to receive a $25.00 gift card. The gift card will be awarded through a random drawing of participants at each study site. Names of participants will be submitted to the principal investigator by the course instructor.

Confidentiality: **In published reports, there will be no information included that will make it possible to identify you. Research records will be stored securely and only approved researchers will have access to the records.**

Voluntary Nature of the Study: **Participation in this study is voluntary. If you withdraw or decline participation, you will not be penalized or lose benefits or services unrelated to the study. If you decide to participate, you may decline to answer any question and may choose to withdraw at any time.**

Contacts and Questions: **If you have concerns or complaints about the research, the researcher(s) conducting this study can be contacted. Tamera McCuen can be contacted by phone at either 405-325-4131 or by email at tammymccuen@ou.edu. Dr. Xun Ge can be contacted at 405-325-8418 or by email at xge@ou.edu. Contact the researcher(s) if you have questions, or if you have experienced a research-related injury.**

If you have any questions about your rights as a research participant, concerns, or complaints about the research

Questionnaire

Section Description and Instructions:
This section is designed to get an idea of how confident or certain you are about being able to successfully complete tasks in the areas of spatial ability, spatial skills, general construction knowledge, and real-world construction tasks. **There are a total of 16 questions in this section** for which you will select an answer from a scale of 1 to 10 based on your confidence level. The scale rates your confidence to complete a task at the current point in time with 1 being 'Certain I cannot' and increasing incrementally to 5 being "Moderately certain I can", and 10 being 'Certain I can'.

Just to make sure that you understand how this rating scale works here is an example:

If you were asked how confident you are that you could pick up a ball that weighed 1 pound you would probably be 100% confident that you could do it and would select 10. If you were asked how confident you are that you could pick up a ball that weighed 1000 pounds you would probably be 100% confident that you could not do it and would select 1.

Following are 16 questions about your confidence to complete certain tasks. There is no right or wrong answer. Please answer based on your confidence at this point in time.

How confident are you in your ability to compare a 2D object that has been rotated from its original position to several different positions and then identify the rotated objects that are not the same as the original object?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
○	○	○	○	○	○	○	○	○	○

How confident are you in your ability to compare a series of 3D objects and determine if each object is the same object?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
○	○	○	○	○	○	○	○	○	○

How confident are you in your ability to rotate an object from a 2D view into a 3D view?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
○	○	○	○	○	○	○	○	○	○

How confident are you in your ability to visualize how a 2D object will look in 3D?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
○	○	○	○	○	○	○	○	○	○

How confident are you in your ability to answer general questions about building elements?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
○	○	○	○	○	○	○	○	○	○

How confident are you in your ability to read drawings and correctly identify a building element given a graphical representation and notation?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
○	○	○	○	○	○	○	○	○	○

How confident are you in your ability to perform geometric calculations?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
○	○	○	○	○	○	○	○	○	○

How confident are you in your ability to read floor plan and detail drawings and quantify building areas on the drawing?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
○	○	○	○	○	○	○	○	○	○

How confident are you in your ability to read a full set of construction drawings and identify errors that will effect construction?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
○	○	○	○	○	○	○	○	○	○

How confident are you in your ability to accurately sequence the assembly of building elements on a construction project?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
◎	◎	◎	◎	◎	◎	◎	◎	◎	◎

How confident are you in your ability to plan the work necessary for construction on a real-world site?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
◎	◎	◎	◎	◎	◎	◎	◎	◎	◎

How confident are you in your ability to measure a building's objects from drawings and accurately quantify lengths, areas, and volumes of elements in the drawings for procurement ?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
◎	◎	◎	◎	◎	◎	◎	◎	◎	◎

How confident are you in your ability to compare a 2D building plan that has been rotated from its original position to several different positions and then identify the rotated buildings that are not the same as the original object?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
◎	◎	◎	◎	◎	◎	◎	◎	◎	◎

How confident are you in your ability to compare 3D building representations and determine if the representations are of the same building?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
◎	◎	◎	◎	◎	◎	◎	◎	◎	◎

How confident are you in your ability to rotate a building from a 2D plan view into a 3D view?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
◎	◎	◎	◎	◎	◎	◎	◎	◎	◎

How confident are you in your ability to visualize how a 2D building plan will look in 3D?

1 Certain I cannot	2	3	4	5 Moderately certain I can	6	7	8	9	10 Certain I can
○	○	○	○	○	○	○	○	○	○

Spatial Skills Instructions

<u>**Section Description and Instructions**</u>
This section is a test of your spatial skills and as such includes items about spatial relations, orientation, and visualization for which you must apply your knowledge about graphics, modeling, and building construction.

Each question is marked as a spatial relations, orientation, or visualization type question. **You will have a total of 14 minutes to complete 9 questions.** Your score on this test will be the number marked correctly minus the number marked incorrectly. Therefore, it will <u>not</u> be to your advantage to guess unless you have some idea which choice is correct. Work as quickly as you can without sacrificing accuracy.

Spatial Skills Questions

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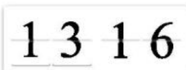


Spatial Visualization: Spatial visualization requires you to view an object from one perspective and then imagine how that object will look from another perspective.

Given the roof plan below, decide whether image A or image B represents the perspective view from the northwest corner of the building. Select A if image A represents the perspective from the northwest corner or select image B if image B represents the perspective from the northwest corner of the building.

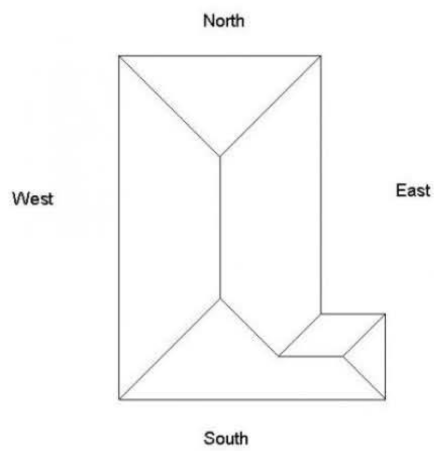


Image A

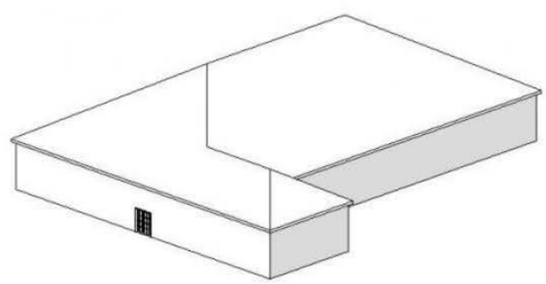
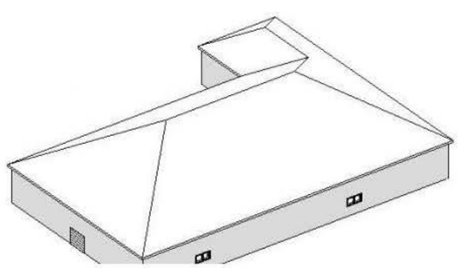


Image B



Spatial Visualization: Spatial visualization requires you to view an object from one perspective and then imagine how that object will look from another perspective.

Given the floor plan below with section cut, decide whether image A or image B represents the section view from the west looking east in the building. Select A if image A represents the section view from the west looking east or select image B if image B represents the section view from the west looking east.

Floor Plan

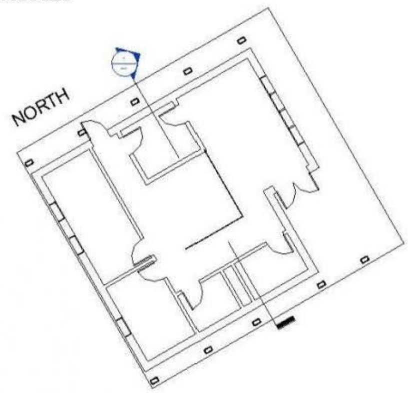


Image A

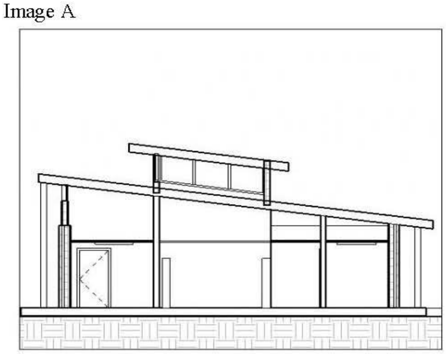
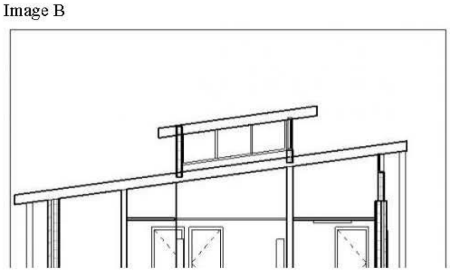


Image B



Spatial Visualization: Spatial visualization requires you to view an object from one perspective and then imagine how that object will look from another perspective.

Given the plan view with roof layout below, decide whether image A or B represents the building's south elevation. Select A if image A represents the building's south elevation view or select image B if image B represents the building's south elevation.

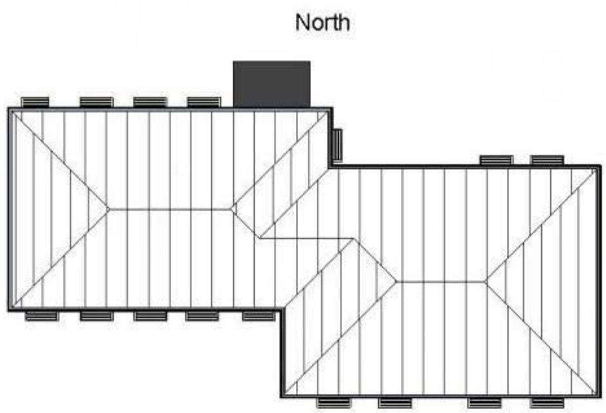
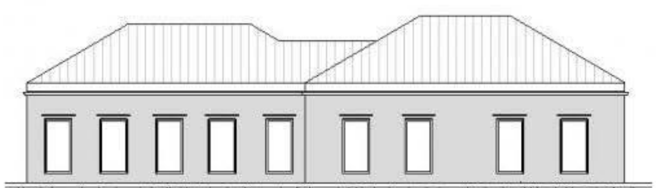


Image A

Image B

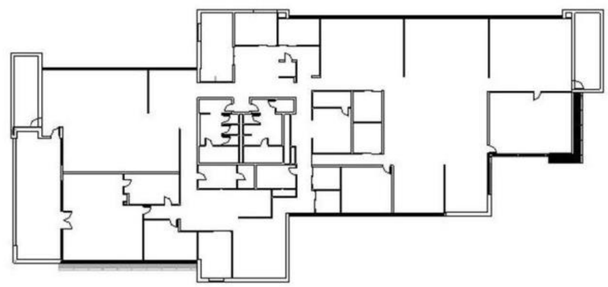


- A - Image A represents the building's south elevation view

Spatial Relations: Floor plans can be rotated or mirrored once created. When rotated, components within the floor plan maintain their original orientation to an interior space whereas when mirrored the plan components will be reversed from their original orientation to the space. Therefore a floor plan that has been rotated is considered the same as the original plan, whereas a plan that has been mirrored is not the same as the original plan.

Given this explanation, decide if the original floor plan A plan and floor plan B are the same. Select **Yes** if the images are the same or select **No** if the images are not the same.

Original floor plan A



Floor plan B

- Yes, floor plan A and B are the same
- No, floor plan A and image B are not the same

Spatial Relations: Floor plans can be rotated or mirrored once created. When rotated, components within the floor plan maintain their original orientation to an interior space whereas when mirrored the plan components will be reversed from their original orientation to the space. Therefore a floor plan that has been rotated is considered the same as the original plan, whereas a plan that has been mirrored is not the same as the original plan.

Given this explanation, decide if the original floor plan A plan and floor plan B are the same. Select **Yes** if the images are the same or select **No** if the images are not the same.

Image A

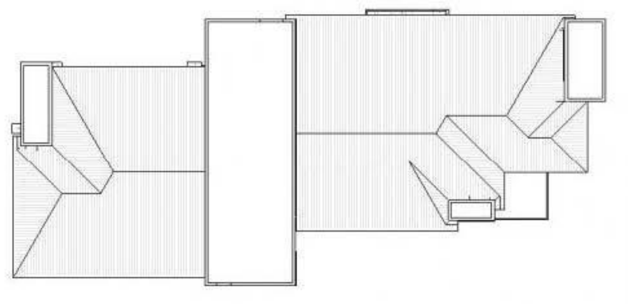
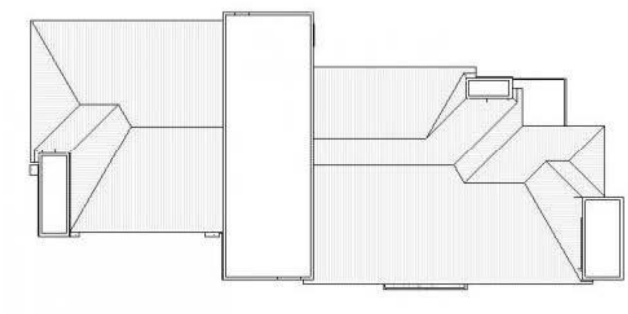


Image B



- Yes image A and image B are the same
- No image A and image B are not the same

Spatial Relations: Floor plans can be rotated or mirrored once created. When rotated, components within the floor plan maintain their original orientation to an interior space whereas when mirrored the plan components will be reversed from their original orientation to the space. Therefore a floor plan that has been rotated is considered the same as the original plan, whereas a plan that has been mirrored is not the same as the original plan.

Given this explanation, decide if the original floor plan A plan and floor plan B are the same. Select **Yes** if the images are the same or select **No** if the images are not the same. Decide whether image A and image B are the same. Select **Yes** if the images are the same or select **No** if the images are not the same.

Image A

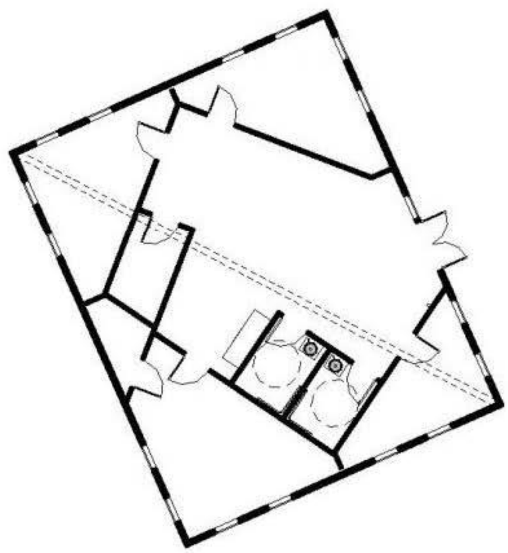
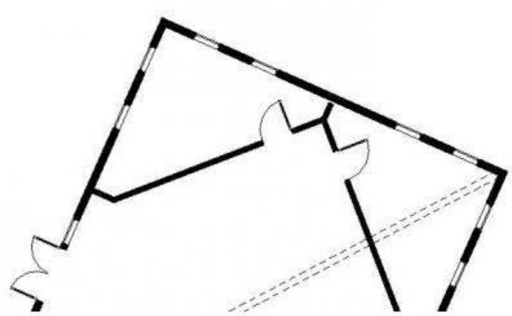


Image B



Spatial Orientation: Spatial orientation requires you to compare two objects from different views and determine if the two objects are the same. It is important to pay attention to the detail elements of the object in addition to the object's overall shape.

Decide whether image A and image B are the same roof layout and select Yes if the images are the same or No if the images are not the same.

Image A

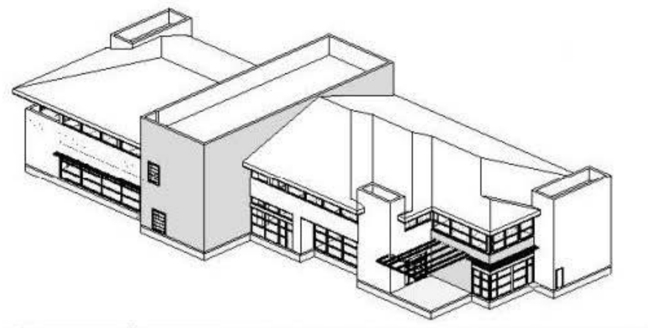
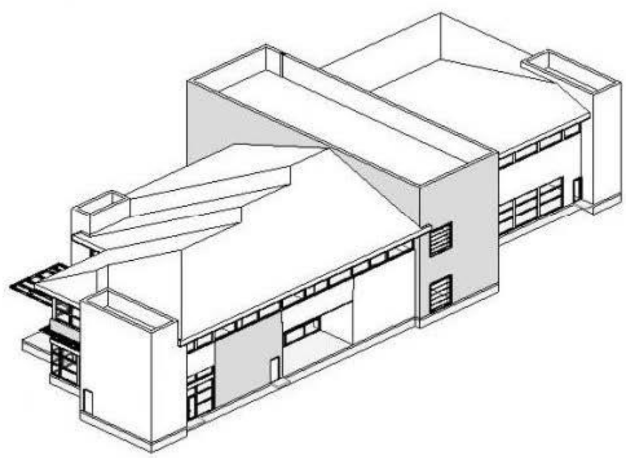


Image B



- Yes image A and image B are the same
- No image A and image B are not the same

Spatial Orientation: Spatial orientation requires you to compare two objects from different views and determine if the two objects are the same. It is important to pay attention to the detail elements of the object in addition to the object's overall shape.

Decide whether image A and image B are images of the same roof layout and select Yes if the images are the same or No if the images are not the same.

Image A

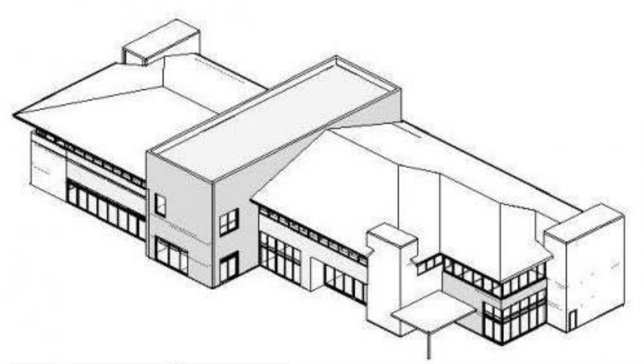
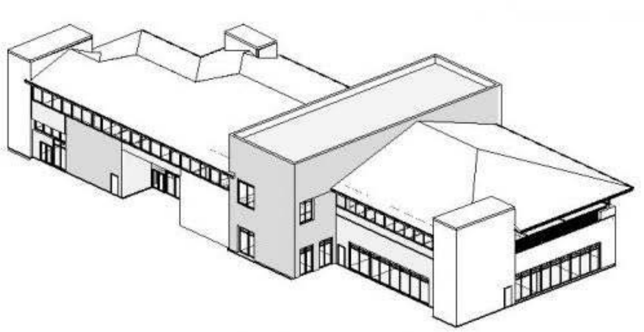


Image B



- Yes image A and image B are the same
- No image A and image B are not the same

Spatial Orientation: Spatial orientation requires you to compare two objects from different views and determine if the two objects are the same. It is important to pay attention to the detail elements of the object in addition to the object's overall shape.

Decide whether image A and image B represent the same building plan and select Yes if the images are the same or No if the images are not the same.

Image A

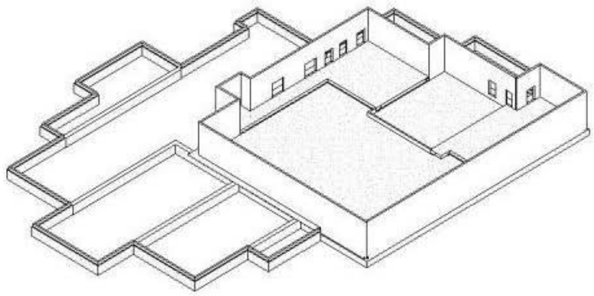
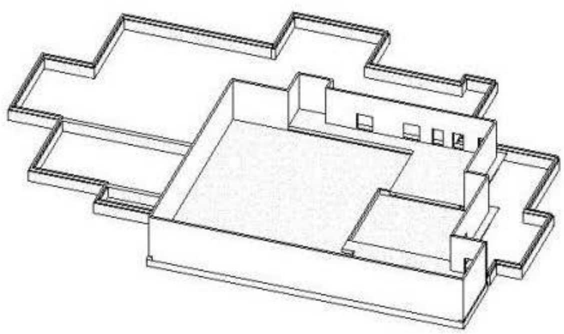


Image B



- Yes image A and image B are the same
- No image A and image B are not the same

Domain Knowledge Test Instructions

Section Description and Instructions

This section tests your knowledge about the 1) graphics and nomenclature of construction drawings, 2) building layout for construction, and 3) calculating quantities of building systems for construction. **There are a total of 10 questions distributed across three parts. Each part is timed as follows: Part 1 - 3**

minutes, Part 2 - 8 minutes, and Part 3 - 6 minutes.

Included in this section are questions that require calculations therefore you may use paper, pencil, and a calculator to answer the questions in this section. There is only one correct answer for each question so answer carefully.

Domain Knowledge Test Part 1 (3 questions - 3 minutes)

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0216

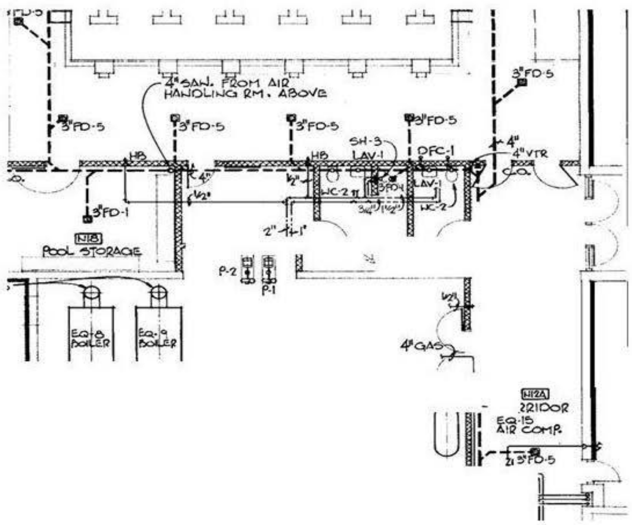
VTR is an abbreviation found in the Mechanical/Electrical/Plumbing drawings. What system is the VTR connected to?

- Storm Sewer
- Sanitary Sewer
- Domestic Water
- Sprinkler System

Given the Plumbing Pipe Schedule and the Plumbing Plan answer the following question

What is the size of the domestic hot water connection to the EWC?

Plumbing Pipe Schedule							
FIXTURE	COLD	HOT	WASTE	RE VENT	MAIN VENT	TRAP SIZE	REMARKS
WATER CLOSET	1"	- - -	4"	2"	3"	4"	FLUSH VALVE
URINAL	3/4"	- - -	2"	2"	2"	2"	WALL MTD.
LAVATORY	1/2"	1/2"	1-1/2"	1-1/2"	1-1/2"	1-1/4"	
SINK	1/2"	1/2"	1-1/2"	1-1/2"	2"	1-1/2"	Or as Noted
ELECTRIC WATER COOLER	1/2"	- - -	1-1/4"	1-1/4"	- - -	1-1/4"	
HOSE BIB	3/4"	- - -	- - -	- - -	- - -	- - -	NON-FREEZE
FLOOR DRAIN	- - -	- - -	3"	2"	3"	3"	OR A NOTED
SERVICE SINK	3/4"	3/4"	3"	2"	2"	3"	

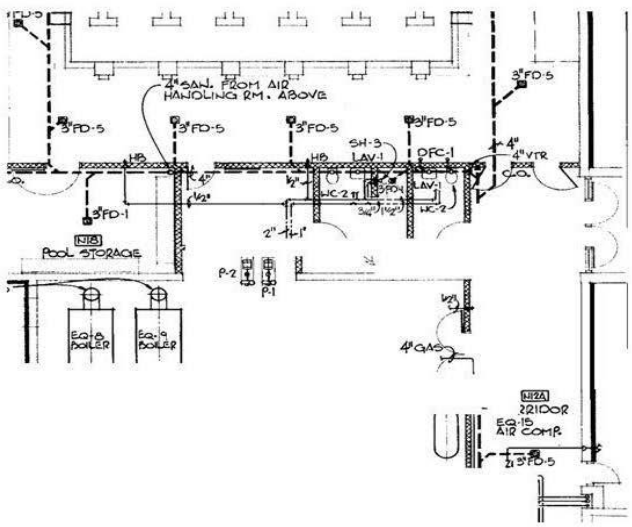


- 0"
- 1/2"
- 3/4"
- 1"

Given the Plumbing Pipe Schedule and Plumbing Plan answer the following question

What is the size of the waste line connection to the WC-2?

Plumbing Pipe Schedule							
FIXTURE	COLD	HOT	WASTE	RE VENT	MAIN VENT	TRAP SIZE	REMARKS
WATER CLOSET	1"	- - -	4"	2"	3"	4"	FLUSH VALVE
URINAL	3/4"	- - -	2"	2"	2"	2"	WALL MTD.
LAVATORY	1/2"	1/2"	1-1/2"	1-1/2"	1-1/2"	1-1/4"	
SINK	1/2"	1/2"	1-1/2"	1-1/2"	2"	1-1/2"	Or as Noted
ELECTRIC WATER COOLER	1/2"	- - -	1-1/4"	1-1/4"	- - -	1-1/4"	
HOSE BIB	3/4"	- - -	- - -	- - -	- - -	- - -	NON-FREEZE
FLOOR DRAIN	- - -	- - -	3"	2"	3"	3"	OR A NOTED
SERVICE SINK	3/4"	3/4"	3"	2"	2"	3"	



- 0"
- 1"
- 2"
- 4"

Domain Knowledge Test Part 2 (4 questions - 8 minutes)

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0716

Given a rectangular structure that is 60'-9" long by 42'-6" wide, what is the diagonal measurement in feet and inches for squaring up the structure during layout?

- 51' - 7 1/2"
- 74' - 1 3/4"
- 74' - 3 7/8"
- 103' - 3"

What is the percentage grade for a slope ration of 1:13 (rise:run)?

- 0.077
- 1.000
- 7.690
- 13.000

Assume you have a right triangle which is 36 feet high and a perpendicular from the baseline. What are the baseline distance and the diagonal distance?

- The baseline is 24 feet, the diagonal is 48 feet
- The baseline is 27 feet, the diagonal is 45 feet
- The baseline is 36 feet, the diagonal is 72 feet
- The baseline is 48 feet, the diagonal is 60 feet

Assume that you have to form and pour a concrete stair that is 4 feet wide with a top landing that is 4 feet by 4 feet. The total rise is 42 inches high and each step has a 7 inch rise and a 10 inch tread which is 6 inches thick and the slant distance is formed on the back side. The forms for the steps will consist of 5 stringers on the slant distance are made from 2" x 12" material and the risers for the front faces are made of 2 inch thick material. Answer the following question about the stairs:

What is the horizontal distance in inches of the stairs?

- 6
- 42
- 50
- 65

Domain Knowledge Test Part 3 (3 questions - 6 minutes)

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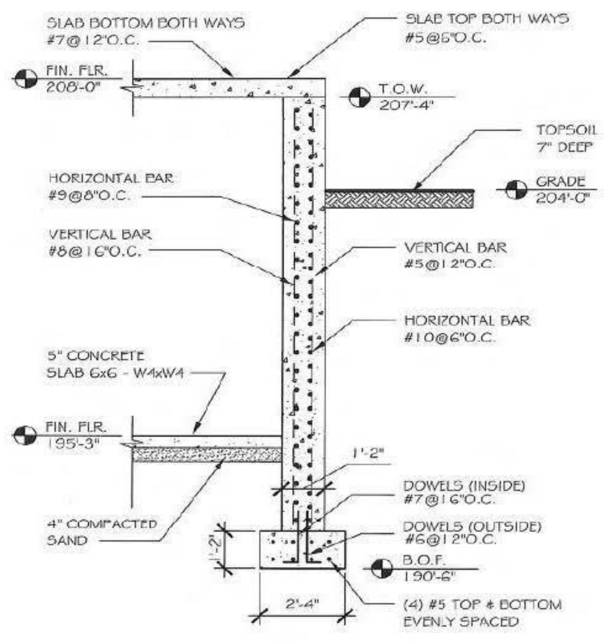
0516

Given the concrete detail answer the following question:

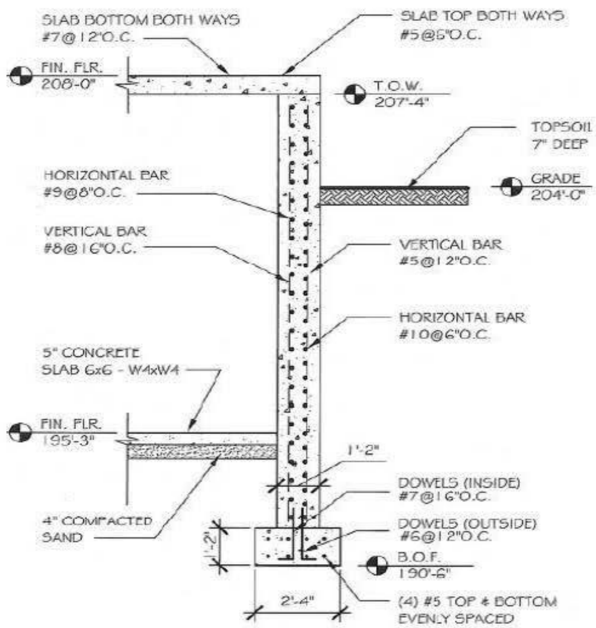
What is the height of the concrete wall?

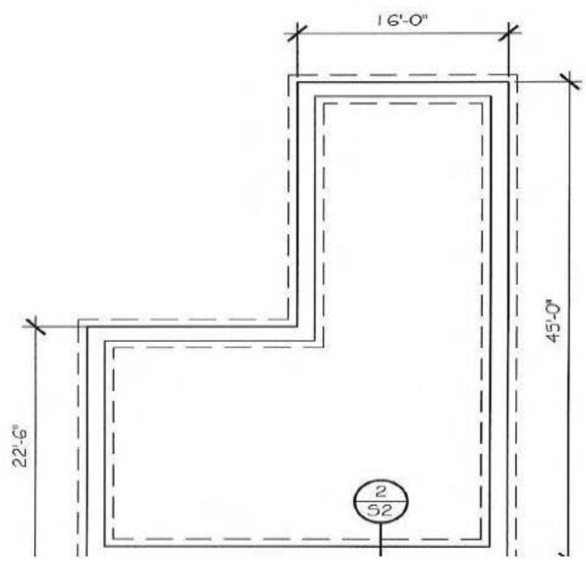


- 12.83'
- 15.66'
- 16.80'
- 18.00'

Given the detail and plan answer the following question:

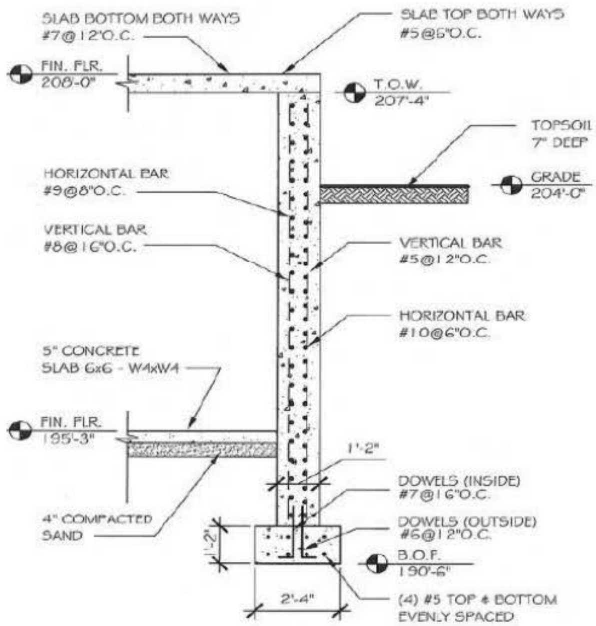
How many total Square Feet of Contact Area (S.F.C.A.) for the wall forms?

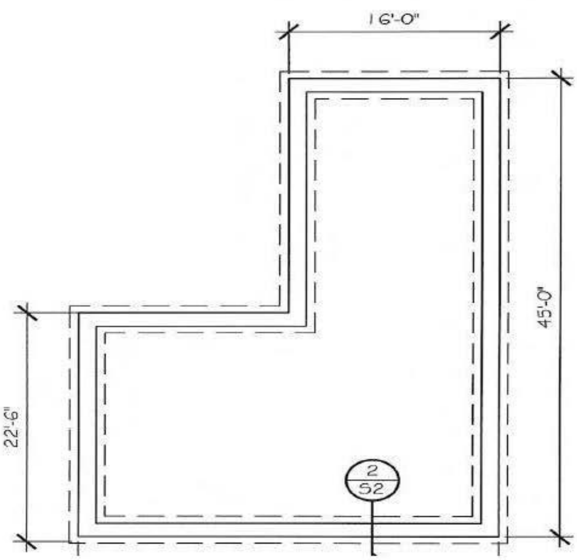




Given the detail and plan answer the following question:

How many cubic yards of concrete for the slab-on-grade?

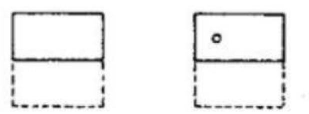


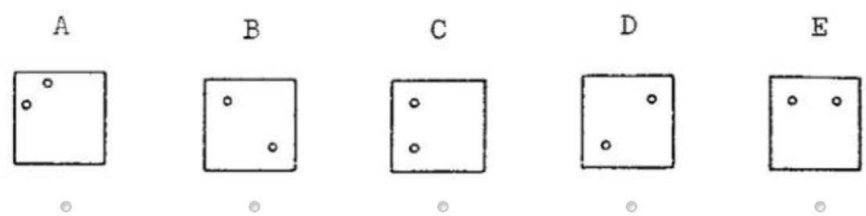


Spatial Visualization- Paper Folding Test Instructions

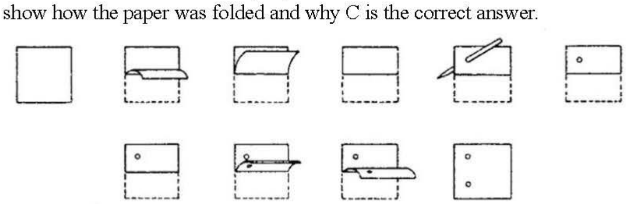
<u>Section Description and Instructions</u>
In this test you are to imagine the folding and unfolding of pieces of paper. In each problem in the test there are some figures drawn on the top row and there are others drawn on the bottom row. The figures on the top represent a square piece of paper being folded, and the last of these figures has one or two small circles drawn on it to show where the paper has been punched. Each hole is punched through all the thicknesses of paper at that point. One of the five figures on the bottom row shows where the holes will be when the paper is completely unfolded. You are to decide which one of the figures on the bottom row is correct and select that figure.

Now try the sample below. (In this problem only one hole was punched in the folded paper.)





The correct answer to the sample problem above is C and so it should have been selected. The figures below show how the paper was folded and why C is the correct answer.



In these problems all of the folds that are made are shown in the figures on the top row, and the paper is not turned or moved in any way except to make the folds shown in the figures. Remember, the answer is the figure that shows the positions of the holes when the paper is completely unfolded.

Your score on this test will be the number selected correctly minus a fraction of the number selected incorrectly. Therefore, it will <u>not</u> be to your advantage to guess unless you are able to eliminate one or more of the answer choices as wrong.

You will have <u>3 minutes</u> for each of the two parts of this test. Each part has 10 questions.

Spatial Visualization - Paper Folding Test - Part 1 (10 questions - 3 minutes)

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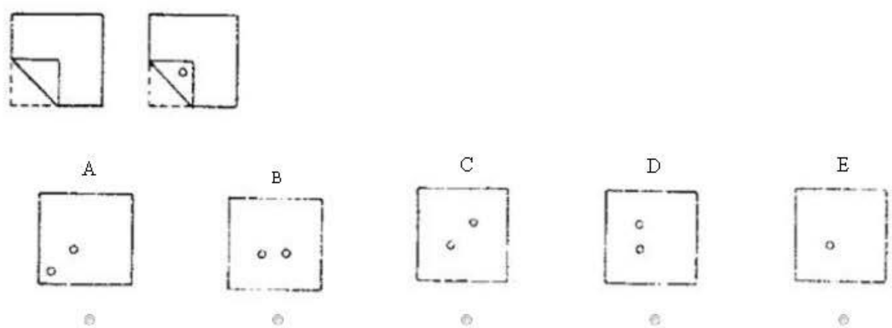
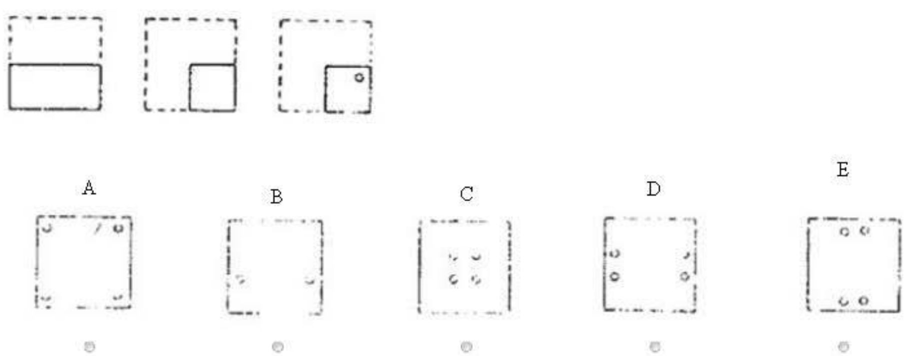
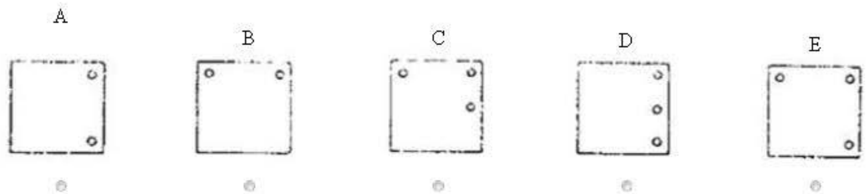
0216






A
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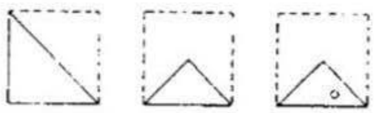

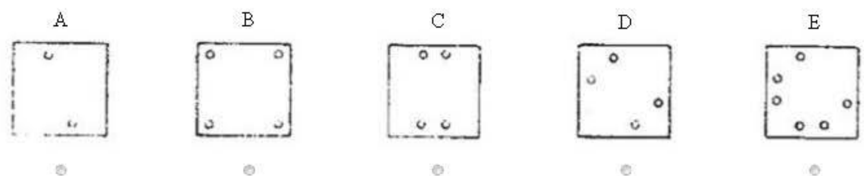
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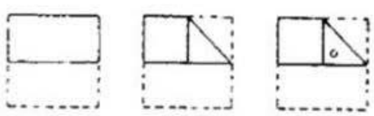

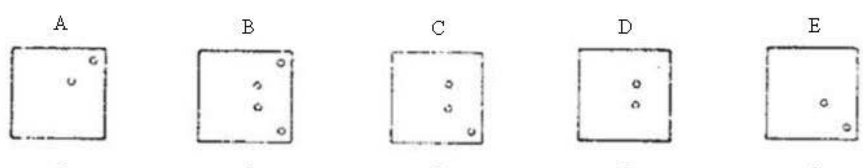
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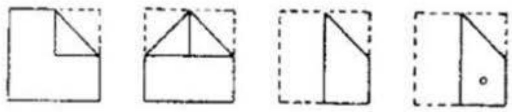
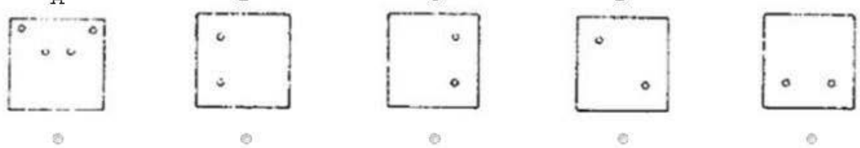
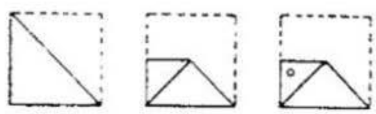
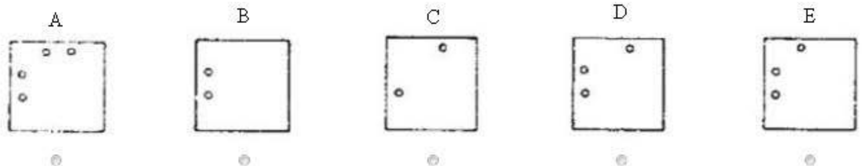


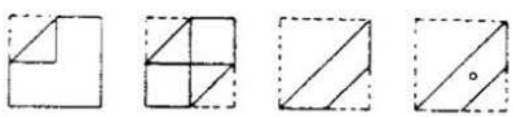
A B C D E



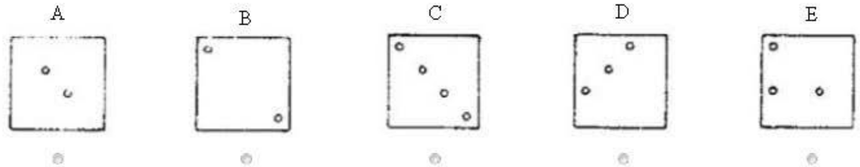


A B C D E

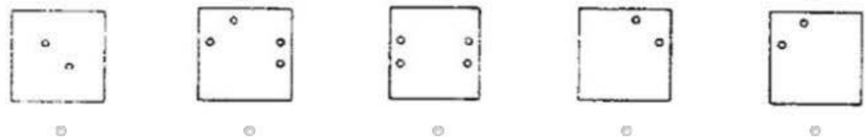


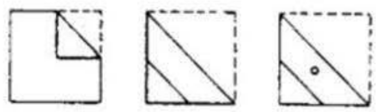


A B C D E

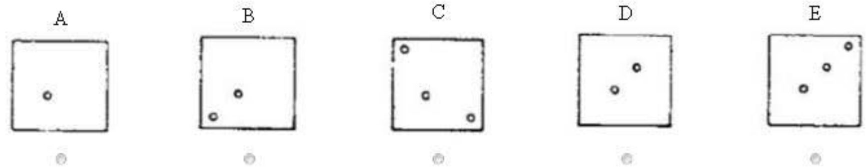


A B C D E





A B C D E



Spatial Visualization - Paper Folding Test - Part 2 (10 questions - 3 minutes)

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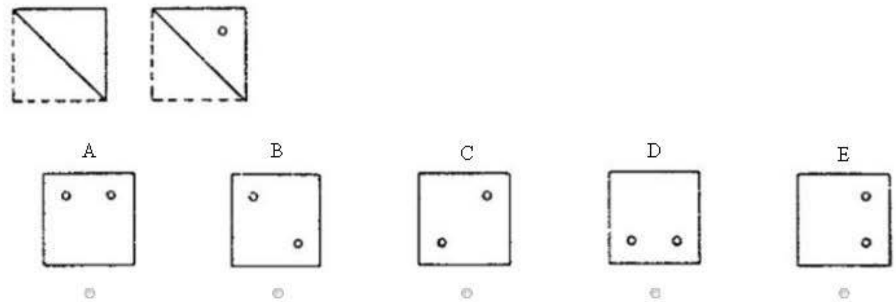
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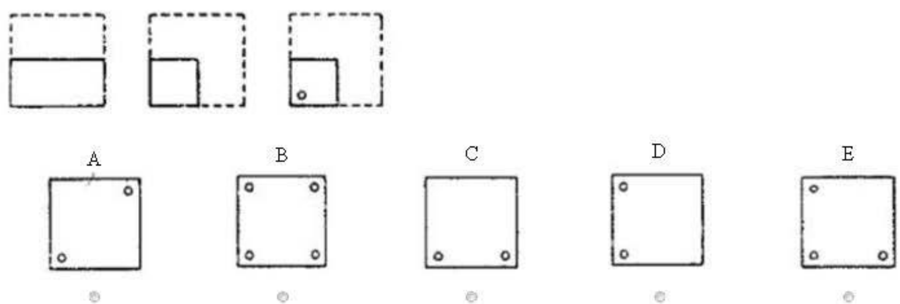
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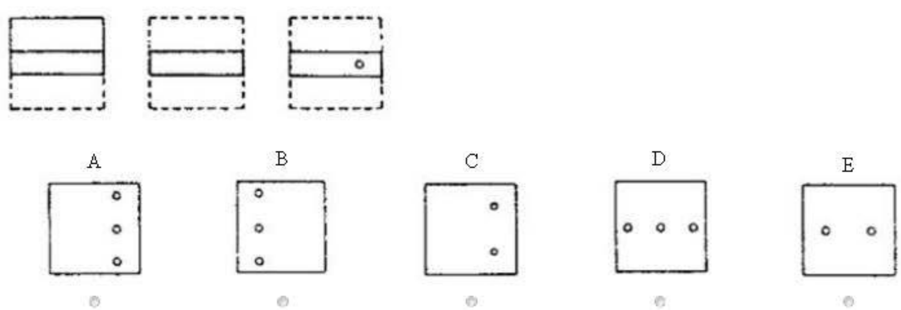
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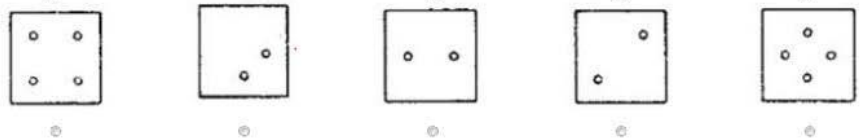
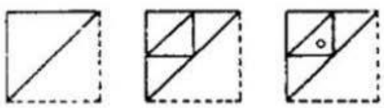
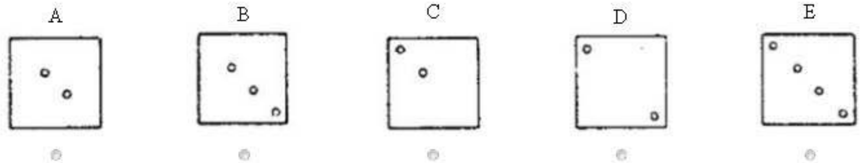
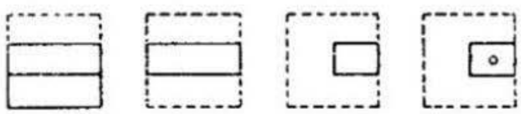
A B C D E



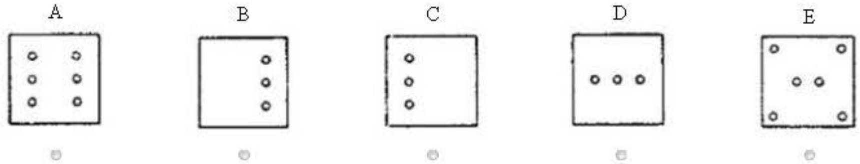


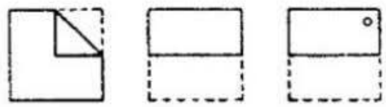
A B C D E



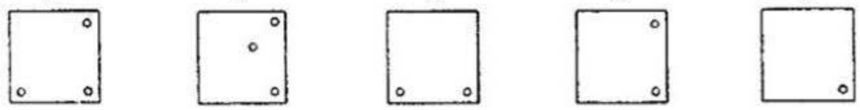


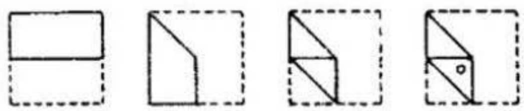
A B C D E



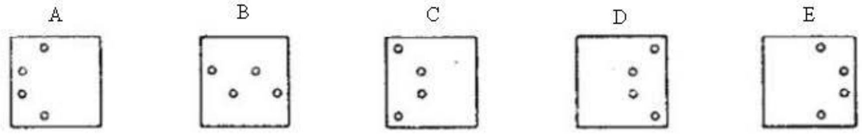


A B C D E

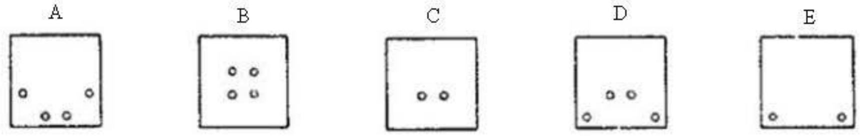




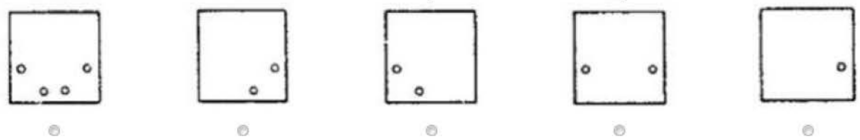
A B C D E



A B C D E



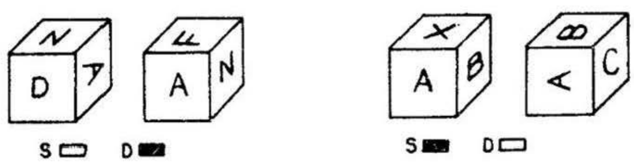
A B C D E



Spatial Orientation - Cube Comparisons Test Instructions

Section Description and Instructions

Wooden blocks such as children play with are often cubical with a different letter, number, or symbol on each of the six faces (top, bottom, four sides). Each problem in this test consists of drawings of pairs of cubes or blocks of this kind. Remember, there is a different design, number, or letter on each face of a given cube or block. Compare the two cubes in each pair below.

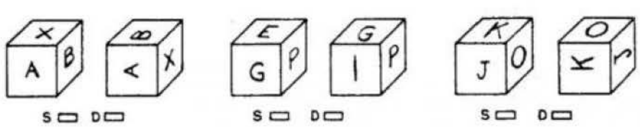


The first pair is marked D (Different) because they must be drawings of <u>different</u> cubes. If the left cube is turned so that the A is upright and facing you, the N would be to the left of the A and hidden, not to the right of the A as is shown on the right hand member of the pair. Thus, the drawings must be of different cubes.

The second pair is marked S (Same) because they could be drawings of the same cube. That is, if the A is turned on its side the X becomes hidden, the B is now on top, and the C (which was hidden) now appears. thus the two drawings could be of the same cube.

<u>Note:</u> No letters, numbers, or symbols appear on more than one face of a given cube. Except for that, <u>any</u> letter, number or symbol can be on the hidden faces of a cube.

Work the three examples below.



The first pair immediately above should be marked D because the X cannot be at the peak of the A on the left hand drawing and at the base of the A on the right hand drawing. The second pair is "different" because P has its side next to G on the left hand cube but its top next to G on the right hand cube. The blocks in the third pair are the same, the J and K are just turned on their side, moving the O to the top.

Your score on this test will be the number marked correctly minus the number marked incorrectly. Therefore, it will not be to your advantage to guess unless you have some idea which choice is correct. Work as quickly as you can without sacrificing accuracy.

You will have 3 minutes for each of the two parts of this test. Each part has 21 questions.

Spatial Orientation - Cube Comparisons Test - Part 1 (21 Questions - 3 minutes)

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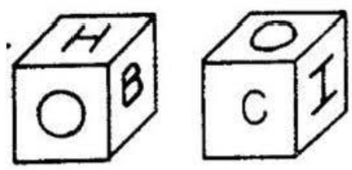

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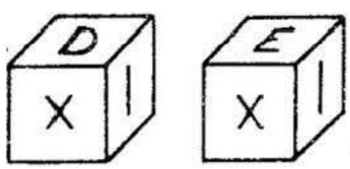

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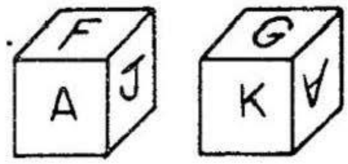

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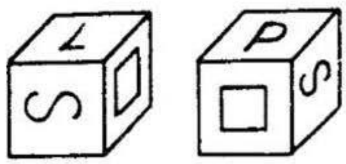

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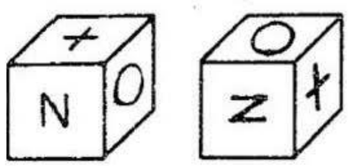

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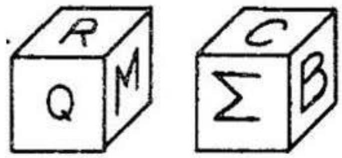

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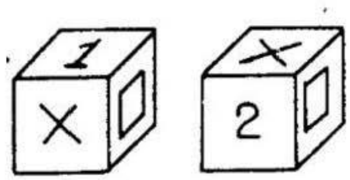

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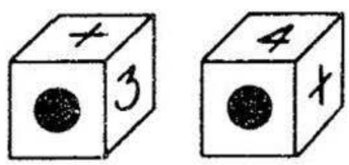

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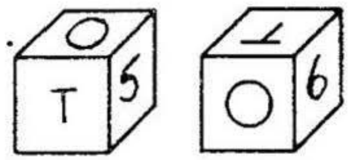

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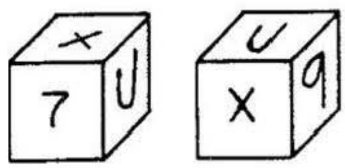

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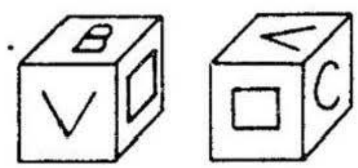

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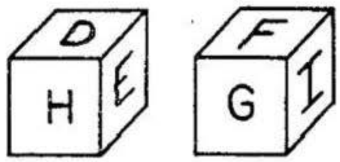

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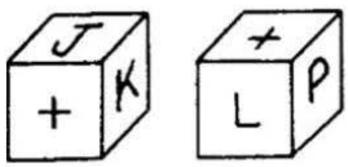

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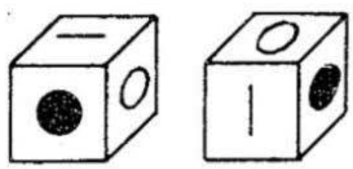

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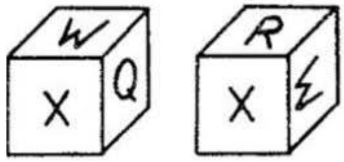

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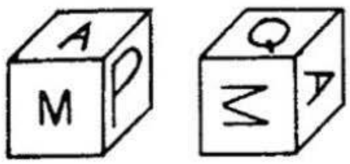

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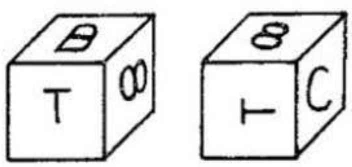

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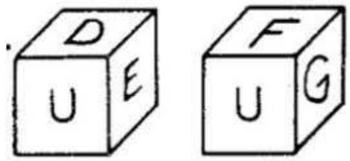

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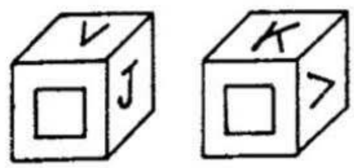

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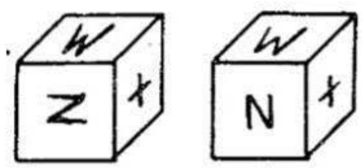

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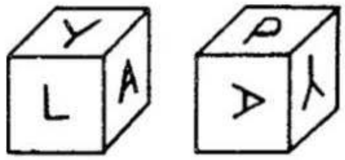

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Spatial Orientation - Cube Comparisons Test - Part 2 (21 Questions -3 minutes)

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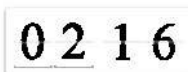

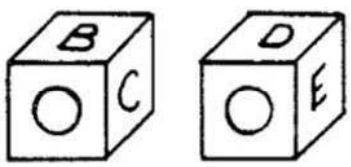

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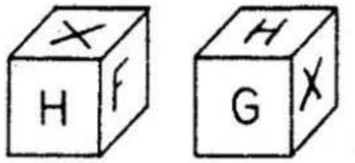

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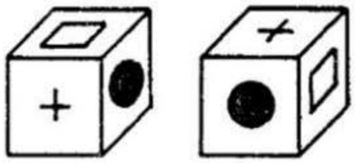

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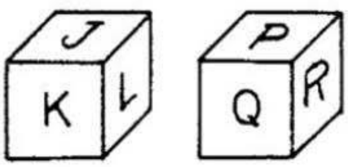

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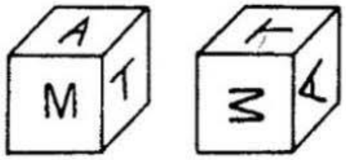

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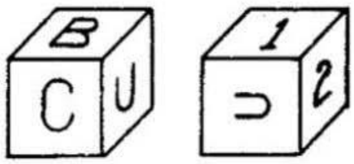

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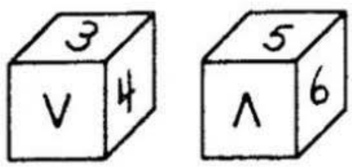

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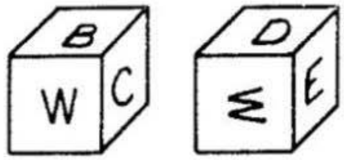

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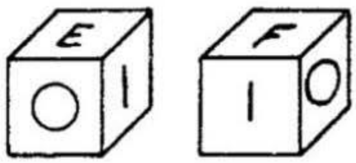

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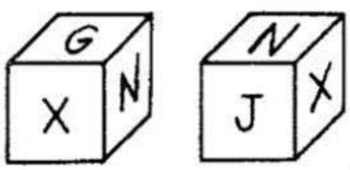

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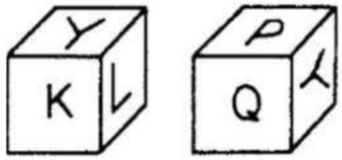

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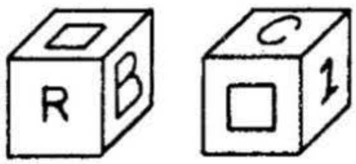

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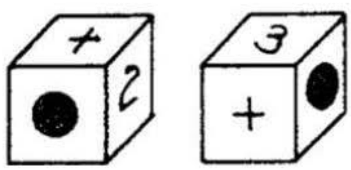

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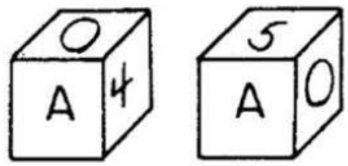

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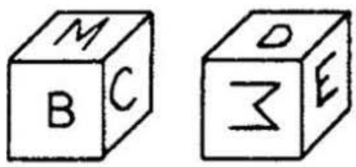

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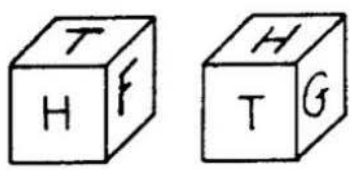

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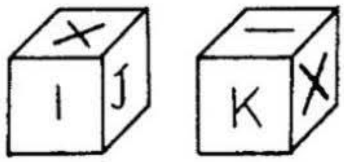

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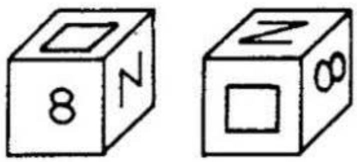

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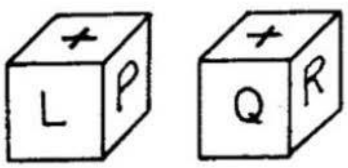

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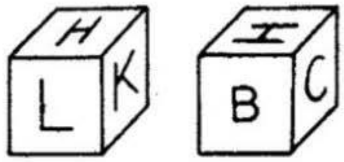

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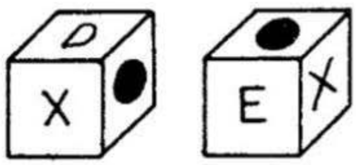

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Spatial Relations - Card Rotations Test Instructions

Section Description and Instructions

This is a test of your ability to see differences in figures. Look at the 5 triangle-shaped cards drawn below.

All of these drawings are of the same card, which has been slid around into different positions on the page. Now look at the 2 cards below:

These two cards are not alike. The first cannot be made to look like the second by sliding it around on the page. It would have to be flipped over or made differently.

Each problem in this test consists of one card on the top row and eight cards on the bottom row. You are to decide whether each of the eight cards on the bottom row is the same as or different from the card on the top row.

Mark the box below each card on the bottom row if the card is the same as the one on the top row. Leave the box blank if the card on the bottom row is different from the one on the top row.

Your score on this test will be the number of items answered correctly minus the number answered incorrectly. Therefore, it will not be to your advantage to guess, unless you have some idea whether the card is the same or different. Work as quickly as you can without sacrificing accuracy.

This test contains 20 questions. You will have 3 minutes to complete the first 10 questions and then 3 minutes to complete the next 10 questions. You will be allotted a total of 6 minutes to complete all of the 20 questions.

Spatial Relations - Card Rotations Test Part 1 (10 questions - 3 minutes)

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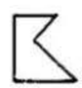

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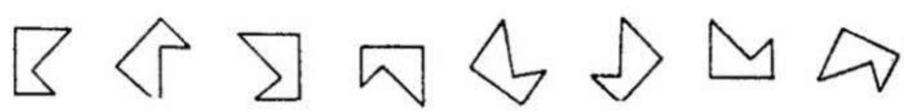

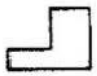
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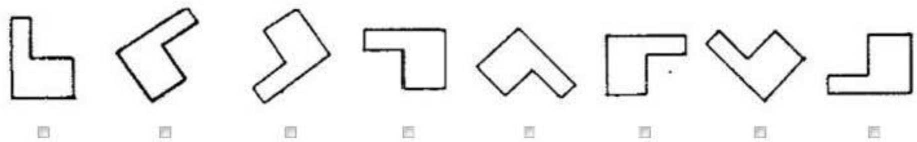


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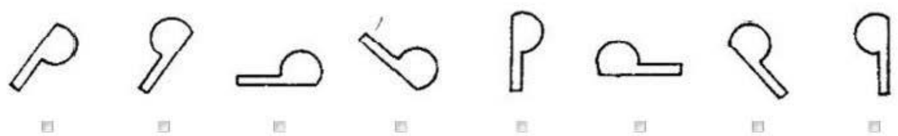


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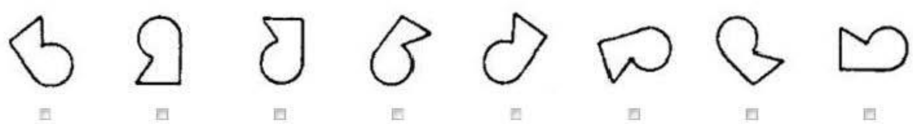

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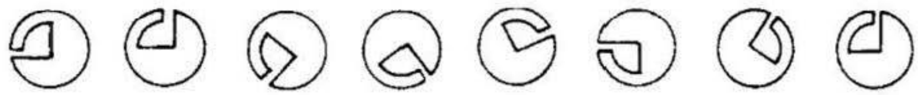

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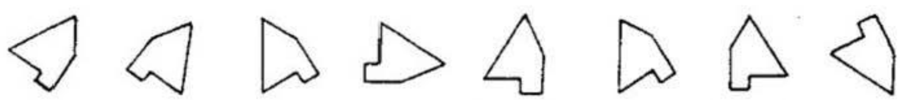

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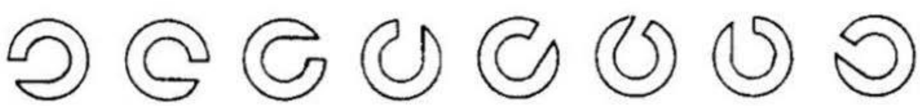

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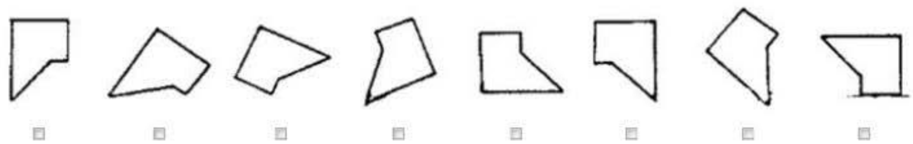

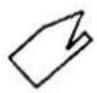

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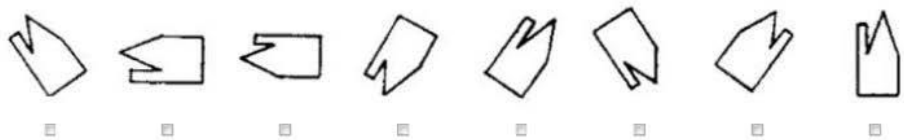

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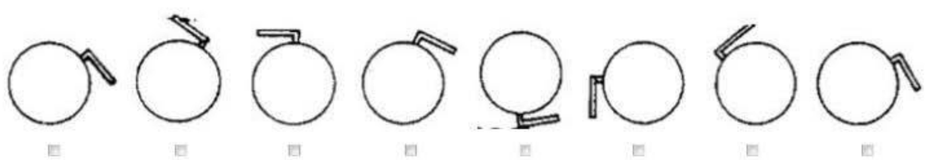

Spatial Relations - Card Rotations Test Part 2 (10 questions - 3 minutes)

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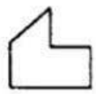

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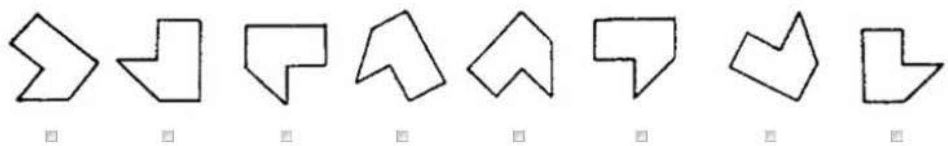

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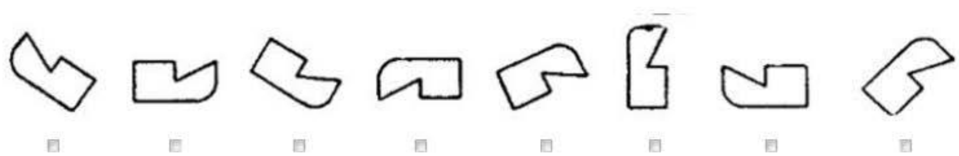


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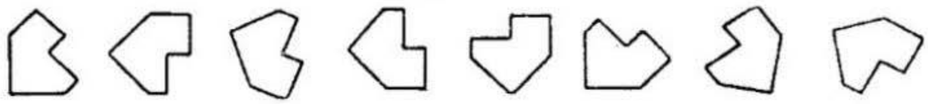

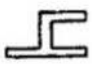
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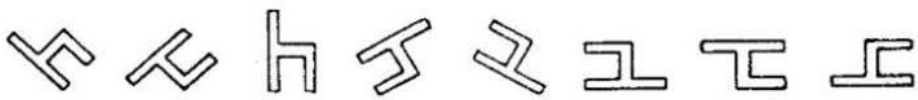


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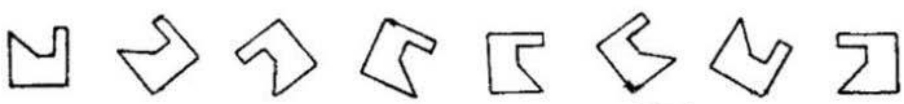

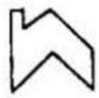
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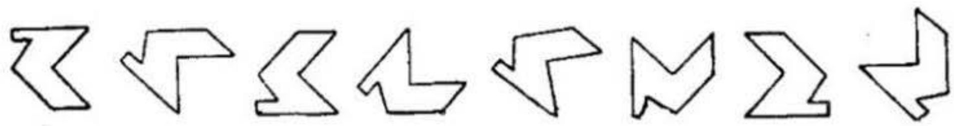


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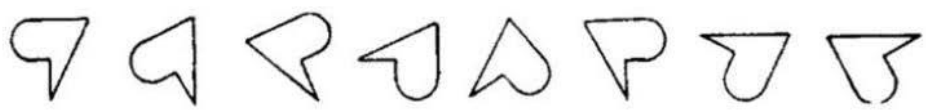

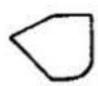
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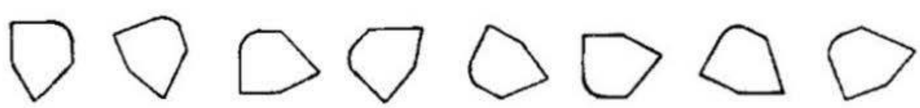

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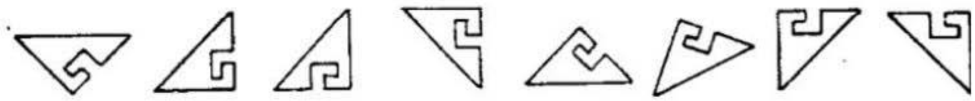

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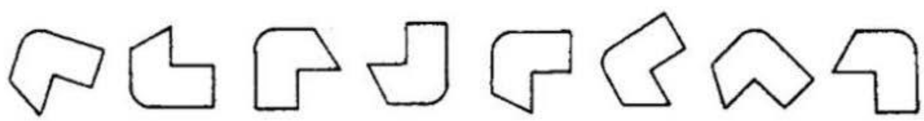

Demographic Questionnaire

Please select the option that indicates your current university classification as an undergraduate

Freshman	Sophomore	Junior	Senior

Please select the option that indicates your current construction major program classification as an undergraduate

- Freshman
- Sophomore
- Junior
- Senior

Please select the option that indicates your gender

- Female
- Male

Please select the option below that indicates your current grade point average

- Below a 2.0
- 2.0 - 2.49
- 2.50 - 2.99
- 3.0 - 3.49
- 3.50 - 3.99
- 4.0 or higher

Do you have real-world construction experience? Your experience may be paid or volunteer.

- Yes
- No

Please select from the options below the one that best describes your real-world construction experience. Include all experience, paid or volunteer. Choose all that apply.

- Field/Project Site Experience
- Office Experience
- Design Firm Experience

Please select the option(s) below that best describes the type of tasks you completed during your real-world construction experience. Experience may be paid or voluneer. Choose all that apply.

- General Contractor preconstruction - estimating, scheduling, etc.
- General Contractor construction site - RFIs, submittals, meeting minutes, etc.
- General Contractor - building information modeling
- Trade Construction - fabrication, installation, etc.
- Design Firm Preconstruction - drawing, modeling, estimating, etc.
- Design Firm - building information modeling
- Residential Builder - field supervision
- Residential Builder - fabrication, installation, etc.
- General Contractor - field supervision

Please select the option(s) below that best describes the amount of real-world construction experience you have. Experience may be paid or volunteer.

- 1 - 6 months part-time experience (less than 40 hours per week)
- 7 - 12 months part-time experience (less than 40 hours per week)
- 13 - 18 months part-time experience (less than 40 hours per week)
- 19 - 24 months part-time experience (less than 40 hours per week)
- Over 24 months part-time experience (less than 40 hours per week)
- 1 - 6 months full-time experience (40 hours or more per week)
- 7 - 12 months full-time experience (40 hours or more per week)
- 13 - 18 months full-time experience (40 hours or more per week)
- 19 - 24 months full-time experience (40 hours or more per week)
- Over 24 months full-time experience (40 hours or more per week)