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EXPLORING SPATIAL REASONING ABILITY AND DESIGN COGNITION IN UNDERGRADUATE ENGINEERING STUDENTS

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ABSTRACT

This paper presents preliminary results from the first phase of a longitudinal study of design cognition and the effects of design education on design practice. The study aims to monitor the development of engineering design thinking through a three-year protocol study of two control and experimental groups of engineering students. Using innovations in cognitive science that include ontologically-based coding of protocols and new methods of protocol analysis, it is intended to characterize their cognitive development, identify differences over time, and relate them to their education.

The first phase of this study is focused in assessing students' spatial reasoning ability. Spatial reasoning is the ability to process and form ideas through spatial relationships between objects. It has been found to correlate strongly with design ability as it pertains to one's ability to generate, conceptualize, and communicate solutions to problems. Study participants (sophomore students entering the two investigated majors) took four different spatial reasoning tests (Paper Folding, Vandenberg, Mental Rotation, and Spatial Imagery Ability) that tested their ability to visualize objects and mentally manipulate them over an ordered sequence of spatial transformations.

The results of these tests are presented in this paper. Tests are conducted to investigate statistical significance in order to evaluate whether or not a student's spatial reasoning ability influences their choice of engineering major. The students' performances on these tests are also compared with existing data from other fields (e.g., architecture, visual arts, science, and humanities).

1 INTRODUCTION

Much of the current research in design education focuses on describing approaches to teaching. This research includes important work on design across the curriculum [1-3], the effects of project type on underrepresented groups [4, 5], and the development of assessment tools [6-9]. Researchers at the Transferable Integrated Design Engineering Education (TIDEE) project [10] at Washington State University, for example, have focused on course design, emphasizing materials for both teaching and assessment. TIDEE researchers have developed a framework for curriculum design [11], identified national trends in assessment [12] and developed learning outcomes for design education [13, 14]. They have also developed multiple assessment instruments [9, 15, 16] and provided teaching tools for core skills [16].

In addition to these focused explorations of various dimensions of teaching practice, several researchers have examined design education more broadly. For example, Sheppard examines the disjunction between our teaching of engineering analysis and students' practice of engineering design, where "build-test-build" often dominates [17]. Dym argues strenuously for design across the curriculum [18, 19].

This existing body of research provides engineering educators with important insights into the structure and goals of design courses, as well as tools for assessing certain aspects of student performance. However, it offers less insight into how engineering students develop design knowledge and competencies or how education affects the development of students' design cognition. Yet such studies of design cognition are critical if design education researchers seek to develop

robust, research-based approaches to design teaching. Design education researchers and practitioners alike need robust methods to evaluate the effects of specific pedagogical practices not only on students' design products, or even on their external behaviors, but on their cognitive development as designers to help insure that the knowledge and competencies gained in one context (e.g. a course) can transfer to another (e.g. a workplace).

Some work in this area does exist, primarily from the Center for Engineering Learning and Teaching (CELT) at the University of Washington [20], where Atman and her colleagues have used verbal protocol analysis to study design behaviors. Using a coding scheme derived from representations of the design process in engineering texts [21], CELT researchers have examined differences across experience levels (freshmen, seniors, experts) [22-24], the influence of reflection [25], team self-evaluations versus observed performance [26], and the ability to effectively contextualize design problems [27-29]. Work by CELT researchers emphasizes comparison of design behaviors, as defined by current definitions of the mechanical engineering design process. Their work has been instrumental in helping educators understand engineering design behaviors at different levels of expertise and identify potential gaps in students' development of design practice.

Yet more work remains in understanding both how students' design cognition develops and how educational experiences affect this development. It is particularly important to develop approaches that examine not only students movements through the steps of a canonical design process, but also their engagement at a cognitive level with the interplay of the more fundamental concepts of product design: identifying and defining product function, structure, and behavior.

1.1 Exploring the Effects of Design Education

To enrich our current understanding of design learning, the authors are currently collaborating on a three-year, longitudinal study that will monitor the cognitive progress and development of design thinking in engineering students. To observe potential effects of engineering education on this development, two different engineering majors will be analyzed and compared: (i) an engineering mechanics program that adopts a first-principles approach and emphasizes computational analysis and a robust theoretical understanding of solids, fluids, and dynamics, and (ii) a mechanical engineering program that includes hands-on design experiences, machine design principles, and courses dedicated to design methods and product realization techniques.

In order to provide a uniform basis for comparing design students across projects and years, the study will use a task-independent protocol analysis that examines designers' movements back and forth through the functional, behavioral, and structural domains of design [30, 31]. Drawing on advances in cognitive science, Gero and colleagues have created a protocol analysis based on the FBS ontology. Based on the assumption that cognitively, design processes are

ontologically the same, the FBS ontology models designing in terms of three classes of ontological variables: function, behavior, and structure (Gero 1990).

The study begins with spatial reasoning tests to provide baseline data regarding students' abilities in the two majors. The results provide insights into students' potential as designers and allow us to explore whether spatial reasoning itself is a predictor of major choice. With this baseline data identified, potential changes in design cognition that emerge due to curricular differences will be more easily identified.

Subsequent phases of the study are dedicated to identifying changes in design cognition and behavior. In these phases, student volunteers from each major will participate in annual verbal protocol studies of design practices: pairs of students will be given a design scenario (e.g. product design for individuals with specific physical limitations) and asked to work together to develop a suitable conceptual design to address the need. Pairs will be asked to speak aloud as they work, and the entire process will be video-recorded. Transcriptions of the recordings will be analyzed using the FBS ontology and other advancements in cognitive science; the results of which will be analyzed using a variety of techniques to map individuals' cognitive movements back and forth across the FBS domains.

This analysis can be used to evaluate the effects of education on design cognition across a wide range of contexts. In doing so, it addresses underlying cognitive processes and provides a common basis for design education researchers to compare learning across contexts – including non-engineering contexts – and ultimately test the effects of specific educational interventions.

1.2 Evaluating Spatial Reasoning Ability

The results from the first phase of this longitudinal study serve as the focus of this paper. To ensure that the cognitive abilities of the participants who volunteer for the verbal protocol analysis are representative of their peers, the authors administered four spatial reasoning ability tests (Section 2). In addition to providing baseline data for the subsequent phases of the study, the contrary nature of the participants' majors affords an opportunity to answer the question: *Do students self-select an engineering major based on their spatial reasoning ability?*

The experimental method and the nature of the participants are described in Section 3. Results from the spatial reasoning ability tests are analyzed in Section 4. Closure is offered in Section 5.

2 SPATIAL REASONING ABILITY

2.1 Theory

Spatial reasoning ability in humans presumably evolved to allow them to navigate their environment and to make sense of persistent objects. Spatial reasoning is concerned with the representation and use of objects and their relationships within

a world conceived of both topologically and geometrically in two and three dimensions, with or without time as a fourth dimension. Spatial intelligence, which includes spatial reasoning, is one of the claimed multiple intelligences of humans [32].

Engineering design involves the creation of objects and their relationships to satisfy a set of requirements [33] and as such involves spatial reasoning. The objects could be physical components, their geometry and their topological relations. Here spatial reasoning involves imagining the objects. The objects could be symbols for physical components, their geometry and their topological relations. Here spatial reasoning commences with conceiving of the symbols as objects and then reasoning about the symbols spatially. The objects could be symbols for processes and their topological relations. Here spatial reasoning commences with conceiving of the symbols as objects and then reasoning about the symbols spatially. Visual and spatial reasoning also applies to the objects themselves [34, 35].

Spatial reasoning ability tests have been developed that show various degrees of correlation with gender, age and educational discipline. Apart from the development of spatial reasoning ability with age, the strongest correlation of differences are with gender [36-39]. There are a number of publications on the spatial reasoning abilities of engineers or engineering students using standardized tests and some using non-standardized tests [40, 41]. The results from non-standardized tests are not comparable with those from standardized tests. Where standardized tests have been used, differences across engineering disciplines have been observed as have differences across engineering educational institutions [42, 43].

Standardized tests [44], of which there are more than one, have the advantage of producing results that can be compared across space and time and across type of testee. It becomes possible to compare engineers with the general populace, with other non-engineer designers and across an individual's educational experience. The spatial tests reported in this paper are just one aspect of a larger longitudinal study of the effects of education on engineering students' design cognition. The study focuses on the design issues, design processes and their relationships and deployment that students employ while designing in an open-ended design environment as measures of design cognition. The measures of spatial reasoning abilities are external correlates to be tested as part of the study.

2.2 Test Types

To test spatial ability, the authors chose four tests: three from *Kit of Factor-Referenced Cognitive Tests* [44] and one that tests spatial relations, the Spatial Imagery Ability Test [45], as this is one of a small number of such tests that can be self-administered. The four tests implemented were the Paper Folding Test (PFT), the Vandenberg-Kuse Mental Rotation Test (VMR), the Shepard-Metzler Mental Rotation Test

(MRT), and the spatial Imagery Ability Test (SIA). Each test is briefly described in this section.

2.2.1 Paper Folding Test

The Paper Folding Test measures the ability to imagine spatial relations under constraints and spatial visualization ability, which is the ability to apprehend, encode and mentally manipulate abstract spatial forms. In this test, participants are asked to imagine the folding and unfolding of pieces of paper. A typical problem is presented in Figure 1. The figures presented at the left of the vertical line represent a square piece of paper being folded. The last of these figures has one or two small circles on the paper, which represent punched holes. The participant is asked to choose which of the five figures on the right of the vertical line correctly indicate where the holes will be once the paper is unfolded.

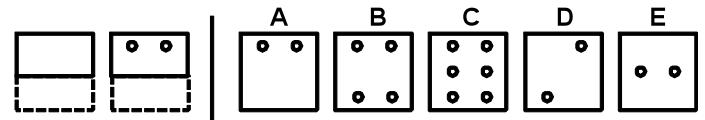


Figure 1. Sample Paper Folding Test Problem

The test is composed of 20 total questions that are divided into two equal parts. Participants are given three minutes to complete each half. To dissuade guessing, a penalty is imposed for every incorrect answer. Specifically, the participant's test score, S , is calculated as shown in Equation 1, where C is the total number of correct answers and I is the total number of incorrect answers.

$$S = (C - I/4)/2 \quad (1)$$

It is claimed that performance in this cognitive task is connected with some aspects of designing based on a phenomenological correlation (Blazhenkova 2008; Yukhina 2007).

2.2.2 Vandenberg-Kuse Mental Rotation Test

The Vandenberg-Kuse Mental Rotation test (VMR) [46] measures mental rotation transformation ability - i.e., the ability to take a solid object and determine whether another view of a solid object is the same as the first object.

A typical VMR test problem is provided in Figure 2. A primary object is presented at the far left. Participants are to choose which two of the four objects on the right are the same as the primary object. The only difference between the primary object and the chosen objects are that they are presented at different angles.

An answer is only recorded as correct if both correct choices are identified. Similar to the Paper Folding test, the Vandenberg test features two sets of 10 questions; participants are given three minutes to complete each half. Although participants are encouraged not to guess, the participant's score is recorded as the simple sum of the correct answers (i.e., no scoring penalty exists for incorrect answers).

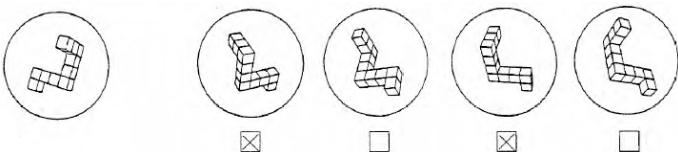


Figure 2. Vandenberg-Kuse Mental Rotation Test Problem

It is claimed that performance in this cognitive task is connected with some aspects of designing based on a phenomenological correlation [47].

2.2.3 Shepard-Metzler Mental Rotation Test

The Shepard-Metzler Mental Rotation Test (MRT) [48] measures a similar ability as the Vandenberg-Kuse test, which derived from it. As it measures one's ability to imagine the rotation of objects from a fixed perspective, it is used as a confirmation of mental rotation ability.

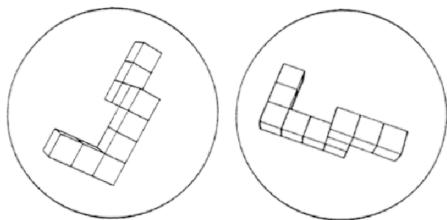


Figure 3. Shepard-Metzler Mental Rotation Test Problem

Unlike the paper-based PFT and VMR tests, the MRT test is taken using a computer. The computer is necessary as both accuracy and response time are measured. Participants are faced with 36 problems that resemble that presented in Figure 3. The student is shown pairs of shapes and is asked to determine whether the shape on the right is the same or different from the shape on the left. A left-mouse button click indicates that the shapes are the same; a right-mouse button click indicates that they are different.

2.2.4 Spatial Imagery Ability

The Spatial Imagery Ability test (SIA) [45, 49] measures one's ability to mentally manipulate objects and various spatial relations between two objects. This is a relatively new test for which good background results are not yet available.

Participants are faced with a total of 24 problems, grouped into three parts: the wireframe test (Figure 4), rotation of two figures test (Figure 5), and the folded box test (Figure 6). In the wireframe test, participants are shown a figure which features a wire frame shape and asked to identify how the frame might look from a given viewpoint. In the rotation of two figure test, participants must determine the shape that would result from two separate shapes rotating into the same space. Finally, in the folded box test, participants are provided with an image showing six-sides of a flat box; they are then asked to identify the 3D figure that would result from folding the shape into a box.

You are looking from **beneath**.
Please choose the correct
Wire Frame appearance from
the views below.

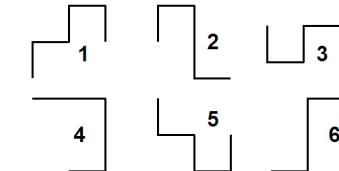
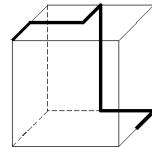


Figure 4. SIA Wireframe Test Problem

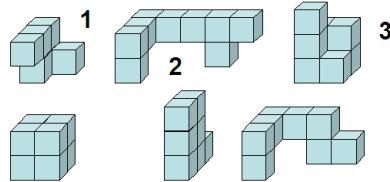
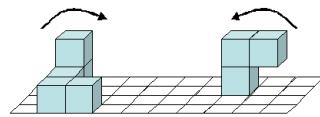


Figure 5. SIA Two Figure Rotation Test Problem

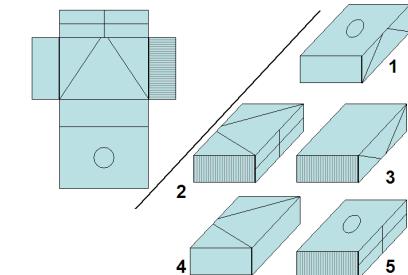


Figure 6. SIA Folded Box Test Problem

3 EXPERIMENTAL METHOD

The site for this research is a large mid-Atlantic land-grant university. The engineering college, which features an enrollment of 25% of the total university student body, is the largest within the university. As discussed in Section 1.1, the study will monitor the development of design thinking in engineering students in two different disciplines. Aside from a common experience in a required sequence of first-year engineering courses (which features a four-week module that discusses the design process), and the traditional engineering pre-requisites (e.g., calculus, chemistry, physics, statics, etc.), these two cohorts have very little curricular overlap. One cohort, the control group (“engineering mechanics”), will have little or no exposure to design education. The other cohort, the experimental group (“mechanical engineering”), will be tracked through their design education.

3.1 Control Group: “Engineering Mechanics”

The control group is drawn from a major focused in engineering mechanics. This major has a theoretical orientation with a first-principles, engineering sciences approach that focuses in mathematical modeling more so than in design. This major offers an interdisciplinary curriculum that combines the fundamental principles of engineering mechanics with applied physics and mathematics to develop a strong combination of science and engineering skills. The curriculum includes rigorous courses in advanced mathematics (including vector and complex analysis and operational methods such as Laplace transforms, Fourier series, partial differential equations, and Sturm-Liouville problems) to ensure that students have the ability to model complex systems in multiple domains. In addition, advanced course in fluid mechanics, solid mechanics, dynamics, and vibration and control ensure that students develop a facility with underlying engineering principles that is both broad and deep.

This emphasis on first principles and fundamentals enables graduates of the program to move into many of the more applied fields of engineering such as mechanical, civil, and aerospace. The department graduates approximately 30 students annually (~25% female). Almost half of these students go on to graduate study either at another university or through a university-wide program that allows students to complete bachelors and masters degrees in a combined five-year program.

3.2 Experimental Group: “Mechanical Engineering”

In contrast, the experimental group is drawn from a mechanical engineering major that uses design as a context for its curriculum. This cohort is almost an order of magnitude larger than the control group described in the previous subsection. The curriculum reflects the breadth of the discipline as it features four primary content areas: (i) electrical and control theory, (ii) thermal fluid sciences (e.g., heat and mass transfer, thermodynamics, fluid dynamics), (iii) mechanics (e.g., machine elements, system dynamics, vibrations), and (iv) design.

The design curriculum serves as the backbone of the overall curriculum as it provides students the opportunity to synthesize and apply the content knowledge gained in the analysis-centered courses of the other three mechanical engineering content areas. Including the first-year design experience, this group’s curriculum is composed of four courses focused in design: a sophomore-level design methodology and product development course and a capstone design experience that spans both semesters of the senior year. These courses, and their associated team-based projects, not only provide students experience in applying discipline knowledge to open-ended problems, they also provide an opportunity for students to gain understanding of design-related concepts including systematic design methodology, design for manufacturing, product architecture, solid modeling,

manufacturing, professional communication, and engineering economics.

3.3 Testing Procedure

The four spatial ability tests outlined in Section 2.2 were administered to all sophomore-level students of enrolled in both majors in the fall semester of 2009. While students were given the opportunity to not have their results included in the research study, all students were required to complete each of the four tests; their participation was accounted as a homework assignment.

The paper-based tests, PFT and VMR, were conducted during class using Opscan bubble forms. Study participants completed the MRT and SIA tests, which are computer-based tests, out-of-class. Participants were given two weeks (one week for each test) to download the executable test files, install and take the tests, and to upload the resultant output files to the course website. While the PFT and VMR tests were administered at the same time and day of the week to reduce the number of experimental variables, this could not be accomplished for the MRT and SIA tests. However, the large sample size and randomness of time at which the tests were taken are believed to negate any potential effects on the results.

4 RESULTS AND ANALYSIS

The overall results of all four spatial reasoning tests for both cohorts are presented in Figure 7. As depicted, both majors (“engineering mechanics” labeled as cohort 1 and “mechanical engineering” labeled as cohort 2) attained the highest scores for the MRT followed by the SIA, the PFT, and the VMR test.

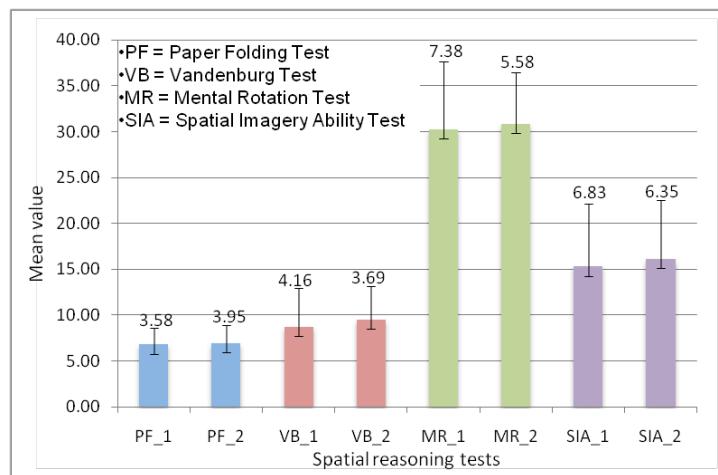


Figure 7. Spatial Reasoning Test Results for Both Cohorts

JMP 8.0, a statistical analysis software, was used to further examine any statistical differences between the performances of the two groups of students. Statistically significant differences were assumed at a significance level (α) of 0.05.

The normality assumption was tested using the Shapiro-Wilk W test. The results are reported in Table 1. Aside from the PT and VMR test results for the “engineering mechanics” students, none of the test results followed a normal distribution.

Table 1. Normality Test Results

Test	“Engineering Mechanics”		“Mechanical Engineering”	
	Shapiro-Wilk W	p-value	Shapiro-Wilk W	p-value
PFT	0.967	0.544	0.965	<0.001*
VMR	0.933	0.119	0.989	0.048*
MRT	0.698	<0.0001*	0.743	0.0000*
SIA	0.875	0.049*	0.940	<0.001*

* p < 0.05

Since most of the test results did not meet the normality assumption, non-parametric statistics were used. The Wilcoxon rank sum test, a non-parametric test used to identify differences between two samples, was conducted to make comparisons between the two groups of students. As seen in Table 2, the results of this analysis indicate that there is no statistically significant difference between the two cohorts for any the spatial reasoning test results.

Table 2. Statistical Analysis Results

Test	“Engineering Mechanics”		“Mechanical Engineering”		p-value
	N	Mean (STD)	N	Mean (STD)	
PFT	27	6.78 (1.79)	266	6.86 (1.98)	0.54
VMR	24	8.75 (4.16)	270	9.48 (3.69)	0.19
MRT	21	30.29 (7.38)	225	30.87 (5.58)	0.95
SIA	14	15.29 (6.83)	179	16.15 (6.35)	0.95

This result appears to be different to results obtained by others [43]. The difference may be due to the demographics of the subjects. In the tests reported here, the subjects were sophomore students in their first semester that had been exposed to very little design teaching prior to the semester of test administration. However, these results imply that there is no spatial cognitively-based self-selection of programs in these two cohorts.

Table 3 presents results from recent studies of spatial testing of design-related subjects [47, 50].

Table 3. Spatial Reasoning Ability Test Results of Other Students

Test	Science	Visual Art	Architecture	Humanities
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
PFT	6.68 (1.35)	4.43(2.48)	6.81 (2.46)	5.25 (2.26)
VMR	8.88 (0.90)	7.38 (1.48)	8.32 (0.9.0)	7.97 (1.045)

Comparing the results of the engineering students (Table 2) with those in Table 3, we can see that both science and architecture students have comparable paper folding and Vandenberg-Kuse performance. This may come as a surprise given the form-giving nature of architecture compared to engineering. These tests are concerned with reasoning about given shapes and relationships and it may be that generating

shapes and relationships is not a complete homomorph to reasoning about given shapes and relationships (Kosslyn 1996). There are few comparative results for SIA.

Engineering students perform better at spatial reasoning ability tests than does the general population as can be seen by comparing results shown in Table 2 with those of the general population in Table 4. This is not a surprising result.

Table 4. Spatial Reasoning Ability Test Results for the General Population

Test	General Population	
	Group I*	Group II*
	Mean (SD)	Mean (SD)
PFT	6.04 (2.25)	5.47 (1.85)

* Group I is represented by 191 college students

** Group II are 11th and 12th graders, ~300 males and ~200 females

Table 4 confirms that spatial reasoning ability is developmental. The results of this longitudinal study will assist us in determining whether it develops as part of the educational process or whether it reaches its peak development before a person enters college, as occurs with many other cognitive skills.

5 CLOSURE

This paper presents preliminary results from the first phase of a longitudinal study of design cognition and the effects of design education on design practice. The study aims to monitor the development of engineering design thinking through a three-year protocol study of control and experimental groups of engineering students. The control group, “engineering mechanics,” consists of students enrolled in an engineering major with a theoretical orientation that has a strong, first-principles, engineering sciences approach that focuses in mathematical modeling more so than in design. In contrast, the experimental group (“mechanical engineering”) features students enrolled in an engineering major that uses design as a context for its curriculum, emphasizing hands-on design experiences, machine design principles, and courses dedicated to design methods and product realization techniques.

Four spatial reasoning ability tests were administered to all sophomore students of the two cohorts to investigate whether or not students self-selected their engineering major based on cognitive ability. The results from these surveys confirmed that students’ spatial cognitive ability is less likely to influence their selection of the major. However, it is expected that students may develop different cognitive skills due to different education. The results also supported that the sophomore engineering mechanics and mechanical engineering students have equivalent foundation in terms of spatial cognitive ability. These preliminary results will be the basis of monitoring and identifying the development of the students’ engineering design thinking. This baseline equality implies that changes in design

cognition that emerge in subsequent phases are much more likely to reflect the impact of curricular differences.

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