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Cognitive Demand of Engineering Information

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By

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Cognitive Demand of Engineering Information

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Construction project performance at the task level is ultimately driven by craft workers. The quality and ease of use of the information they are given is critical to their success. Developments in three-dimensional (3D) computer aided design (CAD) and 3D printing provide new mediums to deliver engineering information to the face of the work. Information types have varying levels of cognitive demand. Appropriate information types should be given to workers considering their finite cognitive abilities. This research studies the cognitive demands of two-dimensional (2D) plan sets, 3D CAD, and 3D printed models on construction workers. Research subject completed scale model structure assemblies using the three information formats. Performance on each assembly was quantitatively measured with construction industry performance metrics. Subjects' cognitive abilities were also determined using standardized testing methods. Statistical analysis supports the research hypothesis that 3D physical models lead to better performance than 2D plans and 3D CAD due to a lower cognitive demand. Additional trends were discovered within the sample population demographics. The primary contribution to the overall body of knowledge is establishing new trends between a person's cognitive abilities and the cognitive demand of the information they are given.

CONTENTS

TABLES

FIGURES

CHAPTER I

INTRODUCTION

The construction industry is an important sector of the US economy accounting for 3.6% of the U.S. Gross Domestic Product (GDP) (Bureau of Economic Analysis 2013). The number of new building permits is often used as a leading indicator to predict turning points for the whole economy. The Organization for Economic Co-Operation and Development (OECD) uses the number of houses started as reported by the U.S. Census Bureau as one of the seven metrics in its Composite Leading Indicator (OECD 2014). The productivity of the construction industry has a great impact on the overall performance of the economy. Studies have shown that construction has fallen behind all other sectors of the economy even having declining productivity since the late 1960s (Teicholz 2001).

Tracking construction industry productivity is a challenging task and an inexact science. The Bureau of Labor Statistics (BLS) maintains productivity indices for most industries other than construction (Bureau of Labor Statistics 2013). The U.S. Census Single-Family Houses index is one commonly used index. It uses a 1974 style home as the basis of comparison and fails to take into account new features built into modern homes. Challenges measuring construction productivity and lack of a uniform scale have lead others to argue that construction productivity has improved since the late 1960s. Goodrum et al. found the construction industry improved at an annual compound rate of 1.2% from 1976 to 1998 (Goodrum et al. 2002). These findings were discovered by analyzing construction at the activity level. This eliminates the need to adjust for inflation of the real output of construction.

Productivity is even more critical at the project level. The construction industry is very fragmented composed of many small firms. The industry is made up of 773,614 companies employing 7,268,000 people (U.S. Census Bureau 2012). The lack of industry unity makes it challenging to implement productivity improvements. Companies must ultimately be proactive in improving their productivity at the activity level. With construction profit margins dropping below 1% in 2010, firms need to pursue any incremental productivity improvements available to them (Stonington 2011). At the activity level, craft workers need the proper tools, information, materials, equipment, and space to be productive. This paper examines opportunities for improving the delivery of engineering information to workers.

CHAPTER II

LITERATURE REVIEW

2.1. Effects of Information Delivery on Construction Productivity

Despite being used for thousands of years engineering drawings are still problematic on construction sites. Liberda et al. asked industry professionals to rank 51 factors effecting construction productivity under the categories of human manpower, management, and external environment. Lack of information ranked 4th of 33 in the management category and 8th of 51 overall (Liberda et al. 2003). Informational issues are even more drastic in the opinion of craft workers. The Construction Industry Institute (CII) interviewed close to 2,000 construction workers to discover issues that slowed construction productivity. Three of the top ten issues are related to engineering drawings (Dai et al. 2009):

2. There are errors in the drawings that I use.

3. When there is a question or problem with a drawing, the engineers are slow to address the issue.

10. My supervisor does not provide me with enough information to do my job.

For the level of construction productivity to catch up to other industries, engineers will need to rethink how they are transmitting project information.

2.2. Engineering Information Formats

2.2.1. Two Dimensional Drawings

The main form of engineering information delivery, 2D drawings, has remained relatively unchanged for years. The earliest known engineering drawing from 2130 B.C. in Babylon depicts the plan view of a temple, a stylus, and a notched bar used as a scale (Barr and Juricic 1994). Small changes were made as building plans slowly developed to their current form. The largest change was in 1795 when French mathematician Gaspard Monge published *Geometrie Descriptive* proving that all spatial problems can be solved graphically using two or more projection planes (Barr and Juricic 1994). Descriptive geometry is still the basis for displaying the same 3D object in multiple 2D views used by computer technology. Today construction documents including plan, elevation, section, isometric, and detail views are the legal basis for design intent and consequently the standard form of engineering information. Constructing one small area of a project often requires numerous drawings from architects, structural engineers, subcontractors, and fabricators. Coordinating information from different sources on different sheets can be complex and lead to errors.

2.2.2. Computer Aided Design (CAD)

The construction industry was forever changed with the introduction of computer aided design (CAD). CAD was voted as the greatest advancement in construction by many prominent industry leaders interviewed by The Architects' Journal, New Civil Engineer, and Construction News publications (Wynne 2012). It has allowed engineers to design and construct much more complex structures. The main benefits of CAD were found to be simplified reuse and revision of drawings, planning construction sequencing and methods, designing site layouts, and coordinating subcontractors (Mahoney and Tatum 1994). Once engineering plans were created they could be printed many times and overlaid with various construction plans and notes. Basic plan sheets are quickly used to produce site layouts, traffic control plans, equipment storage and movements, and work sequencing. One case study found that using CAD to optimize the arrangement of piles facilitated a streamlined design change and saved the contractor thousands of dollars (Mahoney and Tatum 1994). Finally, drawings can be quickly customized to only include information necessary for specific subcontractors. Post project interviews discovered that while subcontractors were initially reluctant to pay for CAD costs, "subcontractors later acknowledged the value of the consistent, up-to-date information they received and would willingly pay for it on future projects" (Mahoney and Tatum 1994). CAD is now common in the construction industry, but the lessons learned from early adopters can be applied to new innovative technologies.

2.2.3. Building Information Modeling (BIM)

Computer aided design in the architectural, engineering, and construction industries has evolved into integrated building information modeling. Building information modeling (BIM) is defined in the *BIM Handbook* as models that contain graphical, data, and behavioral attributes, consistent and non-redundant data, and coordinated data between platforms and trades (Eastman et al. 2011). Conversely, models that only contain 3D graphical data, have no support behavior, are composed of multiple 2D CAD drawings, or allow changes to dimensions in one view that are not automatically updated in other views are not BIM models (Eastman et al. 2011). These small but important classifications are the difference between using computers to replace pencils as drawing tools and using them to manage a central database of project information.

2.2.4. Mobile Information Technology

Mobile information technology (IT) on construction sites seeks to put engineering information into the hands of the people actually building construction projects. Mobile IT on construction sites allows data to be transmitted from the field to the office instantly through the use of smartphones, PDAs, laptop computers, and recently tablet computers. Case studies conducted on eleven construction projects in the United Kingdom found that being able to digitally record and transmit field situations to the office improves the quality of work, increases the efficiency of task allocation, reduced task turn-around time (Bowden et al. 2005). These improvements were generally achieved because the transfer of information was shortened by as much as three weeks. Initially recording the information digitally rather than on paper also benefitted the projects. Instantly generated reports were in a structured format and stored centrally allowing trends (e.g. safety and quality) to be quickly discovered (Bowden et al. 2005). Finally, data was able to be pushed from the central office to the field personnel. Field employees are able to get work orders as they are generated, use downtime to respond to emails, and avoid duplicate work with others (Bowden et al. 2005). At a very basic level mobile IT saves workers a walk back to the job trailer to look up information.

While small mobile devices work for text based information, larger devices are necessary to utilize BIM models in the field. Balfour Betty and other construction companies are replacing standard plan tables with large flat screen TVs. Balfour Betty's implementation of technology on the Dallas Fort Wayne airport project is projected to save them $5M in printing cost alone (Rosoff 2013). Other companies, such as Mortenson Construction, have their TVs in mobile field work stations that lock up at night like a tool box.

2.2.5. Physical Models

Physical models have been used for year in the construction industry as planning and communication tools. Models can consist of the entire project or individual elements built to scale. They were used as checks on design and for construction sequences with model construction cranes and equipment. Certain models could be disassembled to plan the material handling and laydown yard (Oglesby et al. 1989). Models for infrastructure projects are often used during town hall meetings to explain the project to the public stakeholders. Financial benefits of models are difficult to quantify since the benefits occur in a variety of ways. Some qualitative benefits of models are reported that workers understand the model easier than hundreds of drawings, superintendents and foreman can plan work quickly around a model, and erection sequences are easier to plan (Oglesby et al.

1989). Despite the difficulty measuring the impact of models, many owners believed it was a valuable investment.

The increased use of CAD and BIM replaced the use of physical models for preplanning purposes. Development of 3D printers offer the speed and affordability to create physical models again. Academic pilot projects are evaluating the cognitive demand of 3D printed models on craft workers. Tangible models have the potential to remove the learning curve that is associated the usage of BIM software packages.

2.3. Cognitive Demand

2.3.1. Cognitive Ability

Regardless of the information medium given to workers, they must fully comprehend it to successfully complete their job tasks. They have a finite cognitive ability with which to process the information. When interpreting engineering information, workers are using their spatial abilities, specifically spatial orientation. Spatial orientation is the ability to, "perceive spatial patterns or to maintain orientation with respect to objects in space" (Ekstrom et al. 1976). When interpreting information this allows a person to create and manipulate mental images. The steps to do so are encoding, remembering, transforming, and matching spatial information (Lohman 1979). Mentally reassembling orthographic displays leads to ambiguities, omissions, and interferences (Rieber 1995). The Educational Testing Service (ETS) has established two tests to evaluate a person's spatial relations ability, the card rotation test and cube comparison test (Ekstrom et al. 1976). The card rotation test, Figure 2.1, measures one's ability to mentally manipulate objects two dimensionally. Each question illustrates a 2D shape and eight similar objects. Subjects must determine whether each object has just been rotated (“same”) or has been flipped and rotated (“different”).

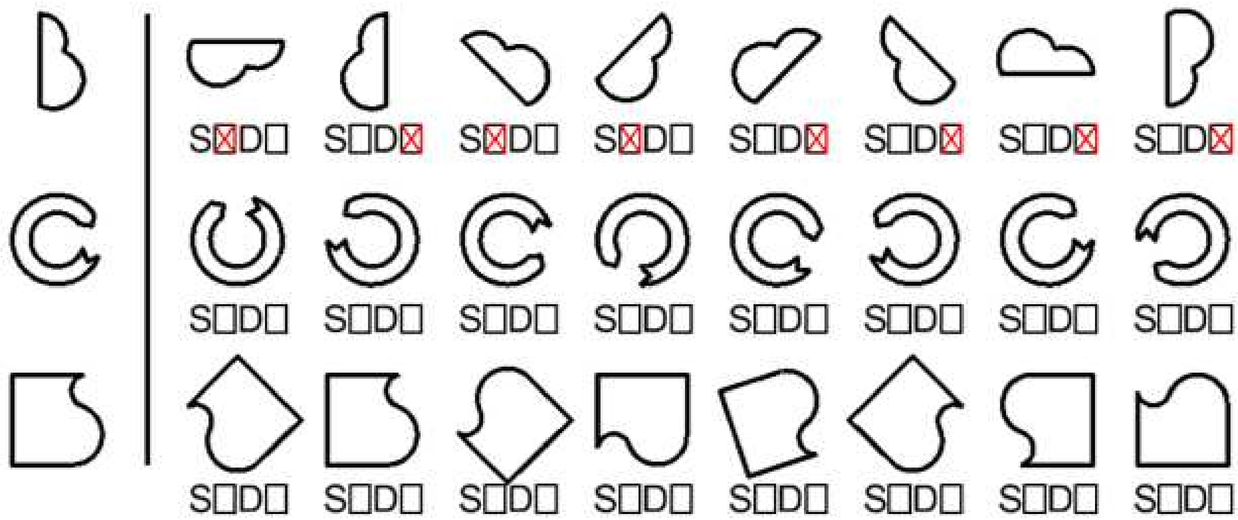

Figure 2.1. Card Rotation Test Questions

The cube comparison test, Figure 2.2, is similar but tests a person’s three dimensional cognitive abilities. Questions depict two cubes marked with a letter on each face (letters are not repeated on a single cube). If the first cube can be turned into a different position to resemble the second cube, the subject marks them as the “same”. If the first cube cannot be turned to resemble the second due to incorrect relative position of the letters, the subject marks them as “different”.

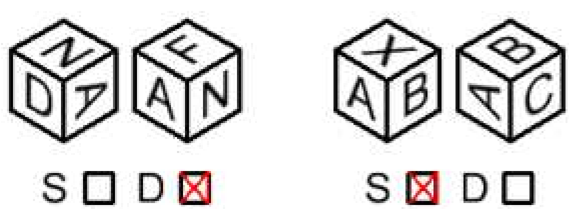

Figure 2.2. Cube Comparison Test Questions

2.3.2. Cognitive Loading

To accommodate workers' varying levels of cognitive abilities on a job site, engineering information should have the lowest cognitive demand possible. Current paper and computer tools available have limited functionality requiring workers to proceed without critical information they need or perform additional steps to change the workflow (O'Brien et al. 2011). The lack of flexibility increases the cognitive demand on the worker. Analysis of a construction superintendent's work tasks determined that information sources must be transportable to the job site, visually editable to display job progress, and accessible to a wide range of workers on the project (O'Brien et al. 2011). Having contextual information present further reduces the cognitive demand on a worker to orient himself/herself. Karmat et al. determined that the real world site conditions provide the best contextual perception and eliminate any effort required to create contextual site conditions in any type of informational format (Kamat et al. 2011). Ideally site conditions would be compared to an information format with similar characteristics. 3D printed models are transportable, physically three dimensional (opposed to visually 3D CAD), and tangible. These aspects give models the potential to greatly lower the cognitive demand on construction workers. This study closely builds upon the work of Dadi et al. examining the cognitive demand of engineering information formats.

Dadi et al. examined the mental loading of 2D plans, 3D CAD, and a 3D printed model on test subjects building scale model assemblies. Research participants put together a scale model assembly three times using each information type as instructions. Through the use of the NASA-rTLX workload measure, subject's mental loading was measured after each assembly. 3D printed models were found to have the lowest average overall mental load for the NASA-rTLX (Dadi et al. 2014). The difference in means was not found to be statistically significant when performing a one way ANOVA analysis of the NASA-rTLX measures. Familiarity with an information medium leads to higher comfort levels with the task involved. Subjects that reference engineering drawings daily experienced a 35% lower temporal demand during the assemblies (Dadi et al. 2014). This finding would suggest that formal training would lower the mental demand on workers and potentially improve their performance. Years of construction industry experience would be expected to lower the mental demand on subjects. The opposite was found to be true. The group with the least experience was found to have a lower mental demand by 16% (Dadi et al. 2014). While the methods used in this study are similar to those of Dadi et al and seek to expand upon its findings, notable changes have been made to attempt to control for confounding variables.

This study has identified and seeks to improve upon limitations in the research done by Dadi et al. The main limitation by Dadi et al. is that test subjects performed the same scale model assembly three times in a row. The result is a statistically significant learning curve that lowered the mental demand by 15% and temporal demand by 19% between the first and third model (Dadi et al. 2014). Simply becoming accustomed to how the model pieces fit together has the potential to produce a learning curve. The model used was fairly simple in both its components and design limiting the likelihood of mistakes. Only two building elements were used, columns and beams. The assembly design, Figure 2.3, was also fairly simple consisting of uniform structural bays that terminated at differing levels. CAD models in this study were accessed through desktop versions of software. With the goal of testing engineering information for field use, appropriate technology needs to be used that can accessed at the face of the work and presents only the information a craft worker would utilize. Finally the only analysis that broke down the mental loading by information type was found to be statistically insignificant. The research methods below describe how this study seeks to build upon the work performed by Dadi et al.

Figure 2.3. Scale Model Assembly (Dadi et al.)

CHAPTER III

RESEARCH METHODS

In order to test the hypothesis that 3D printed models have a lower cognitive demand than 2D plans and 3D CAD, a controlled experiment was designed and executed to determine an individual's cognitive ability and measure their performance interpreting each information medium. The protocol for this research study can be found in Appendix A.

3.1. Scale Model Assembly

The central activity in the experiment is the assembly of three scale model structures. Subjects were given the instructions to construct Assembly 1, Assembly 2, and Assembly 3 via a standard 2D construction drawing plans set, a 3D CAD model on an iPad, and a 3D printed physical model respectively. The complete 2D plan set used is included in Appendix B. An iPad was chosen as the method to display CAD models for two reasons. First, as mentioned tablets allow mobile access to information anywhere on the jobsite removing the previous limitations confining IT to the job trailer and project engineers. Secondly, CAD applications on tablets are designed for field use by only displaying critical information and greatly simplifying model navigation. Simple swiping and pinching gestures that smartphone owners have become accustomed to are all that is needed to navigate tablet CAD models. This negates most of the unfamiliarity with a CAD model and corresponding learning curve.

The assemblies were constructed using building elements from the Post Office Girder and Panel Building Set by Bridge Street Toys. Assembly 1 and the corresponding 2D plan set are illustrated in Figure 3.1. Assembly 2 and the 3D CAD model can be seen in Figure 3.2. Assembly 3 and the 3D Printed model are pictured in Figure 3.3. The assemblies utilized five different building elements: columns, beams, girders, slabs, and joints. The use of three extra piece types as well as asymetrical geometry serves to increase the model complexity.

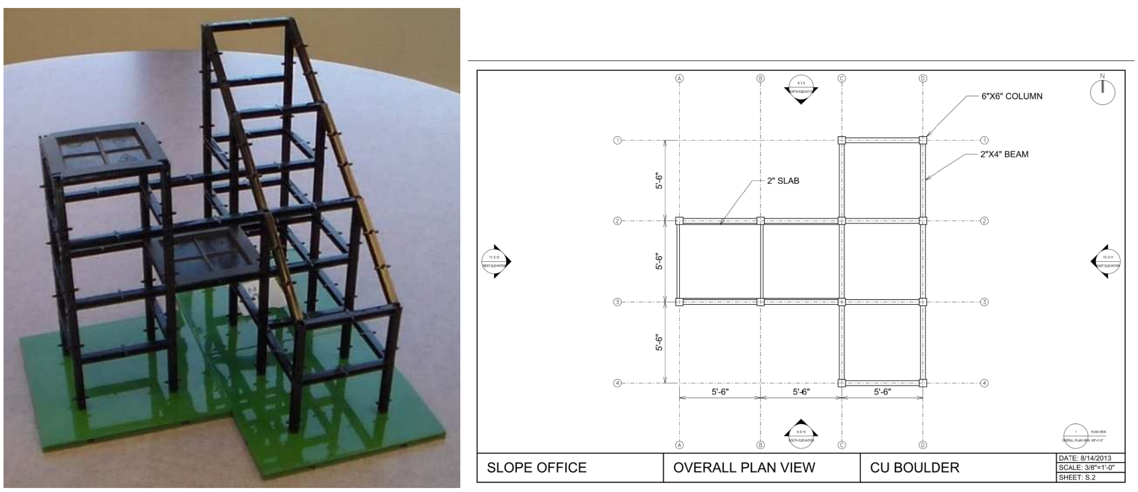

Figure 3.1. Scale Model Assembly 1 and 2D Plan Set

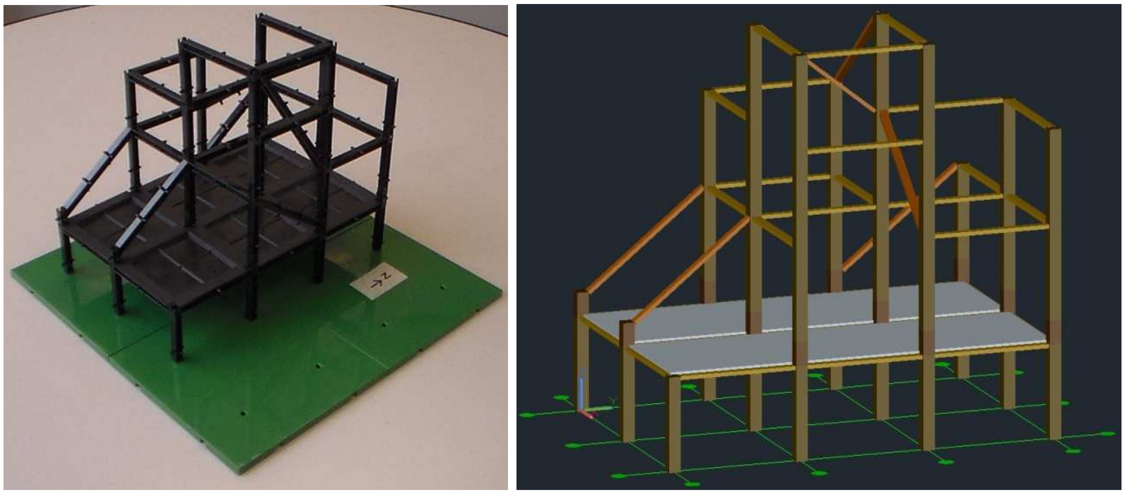

Figure 3.2. Scale Model Assembly 2 and 3D CAD Model

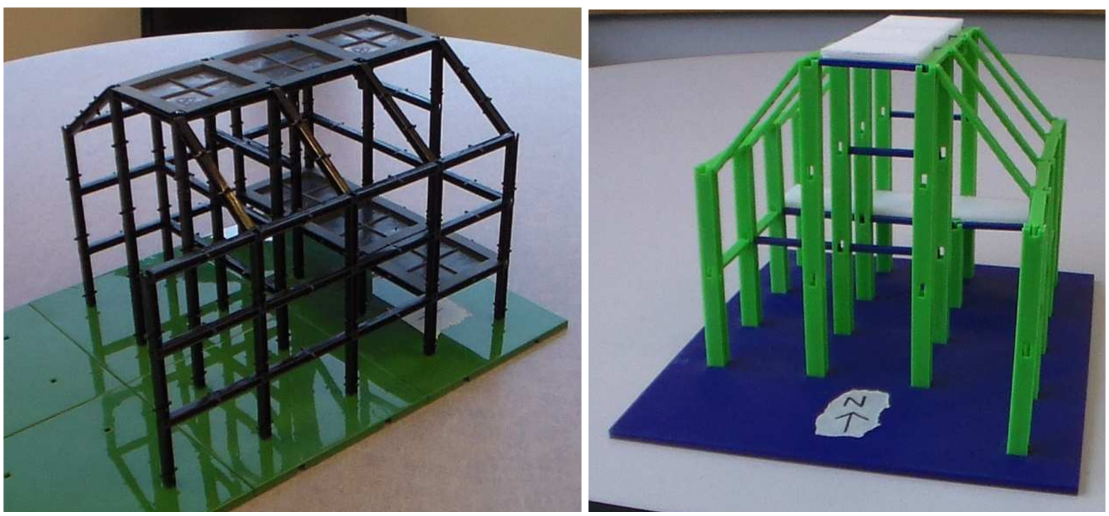

Figure 3.3. Scale Model Assembly 3 and 3D Printed Model

Subjects were recorded on various metrics to measure their performance on each scale model assembly. Subjects were not given a time limit to complete the assemblies. When they determined that they were finished, the time taken and number of errors was recorded. Five minute ratings are a standard construction tool used to evaluate the effectiveness of a work crew (Ogelsby et al. 1989). A five minute rating was performed from a video recording of each assembly process. A sample of the five minute rating form used is in Appendix C. Subjects' times were broken down into percentages spent on direct work, indirect work, and rework.

Direct work is defined as the physical act of installing a piece of the assembly. Indirect work is any action performed toward the completion of the assembly that is not physically installing components. This category included examining currently installed elements and interpreting the engineering information. Rework is the removal or reinstallation of a previously completed part of the assembly. The results can be found in Chapter 4.

Quantitative and qualitative data outside of the scale model assemblies was also collected. Subjects' cognitive abilities were measured using the card rotation and cube comparison tests previously described. The exact card rotation and cube comparison tests used can be found in Appendix D and F respectively. Participants were given a demographics questionnaire, Appendix 0, and post assembly questionnaire, Appendix I. This data was also used to explore trends when interpreting engineering information.

The two variables of potential learning curve and varying difficulty between each scale model assembly were controlled for by design. The original decision to use three different assemblies was made to avoid a learning curve on subsequent assemblies. Additionally, subjects received the three assemblies and corresponding information mediums in varying order. Subjects completed a sample scale model assembly using a 3D CAD model on the iPad. This reduced any delays caused by unfamiliarity of how the assembly pieces fit together or how to navigate CAD models on the iPad. To ensure a comparable level of difficulty between each assembly, baseline testing was performed in which the information medium was held constant.

3.2. Baseline Testing

3.2.1. Baseline Testing Sample Group

University of Colorado students were recruited to serve as subjects to gather preliminary empirical evidence on the difficulty level of each scale model assembly. Basic demographics of the student population are listed in Table 3.1. The students went through the prescribed research experiment with one change. They were given the assembly instructions via the 3D CAD model for all three assemblies. In an ideal scenario with equally difficult assemblies and constant information type, the recorded metrics for an individual would be the same for all three assemblies.

Table 3.1. Baseline Testing Sample Demographics

Demographics	Practitioners
Number	10
Age range	19-45
Formal training with blueprints	8/10
Years of experience	0-18
Current Occupation	Student

3.2.2. Baseline Testing Results

Metrics from the baseline testing sample group demonstrate the comparable level of difficulty of the three model assemblies. The averages for each metric are illustrated in Table 3.2. High performance on an assembly would result in a high percentage direct work and low numbers for indirect work, rework, time to completion, and number of errors. Model 2 is the most difficult having the lowest direct work and highest indirect work, rework, and time to completion. Model 1 is the least difficult model with the lowest time to completion and percentage of indirect work. Although the number of errors refutes these claims, analysis will show that this metric is not a good indicator given the small sample size. The analysis below suggests that the slight variation in difficulty between the three models is negligible. The raw data from the baseline testing group is in Appendix J.

Table 3.2. Baseline Testing Results

Model Assembly	**Sample Size**	**Time to Completion (m:s)**	**Number of Errors**	**Direct Work (%)**	**Indirect Work (%)**	**Rework (%)**
1	10	09:14	1.0	74.5	20.9	4.5
2	10	09:56	0.0	69.1	24.5	6.4
3	10	09:54	0.5	74.2	20.9	5.0

3.2.3. Baseline Testing Analysis

Statistical quality control analysis was performed on the data to ensure the variance within each subject was within an acceptable limit. Dr. Shewhart determined that every process has chance cause variation that is naturally inherent and assignable cause variation (Swift et al. 1998). Any process that only has chance cause variation is said to be in statistical control. Range (R) charts are used to measure the within-sample variability when the sample size is ten or less. The within-sample variability for each subject is compared to the average range (R-bar), the upper control limit (UCL), and the lower control limit (LCL). If all three assemblies had the exact same level of difficulty, the variance within each subject's performance metrics would only exhibit chance cause variation and be within the control limits. The R chart for time to completion, Figure 3.4, exceeded the upper limit once.

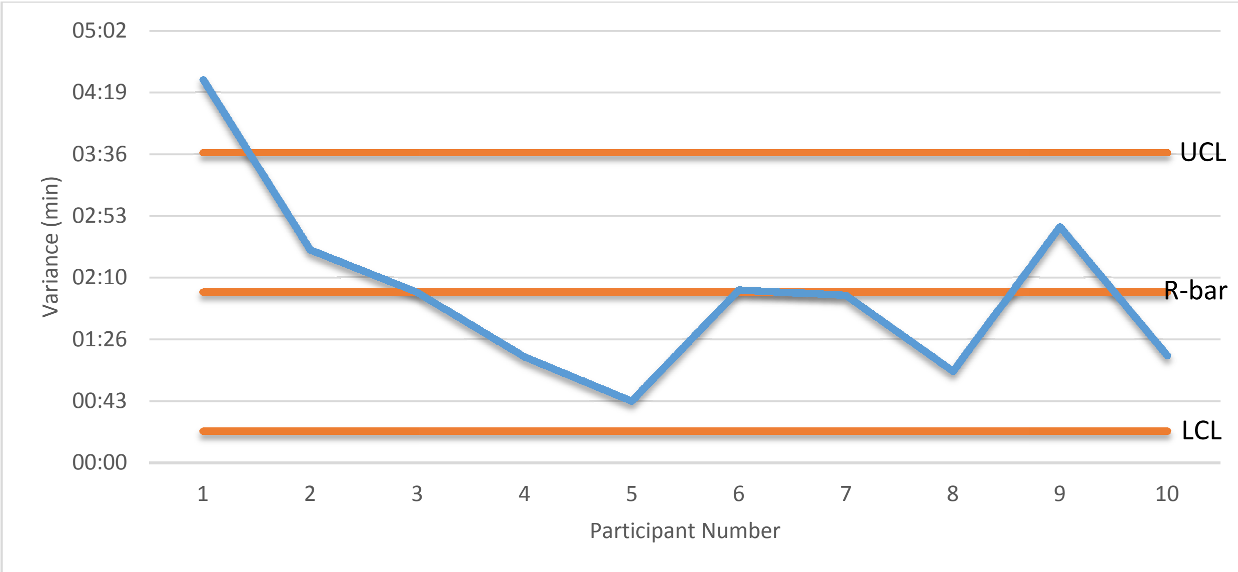

Figure 3.4. Time to Completion R Chart

Participant number 1 caused this deviation. This subject can be treated as an outlier as their time on two models was within two minutes of each other (within control), but the third time was five minutes longer (far outside control). After adjusting the chart by removing participant number one, Figure 3.5, the time to completion is within control limits.

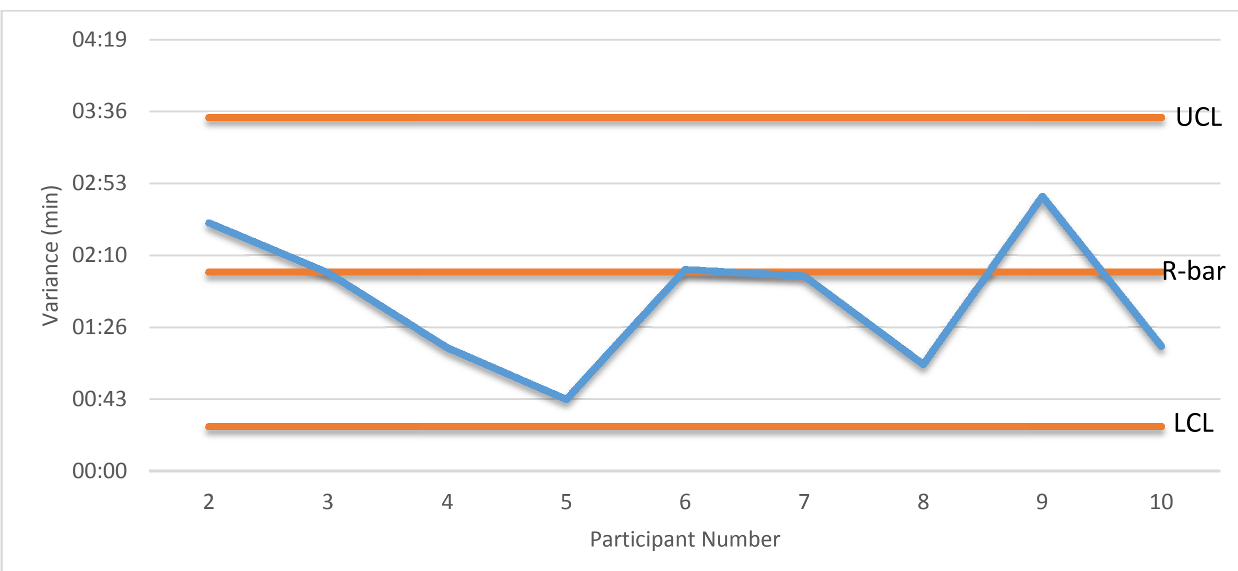

Figure 3.5. Adjusted Time to Completion R Chart

The control chart for number of errors, Figure 3.6, also exceed the upper limit for one participant. Participant number 3 recorded zero, zero, and ten errors for the three assemblies. The ten errors resulted from ten pieces not being installed when the participant determined the assembly process was complete. Failure to double check the completed product caused the ten errors more than the complexity of the model.

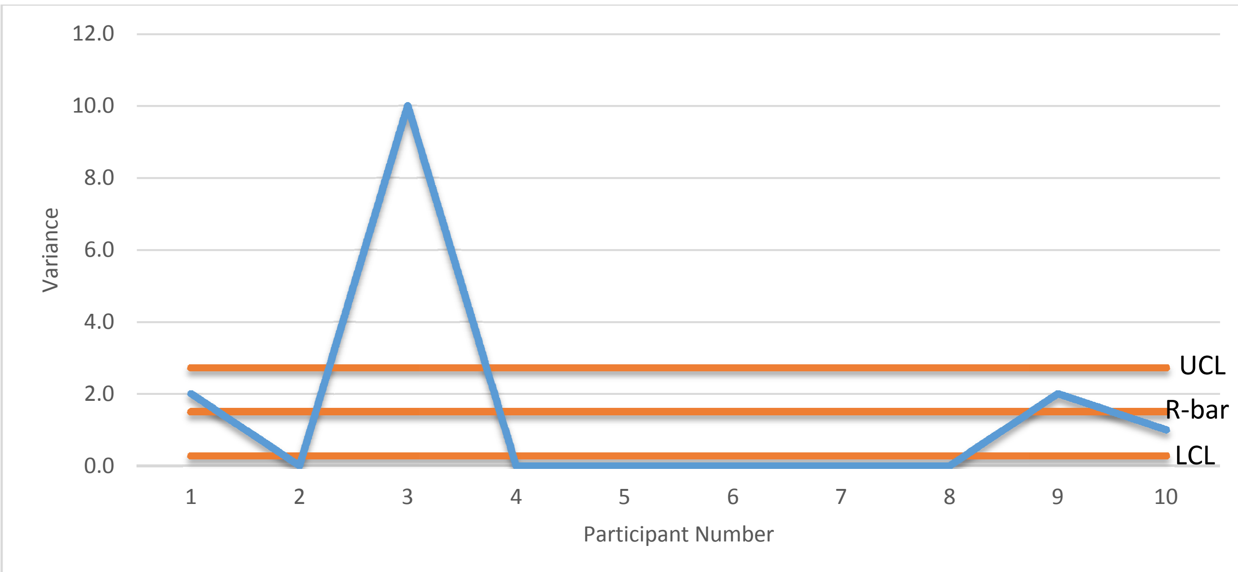

Figure 3.6. Number of Errors R Chart

Participant number 3 was treated as an outlier and removed in the adjusted number of errors R chart illustrated in Figure 3.7. After adjusting the chart participant's number 1 and 9 exceed the upper limit. The number of errors seems to be a binary metric in the sense that participants on one particular assembly either perform multiple errors or perform none. Therefore the variance is zero for most participants which serves to lower the upper control limit. Participants that perform errors on only one or two assemblies have large variances and therefore exceed the upper control limit. The sample size is too small to account for these few, large variations in the population.

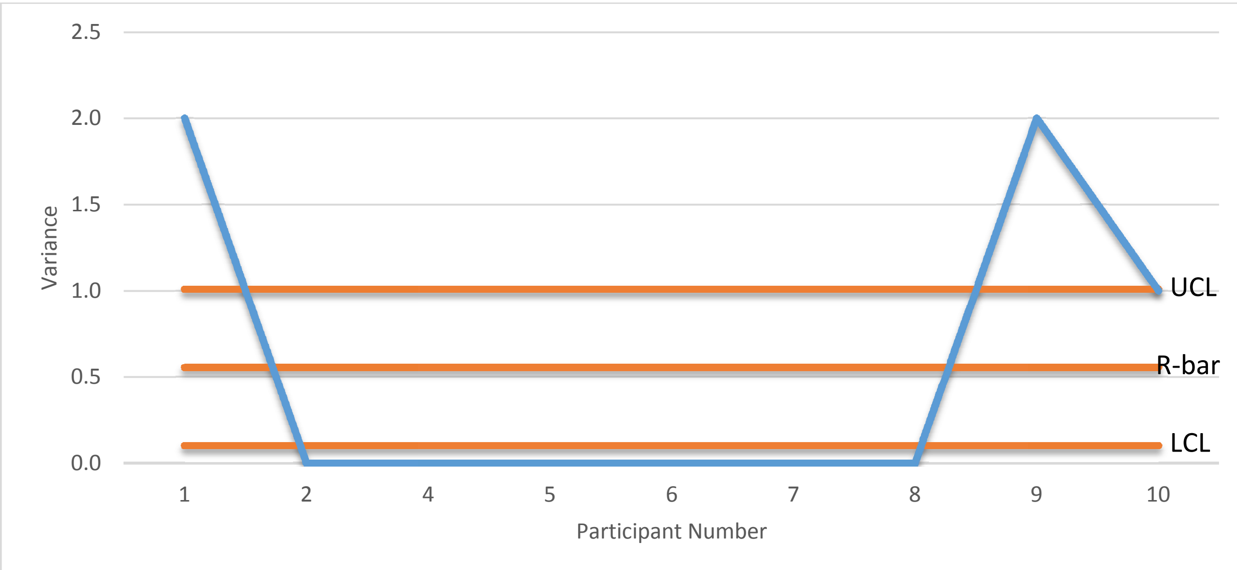

Figure 3.7. Adjusted Number of Errors R Chart

The five minute rating metrics are all within the upper and lower control limits. The direct work, indirect work, rework R charts can be found in Figure 3.8, Figure 3.9, and Figure 3.10 respectively. These standard construction measurements are strong indicators of a task's challenge level. The controlled level of variance indicates that the one dependent variable, model level of difficulty, is comparable between all three instances. The three model assemblies were determined to have a similar level of difficulty that would not impact the results of the research experiment.

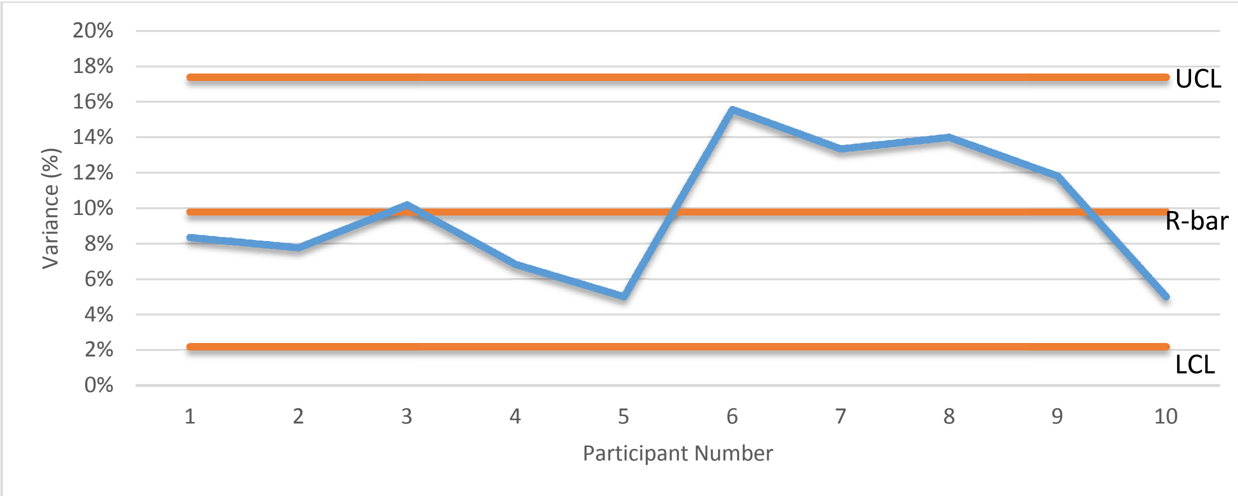

Figure 3.8. Direct Work R Chart

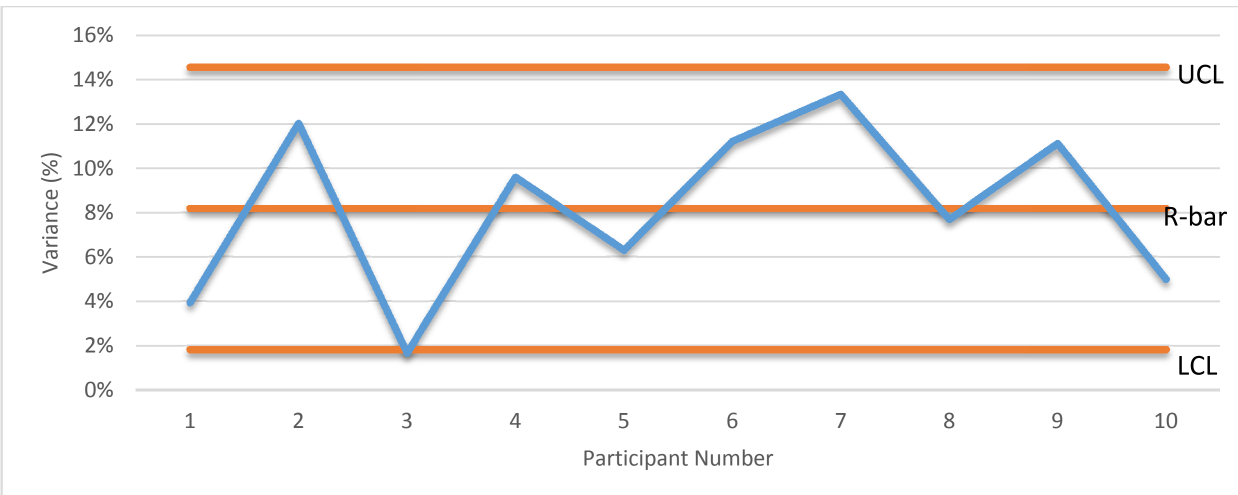

Figure 3.9. Indirect Work R Chart

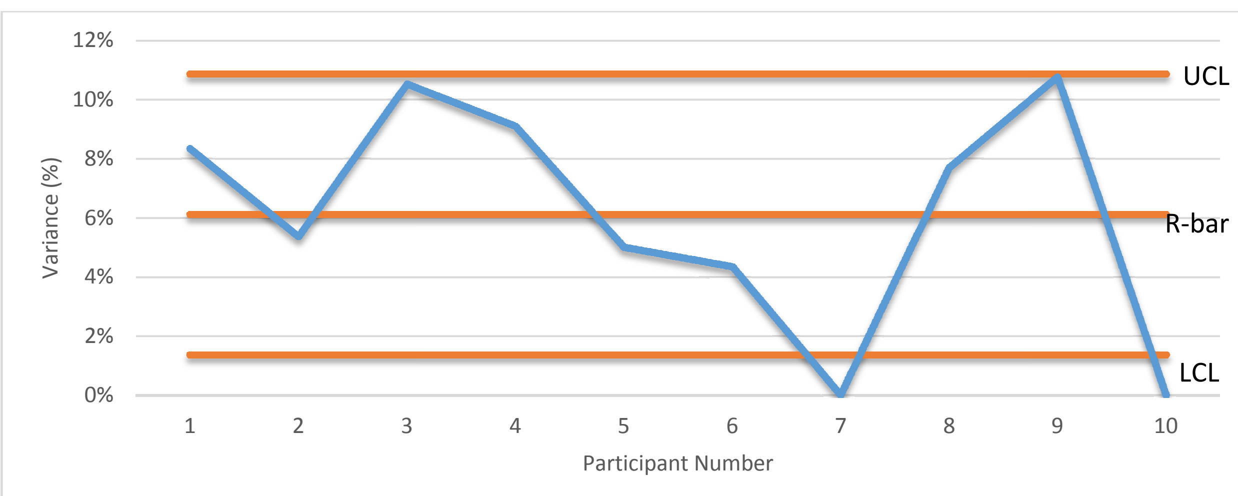

Figure 3.10. Rework R Chart

Finally an ANOVA analysis was run to determine if the three models had any statistically significant effect on the collected data. Each of the five metrics was compared to the three model numbers for influence. The results in Table 3.3 confirm that at 95% confidence there is no statistical difference between the three models for any of the performance measurements. All p-values are greater than 0.05. Statistical analysis for this study was performed using SPSS software. The direct outputs from SPSS for all statistical analyses run are listed in Appendix L. With the difficulty level determined to be statistically the same, the research began field testing to measure the impact of different types of engineering information.

Table 3.3. ANOVA Results 1: Performance Metrics by Model Number

Metric	**Model Number**	**Sample Size**	**Mean**	**Overall Mean**	**F**	**p**
Time to Completion	1	10	09:14	9:41	0.267	0.768
	2	10	09:56			
	3	10	09:54			
Number of Errors	1	10	1.0	0.5	0.699	0.506
	2	10	0.0			
	3	10	0.5			
Direct Work	1	10	74.5%	72.6%	0.948	0.400
	2	10	69.1%			
	3	10	74.2%			
Indirect Work	1	10	20.9%	22.1%	0.681	0.515
	2	10	24.5%			
	3	10	20.9%			
Rework	1	10	4.5%	5.3%	0.256	0.776
	2	10	6.4%			
	3	10	5.0%			

CHAPTER IV

FIELD TESTING RESULTS

4.1. Field Testing Sample Group

Field testing to examine the cognitive demand of 2D plans, 3D CAD, and 3D printed models was performed on subjects that would actually be using them in the construction industry. Construction professionals from a large general contractor working on a vertical, commercial construction project in Colorado served as the sample population. Each subject performed the research experiment described in Chapter 3 above. Unlike the baseline testing, participants received the engineering information for model assemblies 1, 2, and 3 in 2D plans, 3D CAD, and a 3D printed model respectively. Basic demographics of the field testing population are listed in Table 4.1. The raw data from the field trials is in Appendix K.

Table 4.1. Field Testing Sample Demographics

Demographics	Practitioners
Number	20
Age range	22-43
Formal training with blueprints	18/20
Years of experience	0-17
Current Occupations	Project Engineer Project Manager Quality Manager Construction Coordination Manager Assistant Superintendent Superintendent

4.2. Field Testing Analysis

The measured data initially supports the research hypothesis that 3D printed models have a lower cognitive demand than 2D plans and 3D CAD models. Construction professionals performed the best when using the 3D printed model. The averages for the recorded metrics for each information type are illustrated in Table 4.2. The measure for which the 3D physical model did not lead is the number of errors. The 3D CAD model resulted in the lowest number of errors. The 3D physical model had the highest percent of direct work and lowest time to completion, percent indirect work, and percent rework. The 3D CAD model came in second and the 2D plans had the worst results for these four measurements.

Table 4.2. Performance Metric Averages

Information Type	**Sample Size**	**Time to Completion (m:s)**	**Number of Errors**	**Direct Work (%)**	**Indirect Work (%)**	**Rework (%)**
2D Plans	20	13:25	1.1	66.5	30.2	3.2
3D CAD	20	10:50	0.2	72.9	25.1	2.0
3D Physical	20	08:19	0.6	83.8	15.4	0.8

An ANOVA analysis was performed to statistically validate the perceived influence the information type has on each performance metric. The results using 95% confidence are listed in Table 4.3. All the measurements are found to be statistically significant ($p<0.05$) except for the percentage of rework. The p-values for time to completion, direct work, and indirect work are so small that they round to zero at three decimal places. 3D physical models statistically resulted in better time to completion, percentage of direct work, and percentage or indirect work.

Table 4.3. ANOVA Results 2: Performance Metrics by Information Type

Metric	Information Type	Sample Size	Mean	Overall Mean	F	p
Time to Completion	2D Plans	20	13:25	10:51	17.158	0.000
	3D CAD	20	10:50			
	3D Physical	20	08:19			
Number of Errors	2D Plans	20	1.1	0.6	3.196	0.048
	3D CAD	20	0.2			
	3D Physical	20	0.6			
Direct Work	2D Plans	20	66.5%	74.4%	33.202	0.000
	3D CAD	20	72.9%			
	3D Physical	20	83.8%			
Indirect Work	2D Plans	20	30.2%	23.6%	29.561	0.000
	3D CAD	20	25.1%			
	3D Physical	20	15.4%			
Rework	2D Plans	20	3.2%	2.0%	2.574	0.085
	3D CAD	20	2.0%			
	3D Physical	20	0.8%			

The results from the cognitive test were used to determine any relationship between a subjects' cognitive abilities and performance. The card rotation test and cube comparison test had 40 and 14 maximum possible points respectively. Wrong answers counted as negative one point to discourage guessing, and consequently a negative score was possible on both tests. Table 4.4 lists the descriptive statistics for each test. Subjects generally performed better on the card rotation test. Thinking three dimensionally proved to be the more difficult and rare ability among the sample population.

Table 4.4. Cognitive Tests Descriptive Statistics

	Card Rotation Test	Cube Comparison Test
Maximum	40	14
Mean	31	8
Minimum	16	-3
Standard Deviation	6.3	5.1

Both cognitive tests are weighted toward higher scores. A box plot of test scores in Figure 4.1 visually displays this finding. Despite being slightly skewed toward higher scores, the mean scores (31 for card rotation and 8 for cube comparison) are below the median scores (33 for card rotation and 9 for cube comparison). This indicates that a few workers with very low scores are lowering the mean. Failing to take cognitive load into account would disenfranchise this group of workers.

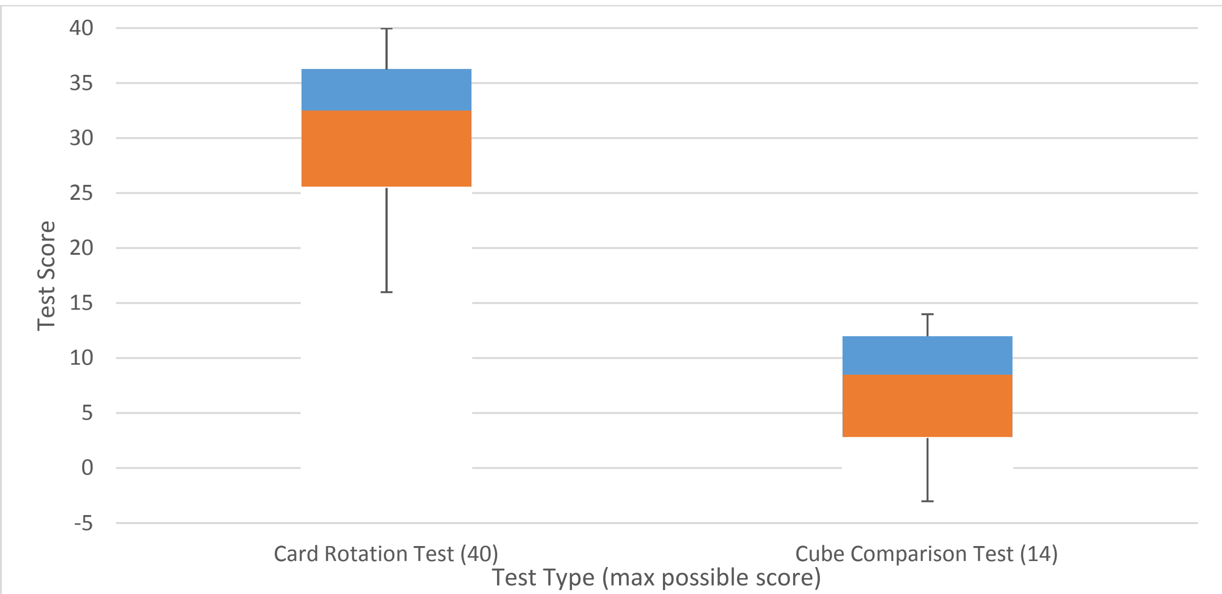

Figure 4.1. Box Plot of Cognitive Test Scores

A person's cognitive abilities must be considered when determining the utility of an information medium. Information acquisition occurs in the context of a person's cognitive abilities. Having a strong (or weak) spatial ability has the potential to determine which medium a person can successfully and easily use. The cognitive test scores were broken down into two groups: high, those above the fiftieth percentile, and low, those below the fiftieth percentile. The performance metrics were grouped by each information type, and an ANOVA analysis was performed to determine if a person's cognitive grouping influenced their performance when using a given information type. The performance metrics split by the card rotation scores are listed in Table 4.5. The same analysis for the cube comparison scores are in Table 4.6.

Card rotation test scores do not statistically change any scale model performance metrics. Despite not having p-values less than 0.05, varying levels of statistical significance hint at possible trends. 3D CAD had the lowest p-values, therefore being the most influenced by the card rotation score, for time to completion, direct work, and indirect work. The lowest values for number of errors and rework belong to 2D plans. 3D physical model had the highest or second highest p-value for every category. This evidence, although not statistically proven, would suggest that performance when using 2D plans and 3D CAD is more susceptible to a person's 2D spatial abilities than when using a 3D physical model.

Cube comparison test scores did provided statistical influence on performance measures. 3D physical model time to completion and number of errors are statistically influenced by a person's cube comparison test. Time to completion is also statistically significant when using the 3D CAD model. All 2D plans measurements are the least significant or second least significant. Logically a person's ability to think three dimensionally has an impact on their use of 3D information. Prescribing the ideal information type for a worker becomes dependent on whether their strength is thinking in two or three dimensions.

Table 4.5. ANOVA Results 3: Performance Metrics by Card Rotation Score (Information Type)

			2D Plans				3D CAD				3D Physical			
Metric	**Card Rotation Score**	**Sample Size**	**Mean**	**Overall Mean**	**F**	**P**	**Mean**	**Overall Mean**	**F**	**P**	**Mean**	**Overall Mean**	**F**	**P**
Time to Completion	High	10	14:13	13:25	0.873	0.363	10:23	10:50	0.991	0.333	08:27	08:19	0.071	0.793
	Low	10	12:37				11:17				08:12			
Number of Errors	High	10	1.2	1.1	0.222	0.643	0.2	0.2	0.000	1.000	0.6	0.6	0.039	0.845
	Low	10	0.9				0.2				0.5			
Direct Work	High	10	66.5%	66.5%	0.000	0.984	73.7%	72.9%	0.312	0.583	83.3%	83.8%	0.167	0.688
	Low	10	66.6%				72.1%				84.3%			
Indirect Work	High	10	30.6%	30.2%	0.060	0.809	24.0%	25.1%	0.622	0.440	15.9%	15.4%	0.225	0.641
	Low	10	29.8%				26.3%				14.9%			
Rework	High	10	2.9%	3.2%	0.293	0.595	2.3%	2.0%	0.176	0.680	0.8%	0.8%	0.000	1.000
	Low	10	3.6%				1.6%				0.8%			

Table 4.6. ANOVA Results 4: Performance Metrics by Cube Comparison Score (Information Type)

			2D Plans				3D CAD				3D Physical			
Metric	**Cube Comparison Score**	**Sample Size**	**Mean**	**Overall Mean**	**F**	**P**	**Mean**	**Overall Mean**	**F**	**P**	**Mean**	**Overall Mean**	**F**	**P**
Time to Completion	High	10	12:37	13:25	0.896	0.356	10:00	10:50	3.856	0.065	07:25	08:19	4.785	0.042
	Low	10	14:14				11:40				09:13			
Number of Errors	High	10	0.9	1.1	0.222	0.643	0.2	0.2	0.000	1.000	0.0	0.6	6.444	0.021
	Low	10	1.2				0.2				0.1			
Direct Work	High	10	66.6%	66.5%	0.002	0.964	73.4%	72.9%	0.134	0.719	84.4%	83.8%	0.305	0.587
	Low	10	66.4%				72.4%				83.1%			
Indirect Work	High	10	30.5%	30.2%	0.025	0.877	24.3%	25.1%	0.351	0.561	15.6%	15.4%	0.018	0.894
	Low	10	30.0%				26.0%				15.3%			
Rework	High	10	2.9%	3.2%	0.277	0.605	2.3%	2.0%	0.176	0.680	0.0%	0.8%	2.250	0.151
	Low	10	3.6%				1.6%				1.6%			

A similar analysis was performed to investigate the impact of information type. The data was grouped into high and low cognitive scores, and an ANOVA analysis was performed to determine the impact information type had on each metric given a high or low cognitive ability. The results for the card rotation test and cube comparison test can be found in Table 4.7 and Table 4.8 respectively.

A majority of the measurements were found to be significantly impacted by the information type, further supporting Table 4.3. These results infer that even having high cognitive levels of both 2D and 3D spatial orientation does not allow a person to make up for the varying cognitive demands of information. The high card rotation and cube comparison test scores measured the best with the 3D printed model and the worst with the 2D plans. Despite their high cognition, they were not able to overcome the larger mental loads of 2D plans. The number of errors and percentage of rework were statistically significant for the high cube comparison group, but not the low group. The data shows that a person's cognitive abilities are critical in whether they will make mistakes. Even adjusting the information medium and subsequent cognitive demand may not be influential enough to overcome workers' abilities with regards to errors and rework. In all other cases the measurements were significant for both groups.

Table 4.7. ANOVA Results 5: Performance Metrics by Information Type (Card Rotation)

			High Card Rotation Score				Low Card Rotation Score			
Metric	**Information Type**	**Sample Size**	**Mean**	**Overall Mean**	**F**	**P**	**Mean**	**Overall Mean**	**F**	**P**
Time to Completion	2D Plans	10	14:13	11:01	12.149	0.000	12:37	10:42	6.236	0.006
	3D CAD	10	10:23				11:17			
	3D Physical	10	08:27				08:12			
Number of Errors	2D Plans	10	1.2	0.7	1.500	0.241	0.9	0.5	1.753	0.192
	3D CAD	10	0.2				0.2			
	3D Physical	10	0.6				0.5			
Direct Work	2D Plans	10	66.5%	74.5%	19.954	0.000	66.6%	74.3%	13.546	0.000
	3D CAD	10	73.7%				72.1%			
	3D Physical	10	83.3%				84.3%			
Indirect Work	2D Plans	10	30.6%	23.5%	16.497	0.000	29.8%	23.7%	12.951	0.000
	3D CAD	10	24.0%				26.3%			
	3D Physical	10	15.9%				14.9%			
Rework	2D Plans	10	2.9%	2.0%	2.127	0.460	3.6%	2.0%	2.038	0.150
	3D CAD	10	2.3%				1.6%			
	3D Physical	10	0.8%				0.8%			

Table 4.8. ANOVA Results 6: Performance Metrics by Information Type (Cube Comparison)

			High Cube Comparison Score				Low Cube Comparison Score			
Metric	**Information Type**	**Sample Size**	**Mean**	**Overall Mean**	**F**	**P**	**Mean**	**Overall Mean**	**F**	**P**
Time to Completion	2D Plans	10	12:37	10:01	7.780	0.002	14:14	11:42	10.928	0.000
	3D CAD	10	10:00				11:40			
	3D Physical	10	07:25				09:13			
Number of Errors	2D Plans	10	0.9	0.4	1.977	0.158	1.2	0.8	2.915	0.071
	3D CAD	10	0.2				0.2			
	3D Physical	10	0.0				1.1			
Direct Work	2D Plans	10	66.6%	74.8%	22.661	0.000	66.4%	74.0%	11.807	0.000
	3D CAD	10	73.4%				72.4%			
	3D Physical	10	84.4%				83.1%			
Indirect Work	2D Plans	10	30.5%	23.5%	20.133	0.000	30.0%	23.8%	11.021	0.000
	3D CAD	10	24.3%				26.0%			
	3D Physical	10	15.6%				15.3%			
Rework	2D Plans	10	2.9%	1.7%	2.844	0.076	3.6%	2.3%	0.930	0.407
	3D CAD	10	2.3%				1.6%			
	3D Physical	10	0.0%				1.6%			

Certain information types require more training than others. Reading 2D plan sets is an ability that is not necessarily intuitive. Most engineers formally learn how to interpret plan sets in class and through estimating projects. Some craft workers receive similar training, often through apprentice programs or union training schools. Most workers, however, learn on the job. Skills developed in plan reading classes would greatly help subjects quickly find the information they are looking for on a drawing. Percentage of indirect work was analyzed by whether a participant has had any formal drawing training, Table 4.9. Despite no statistically significant findings, training is very close to having an impact on indirect work with 2D plans. Intuitively, 3D CAD and 3D physical models are less impacted by this factor. Considering the industry's heavy reliance on 2D drawings, these findings emphasize the need for formal training. Workers need the proper mental tools as well as physical tools to be successful.

Table 4.9. ANOVA Results 7: Indirect Work by Drawing Training

Metric	**Information Type**	**Drawing Training**	**Sample Size**	**Mean**	**Overall Mean**	**F**	**p**
Indirect Work	2D Plans	Yes	16	30.0%	30.2%	3.028	0.099
		No	4	29.7%			
	3D CAD	Yes	16	25.0%	25.1%	0.404	0.533
		No	4	25.8%			
	3D Physical	Yes	16	15.6%	30.2%	1.201	0.288
		No	4	14.9%			

A worker's experience level has the potential to impact their ability to use certain types of engineering information. The population was again split into two groups using the 50th percentile in years of industry work experience. An ANOVA analysis, listed in Table 4.10, was run to determine if a person's experience has a significant impact on their performance for each information medium. One area of significance found was workers' years of industry experience effect on their direct work rate when using the 3D physical model. Workers with less experience had significantly higher direct work rates. A potential theory to explain this finding is that workers get set in their ways of performing tasks. Exposing workers to new information types requires them to have an open mind and adapt their methods of working.

Table 4.10. ANOVA Results 8: Direct Work by Years of Industry Experience

Metric	**Information Type**	**Years of Experience**	**Sample Size**	**Mean**	**Overall Mean**	**F**	**p**
Direct Work	2D Plans	High	10	66.2%	66.5%	0.019	0.891
		Low	10	66.8%			
	3D CAD	High	10	72.2%	72.9%	0.036	0.852
		Low	10	73.6%			
	3D Physical	High	10	81.3%	83.8%	5.262	0.034
		Low	10	86.2%			

A person's age can also have an impact on their ability to interpret information. The results of an ANOVA analysis run to determine the impact a worker's age has on direct work and indirect work is illustrated in Table 4.11. A significant impact was found when using 2D plan sets on indirect work rates (p=0.036) and nearly significant for direct work rates (p=0.051). In both cases, older subjects performed better by having higher direct work rates and lower indirect work rates. Older workers are more likely to have experience working with engineering drawing sets. Their familiarity with them would allow them to find the information quickly and use the saved time on direct work.

Table 4.11. ANOVA Results 9: Direct and Indirect Work by Age

Metric	**Information Type**	**Age**	**Sample Size**	**Mean**	**Overall Mean**	**F**	**p**
Direct Work	2D Plans	High	10	70.2%	66.5%	4.357	0.051
		Low	10	62.9%			
	3D CAD	High	10	72.2%	72.9%	0.230	0.637
		Low	10	73.6%			
	3D Physical	High	10	83.3%	83.8%	0.141	0.712
		Low	10	84.2%			
Indirect Work	2D Plans	High	10	26.8%	30.2%	5.136	0.036
		Low	10	33.7%			
	3D CAD	High	10	25.0%	25.1%	0.016	0.901
		Low	10	25.3%			
	3D Physical	High	10	15.9%	15.4%	0.190	0.668
		Low	10	15.0%			

The impacts of cognitive deficiencies may change over time. Multiple two-way ANOVA tests were run on all potential combinations of cognitive ability (cube rotation test score and card comparison score) and time (age and years of industry experience). A person's cube comparison score and age were discovered to have a significant impact on their time to completion when interpreting the 3D printed model, Table 4.12. The difference in means proposes that a person may not be able to be overcome their cognitive ability through learning, job experience, or training. The times for almost every cognitive pairing are worse for the older group. If a person's cognitive ability cannot be overcome and may worsen over time, finding engineering information formats with low cognitive demands is even more critical.

Table 4.12. Two-Way ANOVA Results 1: Time to Completion by Cube Comparison Score and Age

Metric	Information Type	Cube Comparison	Age	Sample Size	Mean	Overall Mean	F	p
Time to Completion	2D Plans	High	High	6	13:17	13:25	0.013	0.910
		High	Low	4	11:36			
		Low	High	4	14:59			
		Low	Low	6	13:43			
	3D CAD	High	High	6	09:23	10:50	1.978	0.179
		High	Low	4	10:55			
		Low	High	4	12:12			
		Low	Low	6	11:18			
	3D Physical	High	High	6	06:41	08:19	6.568	0.021
		High	Low	4	08:30			
		Low	High	4	10:27			
		Low	Low	6	08:24			

CHAPTER V

CONCLUSION

Building upon previous research, new discoveries were found regarding the cognitive demand of engineering information types. Improved methods enabled the learning curve of previous studies to be removed. Variable level of difficulty was introduced, but statistically controlled for. The resulting data statistically proved the continuing hypothesis from the work of Dadi et al. that 3D physical models lead to better construction performance metrics. The results also further supported the previous findings that workers' familiarity with an information type leads to better performance and that low cognitive abilities are not able to be overcome. A list of the statistically proven results is listed in Table 5.1.

Table 5.1. Statistically Proven Results

Number	Hypothesis	Result
1	3D Printed models have lower cognitive demand than 2D plans and 3D CAD.	Subjects performed the best with 3D physical models in all measured categories.
2	High cognitive ability is not sufficient to overcome the cognitive demand of an information medium.	Both subjects with low and high cognitive abilities followed the same trend of performing the best with the 3D physical model and the worst with 2D plans.
3	Familiarity with an information type leads to better performance.	Older, more experienced workers who are used to 2D plans performed well with them and struggles with the less familiar 3D CAD and 3D physical model.
4	Cognitive Abilities are able to be overcome through training, age, or experience.	The opposite was proven that cognitive abilities cannot be overcome and performance declines over time.

The results found can help guide construction firms seeking to improve their productivity. In addition to the results listed above in Table 5.1, some trends were found but not statistically proven. These trends are listed in Table 5.2. Considering the findings of this study, construction companies need to invest in new methods of delivering information to workers. These decisions should be driven by the cognitive demand of the chosen information type. Providing new information mediums will not guarantee success. Training must accompany new tools to ensure workers are familiar with the information. Finally given that low cognitive abilities are not able to be overcome, emphasis must be placed on the hiring process to build teams of top quality employees.

Table 5.2. Trends Not Statistically Proven

Number	Hypothesis	Result
1	2D spatial abilities affect performance with 2D information types	Card rotation scores had the least amount of influence with using the 3D physical model.
2	3D spatial abilities affect performance with 3D information types	Cube comparison scores had the least impact when using 2D plans and the most when using the 3D physical model.
3	Formal blueprint training improves performance with 2D plans.	Formal drawing training was very close to having a statistical impact on indirect work when using 2D plans.

The findings in this study do come with certain limitations. The three model assemblies were not extremely complex which limits the potential for confusion, rework, and mistakes and reduces the variance of the performance metrics. The complexity level also led to the 3D printed model being visually similar to the scale model assembly. On a real construction site, a 3D printed model would be much more abstract than the actual building components being installed. Given more time and resources the sample sizes could have been increased to strengthen the validity of the statistical analysis. Some of the results presented were not statistically significant but merely trends, especially when comparing the effect of cognitive abilities when grouping the data by each information type. Further research is needed to investigate these areas. Finally, the research was performed in a controlled office setting. Construction sites are dynamic environments with numerous distracting stimulants such as heat, cold, noise, moving people and machinery, etc. Removing these factors makes the performance metrics measured ideal levels of production and not what would be expected in the field.

This research enables multiple opportunities for future work. Further changes to the methodology can be used to strengthen results. Increasing scale model assembly difficulty would result in greater variance in performance levels. The three assemblies could also be refined to standardize their level of difficulty and expand upon the work done with the baseline testing. Another alternative is to only have one scale model assembly with three information types. Each subject would only construct the assembly once. This would eliminate the potential learning curve and level of difficulty between assemblies. The sample size is prohibitive to this method as each subject would only contribute once instead of three times. Future research with larger populations to draw from could potentially use this method. A final change would be to use actual field materials as opposed to scale model toy sets. Small scale steel pieces that are easy to manipulate could potentially be used for the assembly. These changes would server to build upon and improve this work.

CHAPTER VI

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APPENDIX

A. Protocol

University of Colorado
Boulder

TITLE: Tangible and Adaptive Engineering Instructions for Developing Societies

PROTOCOL VERSION DATE: October 22, 2014
VERSION: 3.0

PRINCIPAL INVESTIGATOR (PI):

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KEY PERSONNEL

Name: Dr. Paul Goodrum
Role in project: Faculty Advisor

1. OBJECTIVES

- Describe the purpose of the study, including identification of specific primary objectives/hypotheses. Describe secondary objectives/hypotheses, if there are any.

This study is a proof of concept on the effectiveness of tangible engineering instructions compared to 3D computer instructions and traditional 2D plans. The main hypothesis is that tangible engineering instructions are more accurate, efficient, and less cognitively demanding especially for people with low literacy and no experience in engineering drawings.

2. BACKGROUND AND SIGNIFICANCE

The construction industry is a major contributor to the health of the United States economy. The industry's annual spending is consistently over $800 billion dollars, $893 billion in 2012 (United States Cencus Bureau, 2013). The 2012 spending levels accounted for 3.6% of the U.S. GDP making construction the 8th largest economic sector analyzed by the Bureau of Economic Analysis (Bureau of Economic Analysis, NAICS Data, 2012). The construction industry's performance is critical to the success of the country's economy and crucial to the nearly 6 million individuals it employs (Bureau of Labor Statistics, 2013). Oglesby et al. (1989) divides construction performance into four categories: productivity, safety, timeliness, and quality. Construction productivity has historically lagged behind the manufacturing industry making it a continuous focus of academic studies.

A construction project's productivity ultimately relies on the craft worker practices. They need to be supplied with the proper training, tools, materials, and information to effectively complete their job. Many craft workers feel that information delivery, and further design or construction drawing management, is a significant factor to efficiently performing their job (Construction Industry Institute, 2006; Dai et al., 2009a; Dai et al., 2009b; Mourgues and Fischer, 2008; Rojas, 2008; and Schwartzkopf, 2004). Information delivery has the ability to positively or negatively impact numerous aspects of a project. Rojas (2008) and Schwartzkopf (2004) discuss inefficiencies from design drawings ultimately leading to increased rework on the project. Supervisors and foremen then become focused on correcting engineering errors and rework instead of planning future work and focusing on crew performance.

The need for successful information delivery systems is even more prevalent in developing communities. Serpell and Ferrada (2007) determined that the lack of construction education and formal training in developing countries results in a lack of professionalism in workplace decision-making. The lack of education makes interpreting engineering information a challenge for craft workers. Workers become frustrated and cannot cope with new technologies that are being made available (Datta, 2010). Any new information delivery system must have a low cognitive demand to be easily implemented and accepted by the craft workers. Advances in three dimensional modeling and printing provide opportunities to improve the traditional methods of supplying craft workers with the information they need to complete a job.

3. PRELIMINARY STUDIES

A similar study "Performance of 3D Printed Models as a Means for Spatial Engineering Information Visualization" was performed by Dadi et al. (2013). The study design required subjects to assemble a model column and beam building frame. Subjects were given the assembly information in 2D plans, 3D computer instructions (CAD), or a 3D tangible model. The test subjects were University of Kentucky students and construction professionals from Lexington, KY. The researcher hypothesized that the college students would be more comfortable using new technology such as CAD and 3D printed models, and the construction professionals would be more comfortable with the 2D plans that they use daily at work. The assembly was measured for time to completion, a five minute rating, and the NASA Task Loading Index (NASA-TLX). The five minute rating is used to determine how much time was spent on direct work, assembling the model, and rework, fixing errors. The NASA-TLX is a measurement method used by NASA to assess the mental demand of an activity. This measurement tool provided minimal results. The study found that the 3D tangible instructions lead to the quickest completion time, highest direct work rate, lowest rework rate, and the lowest mental workload. The 2D plans were found to be second with the 3D computer model in third. This study established the baseline that 3D tangible engineering instructions are a promising alternative to 2D plans and 3D computer models. No results were listed regarding the hypothesis on the subjects groups' preferred information medium.

4. RESEARCH STUDY DESIGN

Two differing groups will be included in this study. Once consists of students, both University of Colorado Boulder students and high school students at engineering career fair days. The second is actual construction and craft workers. Workers in developing communities have two identifying characteristics: low-literacy and no experience in engineering drawings. Thus, we will adopt inclusion/exclusion criteria to approximate these two characteristics. For low-literacy, students will be native English speakers and monolingual. They will be tested with engineering instructions written in a foreign language (e.g., Russian), which simulates a low-literacy condition. For no engineering experience, students will be non-engineering majors. The second group of construction professionals will be an exact simulation of our other target group of construction workers in the U.S.

The study will use a between-subject design with 30 subjects in each group (N=90). In the first group, subjects will be given engineering instructions in traditional 2D plans (text and drawings). In the second group, subjects will be given 3D computer instructions (CAD). In the experimental group, subjects will be given tangible engineering instructions. Subjects in all groups will be asked to assemble a miniature shelter following the given instruction. Subjects will be provided with a construction kit consisting of necessary parts to assemble the shelter. The shelter being modeled was originally designed and used for post-disaster reconstruction after Katrina.

We will take quantitative and qualitative observations on efficiency, accuracy, and cognitive ability. Efficiency will be measured as the time each subject takes to complete the assembly and by typical construction productivity analyses techniques, including work sampling and five-minute ratings (Oglesby et al 1988). Each subject is given unlimited amount of time, but we do not anticipate the assembly will take more than 1.5 hours. Accuracy will be measured as the number of errors in the final assembly. Cognitive ability will be measured using a card rotation test. Qualitative data will be gathered through post-assembly questionnaires.

5. ABOUT THE SUBJECTS

Subject Population(s)	*Number to be enrolled in each group*
CU Students	**40**
High School Students	**15**
Construction Workers	**45**

With a subject population size of 100, we expect that a minimum of 90 will be able to complete the study. Each type of engineering instructions (2D plans, 3D BIM model, and physical model) will have the desired 30 subjects. The population will be 18-30 year old University of Colorado students, 17-19 year old high school students, and 18+ year old construction workers. The gender and ethnic distribution will not be monitored or controlled. Inclusion criteria include being a native English speaker and monolingual. The inclusion criteria serve to simulate the low-literacy found in developing communities as the engineering instructions will be written in a foreign language (e.g. Russian). Students with varying levels of engineering background and experience will be recruited. This will serve to simulate the difference between formally trained craft workers of a developed community and poorly trained craft workers of developing communities. Testing U.S. construction workers will allow us to compare the two difference between the two groups.

6. VULNERABLE POPULATIONS

No vulnerable populations will be considered for this study.

7. RECRUITMENT METHODS

List recruitment methods/materials and attach a copy of each in eRA

1. ***Post recruitment flyer around the University of Colorado Boulder campus***
2. ***Ask Engineering Professors to forward recruitment email***
3. ***Read a recruitment script in Engineering classes***
4. ***Ask Industry Professionals to recruit employees.***

The study population will be drawn from the University of Colorado Boulder student body. Flyers will be posted on campus billboards with contact information for general recruitment. Additionally, an email will be sent to colleagues of the faculty advisor asking them if they would be willing to forward it to students in their classes that may be interested in participating. Finally with the permission of University of Colorado Faculty, a script will be read before their classes begin to recruit subjects. The classes will not include any courses taught by the Faculty Adviser. The PI will conduct all recruitment. The materials to be seen are the flyer, email, and class recruitment script (all attached in eRA).

Contacts with industry professional will also help recruit subjects. Industry contacts of the Faculty Adviser will been contacted to help recruit students. They will be send the same flyers, email, and verbal scripts. They have the ability to recruit their own employees, but have been instructed to inform individuals that their willingness to participate and subsequent performance within the study have no outcome on their work. These industry contacts also hold engineering fair days to help educate and motivate student to enter engineering professions. They will pass along the same recruitment material to high school teacher to inform students they have the option to participate in the study. Again students' willingness to participate and subsequent performance within the study have no outcome on their school work.

8. COMPENSATION

Participants are not given compensation for this study.

9. CONSENT PROCESS

Consent for University of Colorado students and all construction workers will be obtained at the start of the subject's visit in ECCE 1B47 where the tasks will be performed. Subjects will be given a copy of form "HRP-502 – Consent" as approved by the IRB prior to the beginning of the test or recording. The consent form outlines the research statement, any risks, benefits, alternatives, confidentiality, and compensation for the subjects and contact information for the PI.

Consent for high school students will be obtained prior to the engineering fair day. The PI will send consent forms to the industry professionals hosting the fair. They will intern give the consent form to high school teacher and then the students' parents. All high school students will be required to have their parents sign the updated consent form written for underage participants. Only upon receiving and completing the paper copy of the consent for with the parent's, student's, and PI's signature will the student be allowed to partake in the study. Parents, teachers, and industry professionals will have the opportunity to call and email the PI with any questions about the study. On the day of the fair students, will also have the ability to ask any questions of the PI before and during the study.

The subjects will not be coerced or under undue influence to sign the informed consent form. If a subject decides against signing the informed consent form, they will be immediately removed from the test sample and thanked for their interest in the study. All subjects will be capable of understanding the guidelines put forth by the informed consent form and will be given every opportunity to ask questions and understand the entirety of their participation in the study.

10. PROCESS TO DOCUMENT CONSENT IN WRITING

Subjects will sign and date a copy of the form "HRP-502 – Consent" with the age appropriate signatory page as approved by the IRB to document their consent in writing.

11. PROCEDURES

Name of instrument/tool/procedure	***Purpose (i.e. what data is being collected?***	***Time to Complete***
Demographics Questionnaire	*Subject background information*	*3 minutes*
Card Rotation Test	*Cognitive ability*	*7 minutes*
Structure Assembly	*Effect of differing instruction types*	*30 minutes*
Stop Watch	*Assembly time*	*N/A*
Video Camera	*Accuracy and efficiency of assembly*	*N/A*
Post Assembly Questionnaire	*Subject opinions*	*5 minutes*

Visit #	***Procedures/Tools***	***Location***	***How much time the visit will take***
Visit 1	• *Demographics Questionnaire* • *Card Rotation Test* • *Structure Assembly* • *Post Assembly*		*3 minutes* *7 minutes* *30 minutes* *5 minutes*

Interview

Subjects will be asked to complete a demographics questionnaire which will collect their age, gender, years of education, highest education level, current occupation, years of engineering work experience, and type of engineering work experience. Subjects will be given a card rotation test which examines their two and three dimensional spatial orientation. Next, the subject will be asked to assemble a simple structure using a scale model construction kit. The assembly instructions will be given to the subject in a 2D drawing set, a 3D CAD model, or a physical model. A stop watch will be used to measure the time is takes to complete the assembly task. The assembly will be video recorded so that the footage can be analyzed for indices of direct work, indirect work, rework, and errors. The video recording is mandatory for the study.

After the assembly task, the subject will be asked to fill out a post assembly questionnaire which will record their preferred type of engineering instructions. The subjects will only be brought in for one visit averaging 30 minutes based on existing participants. Our initial estimates of 1.5-2 hours was overly conservative to make sure subjects reserved enough time to complete the experiment. The largest time savings has resulted from subjects completing the scale assemblies much faster than expected.

The demographic sheet will be useful in characterizing the performance of different sample sets. For instance, what is the effect of years of engineering experience on an individual's ability to interpret spatial information from a certain format? The card rotation test will allow the PI to examine any correlations between spatial ability and performance on the model assembly. The post-test questionnaires will identify the level of mental workload required to complete the task and individual preferences for the information display formats. This information will tell the researchers which information delivery format requires the most loading to complete and also if one format is preferred over another. The videotape will be necessary to identify what percent of time, during the task completion, was spent actually completing the structure versus waiting or making and correcting errors. The researchers will use that information to identify which information delivery format results in the least amount of errors while interpreting the information. All of the information will be considered together to ultimately draw conclusions from the study.

The location will change for each population, but the environment will be similar. University of Colorado students will take part in the study in ECCE 1B47, a basic class room. The high school students will conduct the experiment in a standard conference room at the location of the engineering fair. The exact location is still being decided upon, but students will already be planning to visit the fair. Thus the experiment will not require any additional planning or transportation on the student's part. For construction workers, the PI will travel to the job site where workers are normally reporting to. They will also be held in conference rooms on site. Dates for all test will be determined by the availability of subjects and industry contacts to avoid inconveniencing research subjects.

12. SPECIMEN MANAGEMENT

No specimens are used in this study.

13. DATA MANAGEMENT

The materials and records that will be kept from the study include the informed consent sheet, a general demographic sheet, a card rotation test, videotape from the assembly task, and the post assembly questionnaire sheet.

The paper based data (informed consent, demographic sheet, card rotation test, and questionnaire) will be stored in a locked drawer, in a locked office of the principle investigator for at least two years.

The office is 1111 Engineering Drive, ECCE 153, Boulder, CO 80309. These documents will be transcribed to electronic files by the principal investigator. The electronic files will be stored on a University owned desktop in the locked office of the investigator. The computer account has a password and automatic log off. No unauthorized person will be allowed to access the office, the drawer, or the computer account. Video recordings of the assembly task will be saved onto the same computer immediately after each subject's visit and deleted from the video recorder's memory card. Once the two year timeframe passes, the study materials will be moved to the locked office of the faculty advisor.

All data will have a random number identifier that is consistent across the data for an individual. A Personal Identifying Number (PIN) will be assigned to the study participants and their name will only be on the informed consent form.

When video recording the assembly task, care will be taken to ensure that only necessary portions of the task be videotaped (i.e. the actual task completion, not the subject).

14. WITHDRAWAL OF PARTICIPANTS

Subjects will be withdrawn from the study if they are unable to follow the direction of the study procedures or are unable to complete the structure assembly.

If a subject withdraws from the research before completing the structure assembly task, their collected data will be removed from the study and deleted. If the subject has completed the structure assembly task but withdraws before completing the post assembly questionnaire, the data that has been collected to that point will be included in the study. All subjects that choose to withdraw from the research will be thanked for their interest and to explain their reasons for withdrawing. Replacement subjects, if needed to reach the desired sample size, will be recruited through the same methods.

15. RISKS TO PARTICIPANTS

To the best of our knowledge, the tasks the subjects will be performing have no more risk of harm than they would experience in everyday life. The only foreseen risk is that collected information on paper and portable video recorder will be lost or stolen revealing a subject's participation in the study.

16. MANAGEMENT OF RISKS

As in section XIII Data Management, all collected information will be coded with Personal Identification Numbers (PIN) to remove the subjects' names from research material. The subjects name will only be on the informed consent form. Additionally, portable information (paper and video camera) will be in the possession of the PI during the subjects' visits. It will be taken and secured in the PI's office immediately after each visit.

17. POTENTIAL BENEFITS

There are no direct benefits to the subjects. The potential benefits are to assisting in a contribution to the body of knowledge of the civil engineering and cognitive psychology research fields. The knowledge gained will be critical to understanding how engineering information can be presented for spatial understanding, which will provide unique and insightful findings to the academic and industry communities.

18. PROVISIONS TO MONITOR THE DATA FOR THE SAFETY OF PARTICIPANTS

The data will be reviewed weekly by the PI to ensure that no unauthorized personnel have accessed the secured information.

19. PROVISIONS TO PROTECT THE PRIVACY INTERESTS OF PARTICIPANTS

The data will have a random number identifier that is consistent across the data for an individual. A Personal Identifying Number (PIN) will be assigned to the study participants. Video recording will be focused on the assembly task and care will be taken to exclude the subject from the camera's view as much as possible.

20. MEDICAL CARE AND COMPENSATION FOR INJURY

This study does not involve more than minimal risk.

21. COST TO PARTICIPANTS

There are no costs associated with taking part in the study, other than the subjects' time. The participants will be CU students who will already have to be on campus the day of the test for other classes or meetings.

22. DRUG ADMINISTRATION

No drugs will be administered in this study.

23. INVESTIGATIONAL DEVICES

No investigational devises are used in this study.

24. MULTI-SITE STUDIES

This study will only take place at the University of Colorado Boulder.

25. SHARING OF RESULTS WITH PARTICIPANTS

There are no plans to share the results of the study with the participants.

B. 2D Plan Set

1138 FLAGSTAFF RD.

N

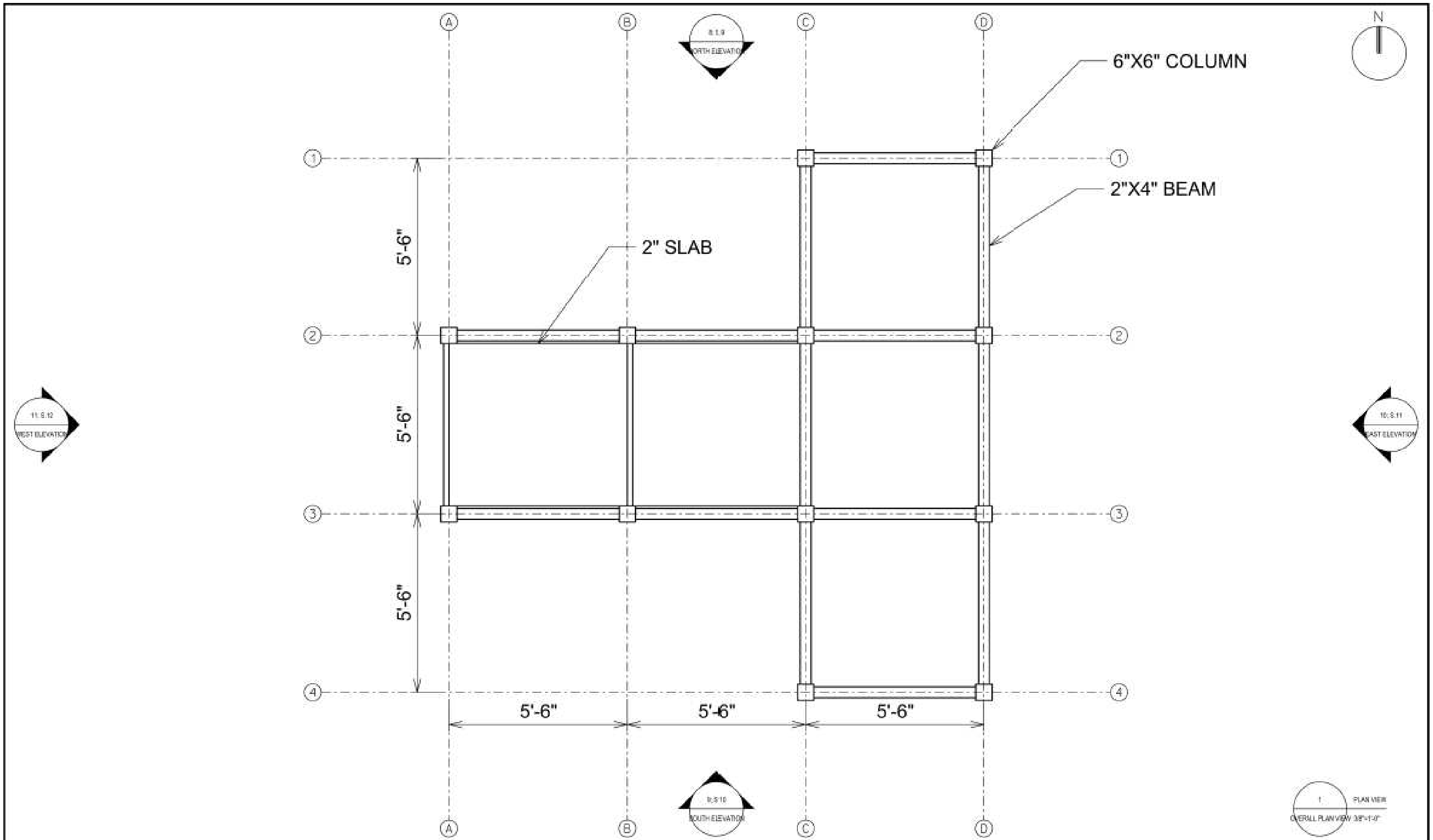
PROJECT TITLE: SLOPE OFFICE
ADRESS: 1138 FLAGSTAFF RD, BOULDER, CO 80302
STATE: COLORADO
COUNTY: BOULDER
CITY: BOULDER
COORDINATES: 40°0'07" N 105°17'29" W

START DATE: 1/9/2012
END DATE: 9/9/2013
PROJECT LIFE SPAN: 50 YEARS
PROJECT BUDGET: $4.5 MILLION

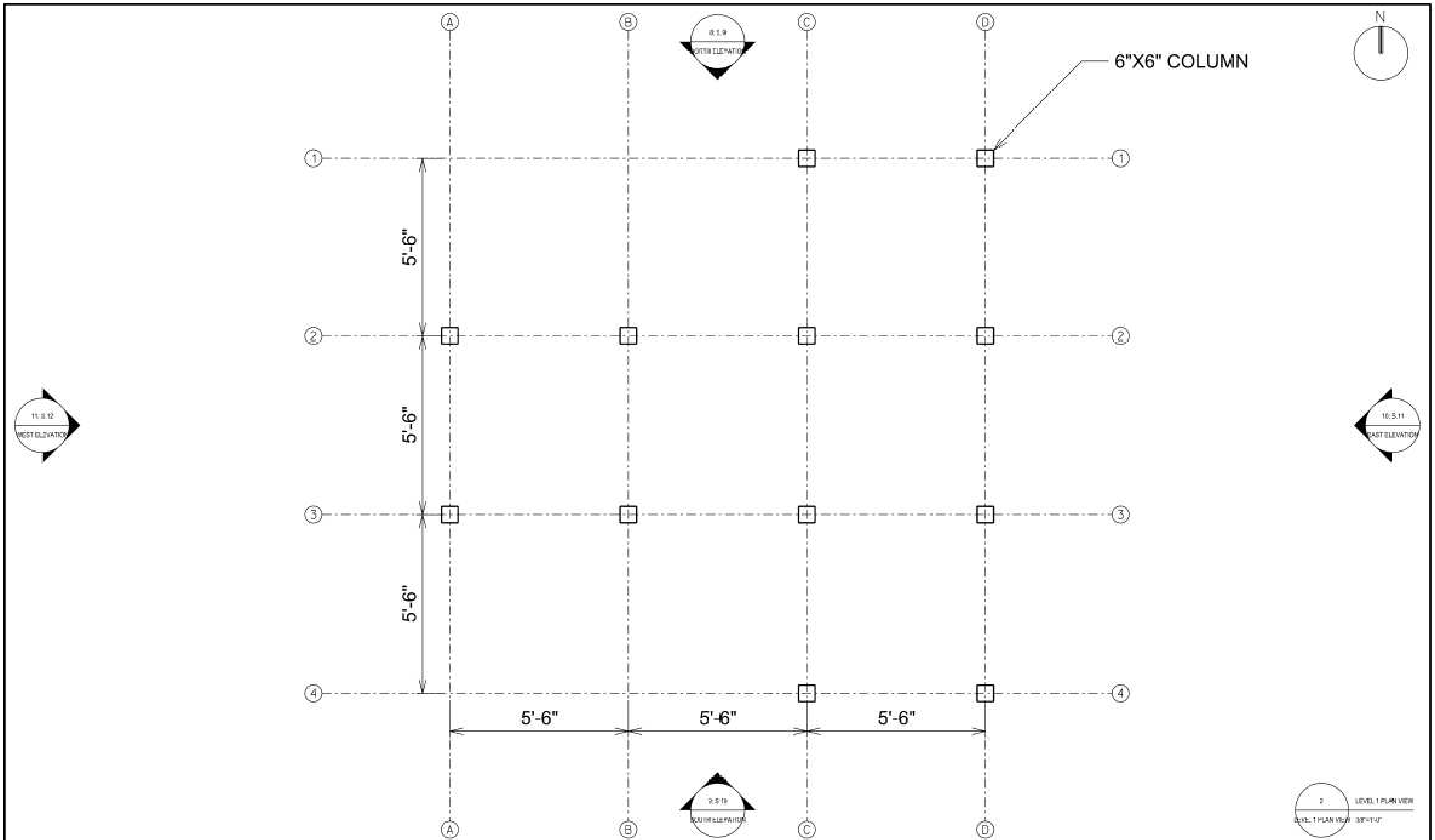
OWNER: IBM
ARCHITECT: FENTRESS BRADBURN ARCHITECTS
DESIGNER: CH2M HILL
CONTRACTOR: LAWRENCE CONSTRUCTION CO.

TABLE OF CONTENTS

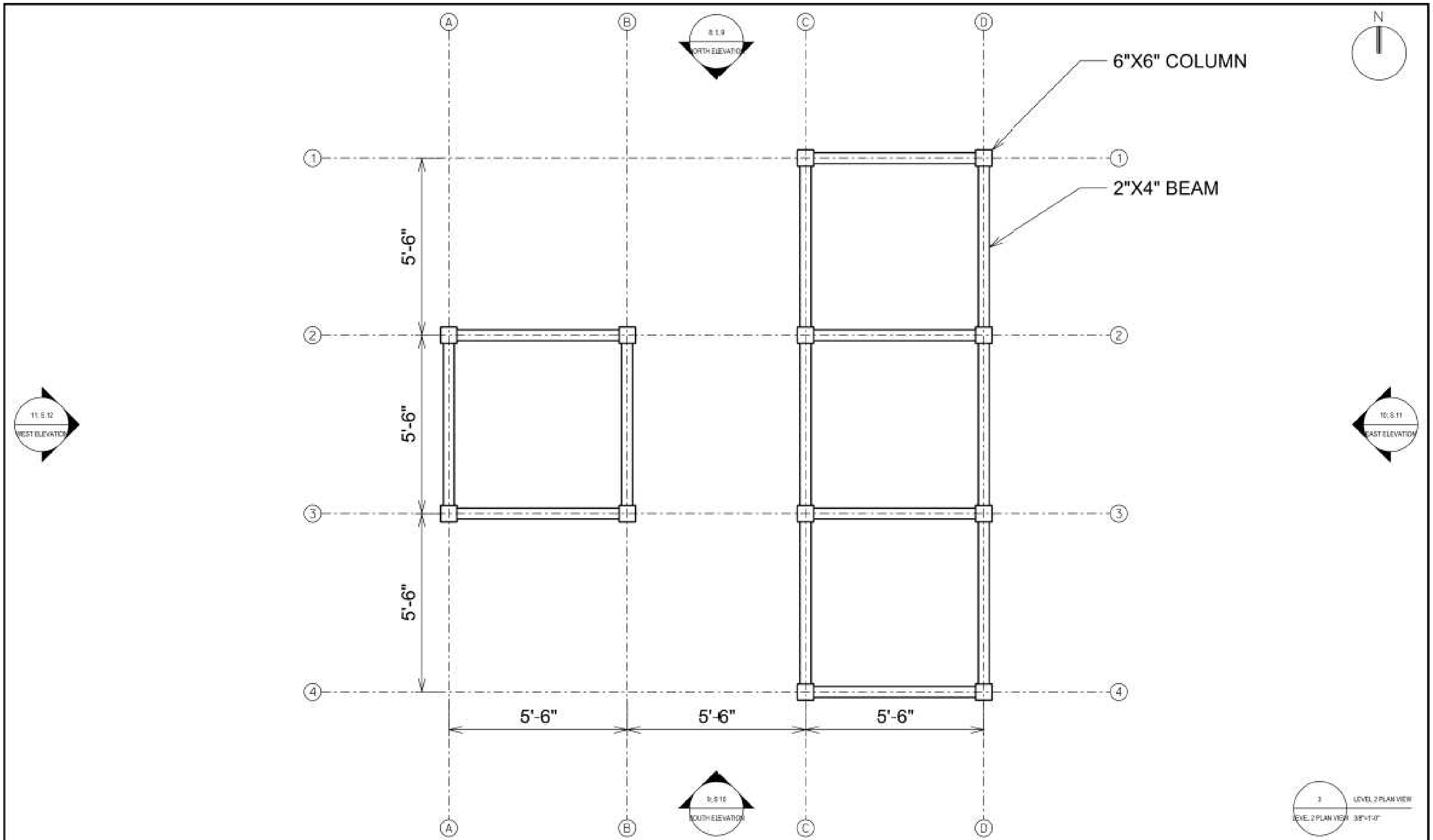
SLOPE OFFICE	COVER SHEET	CU BOULDER	DATE: 8/14/2013 SCALE: 3/8"=1'-0" SHEET: S.1



SLOPE OFFICE	OVERALL PLAN VIEW	CU BOULDER	DATE: 8/14/2013 SCALE: 3/8"=1'-0" SHEET: S.2

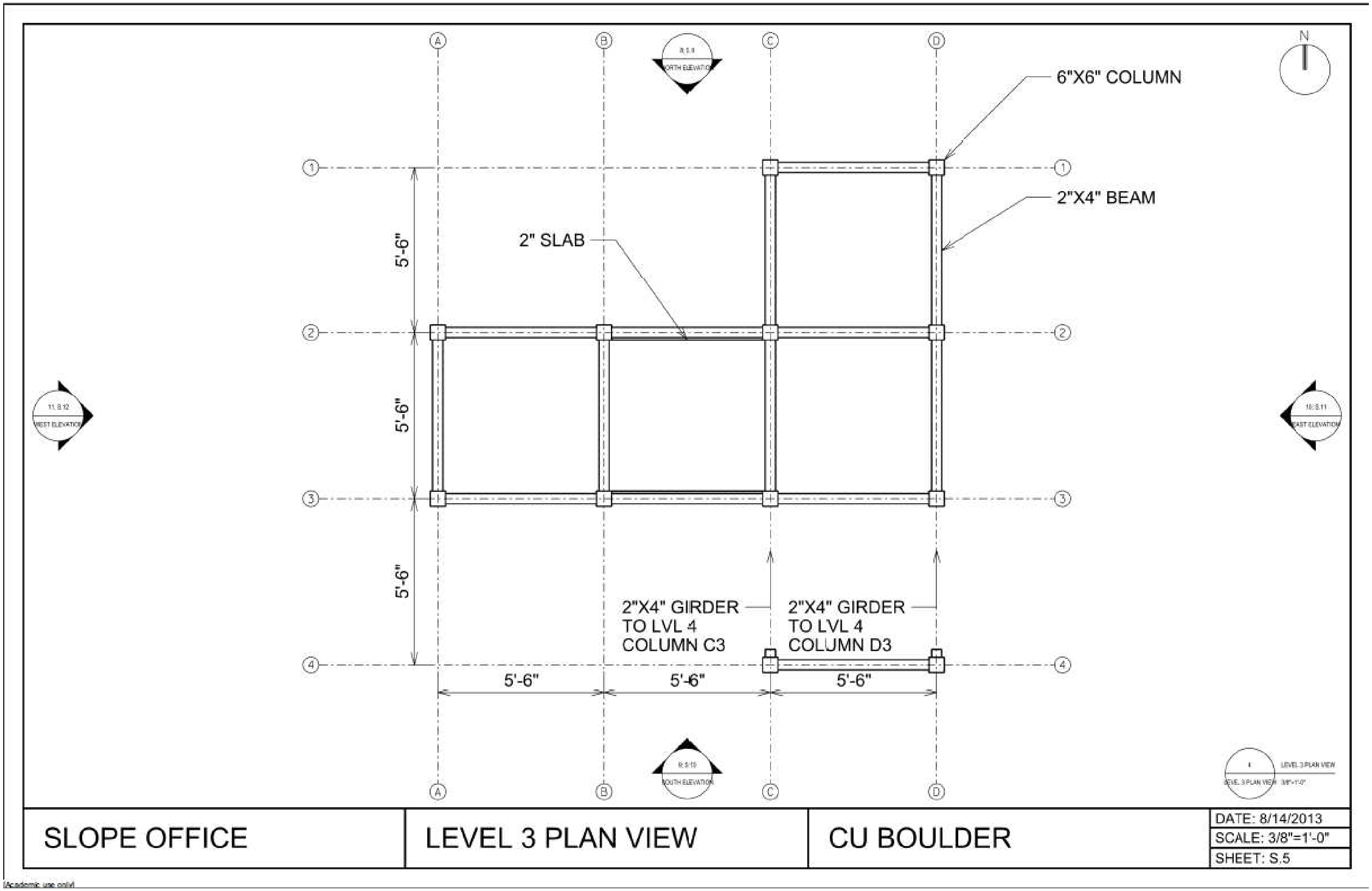


SLOPE OFFICE	LEVEL 1 PLAN VIEW	CU BOULDER	DATE: 8/14/2013 SCALE: 3/8"=1'-0" SHEET: S.3

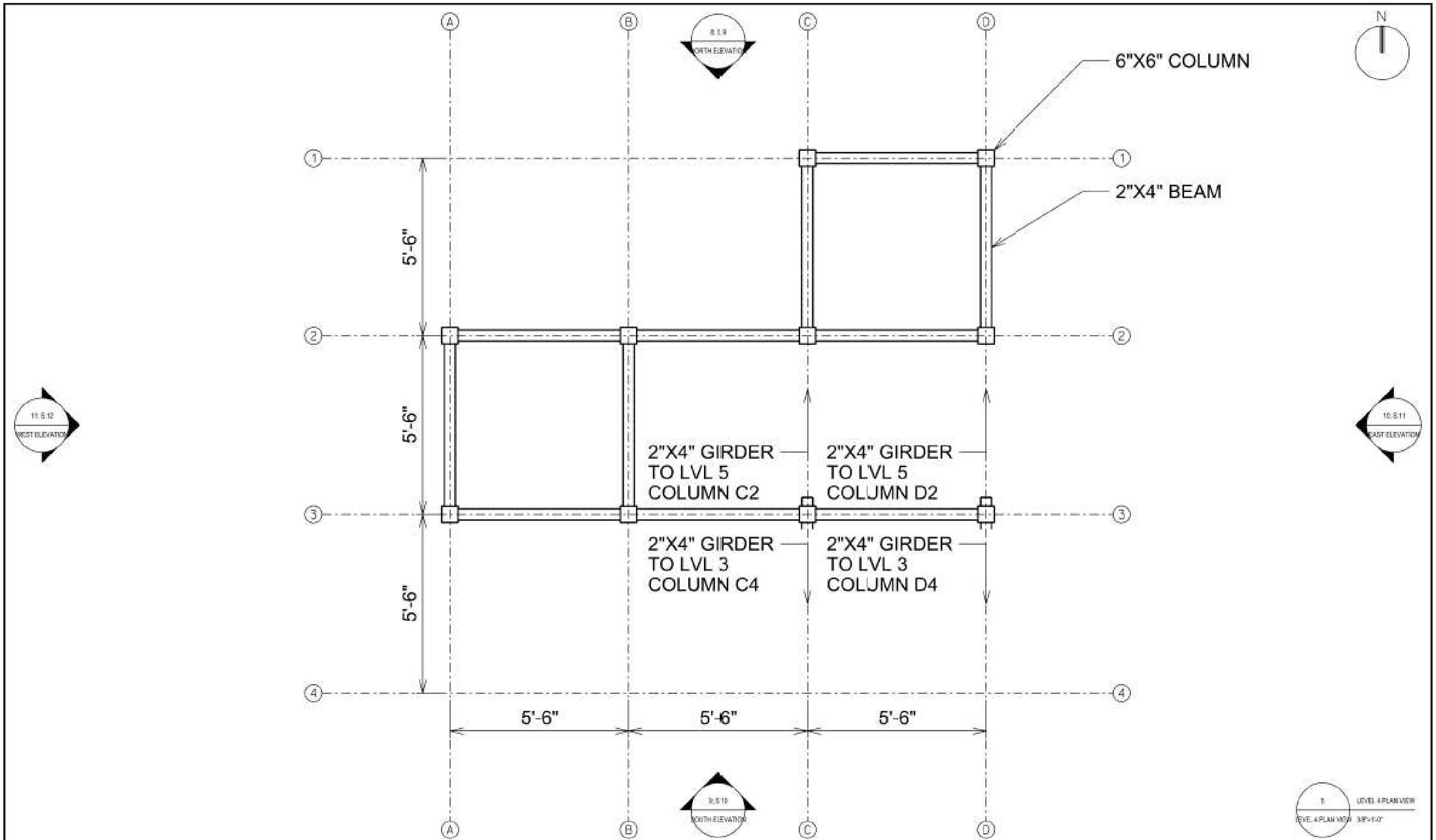


SLOPE OFFICE	LEVEL 2 PLAN VIEW	CU BOULDER	DATE: 8/14/2013 SCALE: 3/8"=1'-0" SHEET: S.4

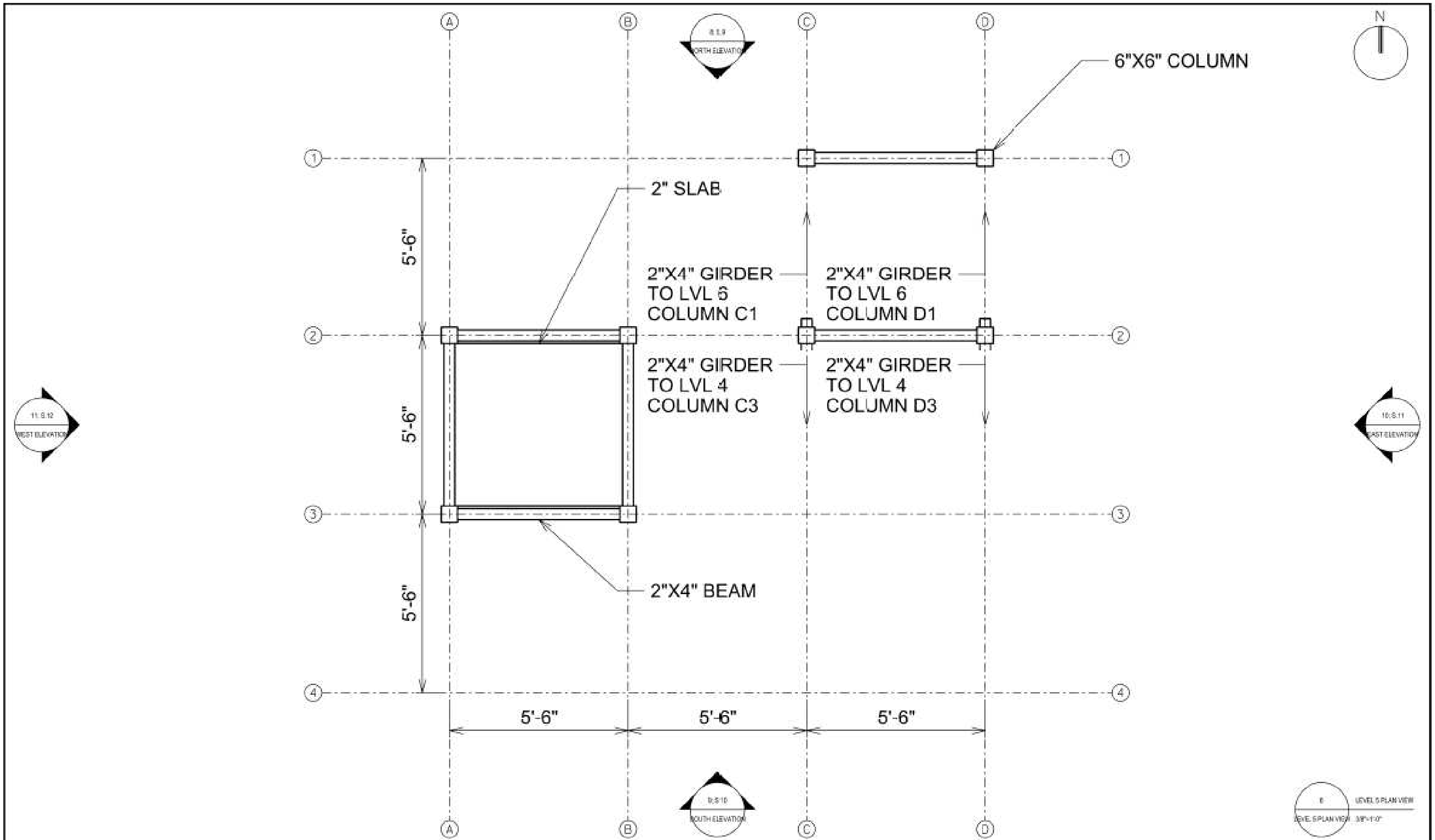
[Academic use only]



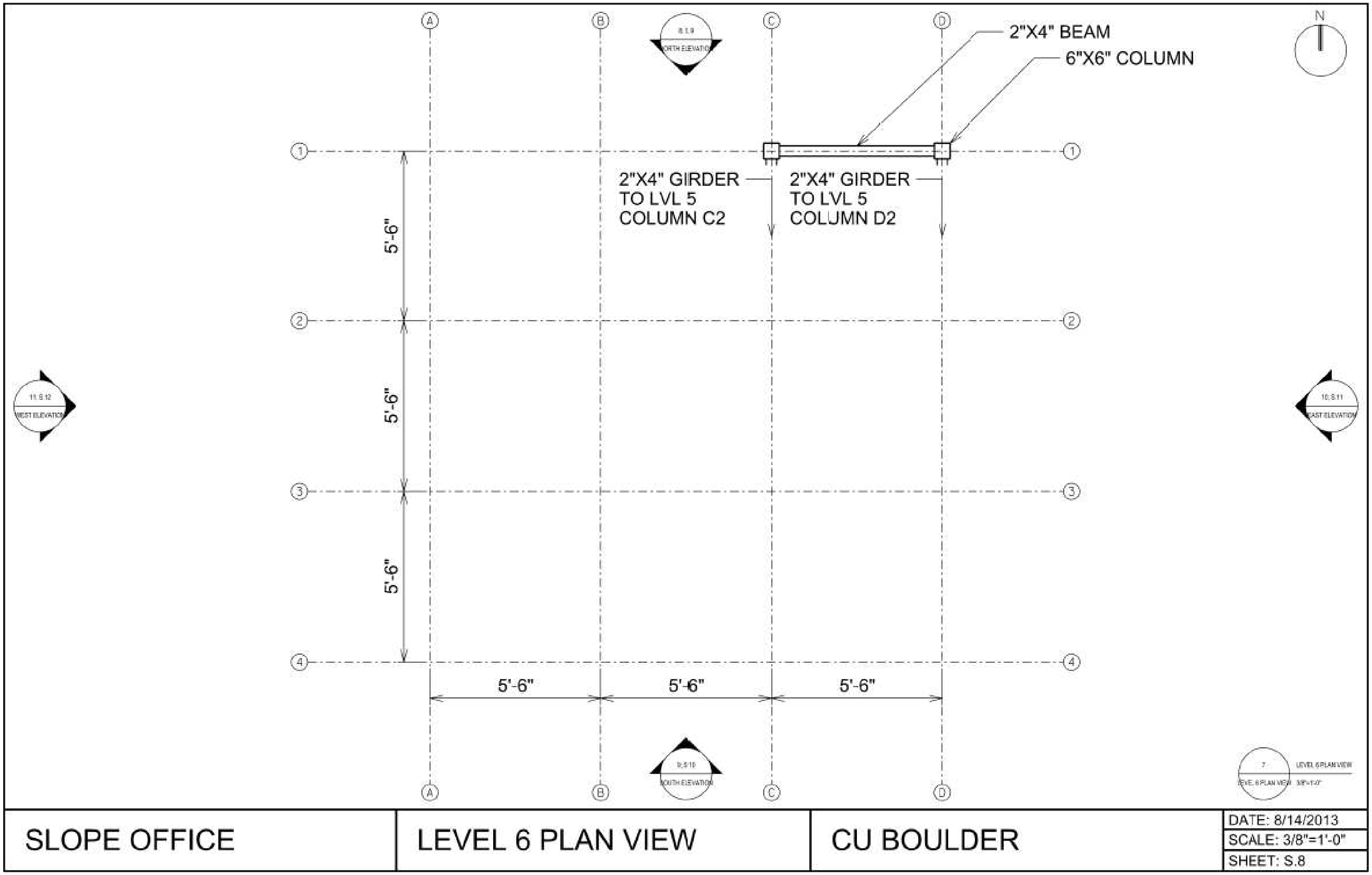
N
6"X6" COLUMN
2"X4" BEAM
2" SLAB
5'-6"
5'-6"
5'-6"
2"X4" GIRDER TO LVL 4 COLUMN C3
2"X4" GIRDER TO LVL 4 COLUMN D3
5'-6"
5'-6"
5'-6"
SLOPE OFFICE
LEVEL 3 PLAN VIEW
CU BOULDER
DATE: 8/14/2013
SCALE: 3/8"=1'-0"
SHEET: S.5
[Academic use only]

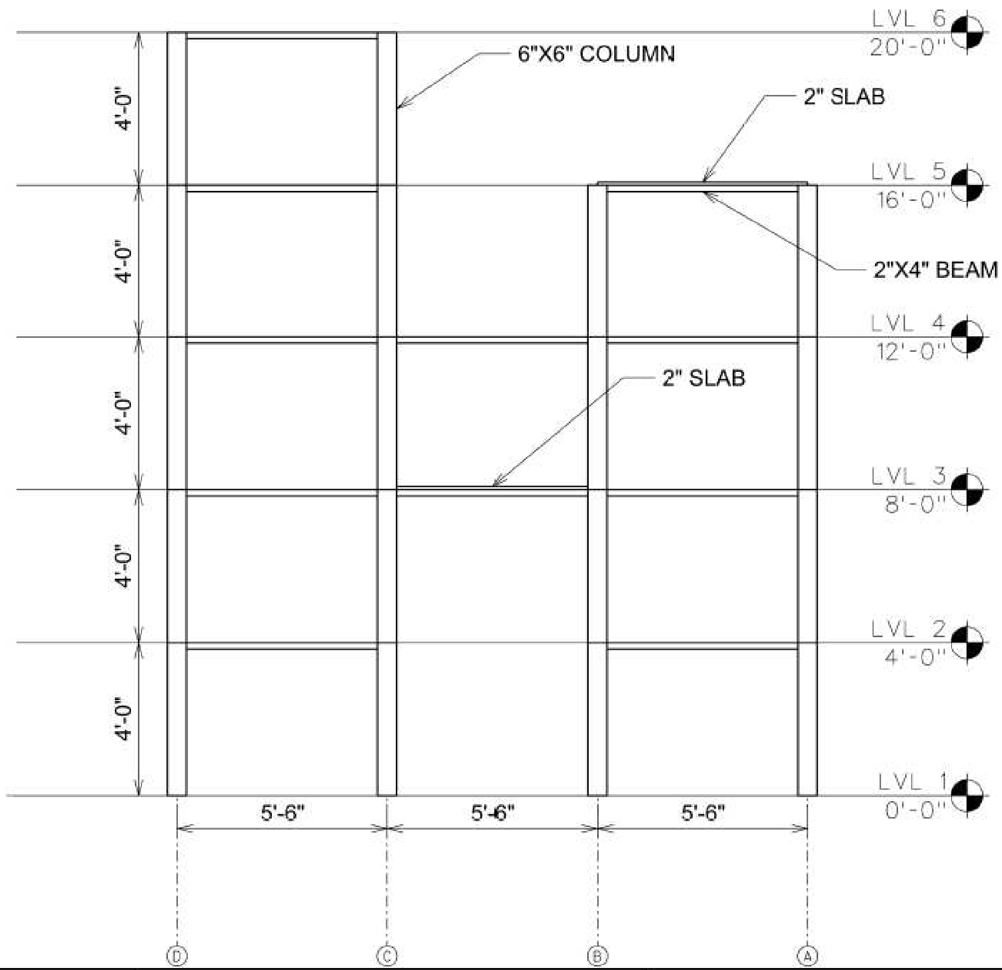


SLOPE OFFICE	LEVEL 4 PLAN VIEW	CU BOULDER	DATE: 8/14/2013 SCALE: 3/8"=1'-0" SHEET: S.6

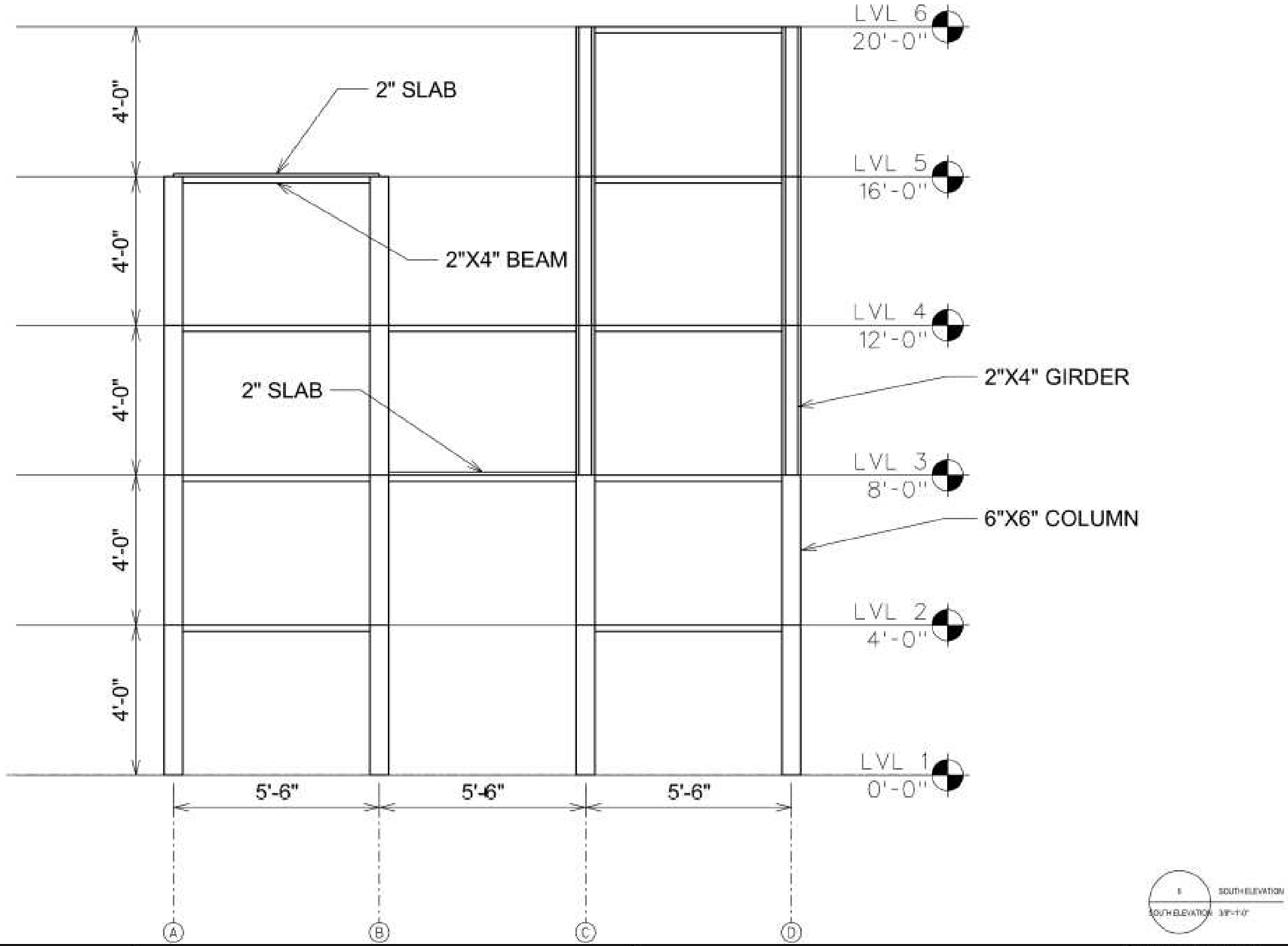


SLOPE OFFICE	LEVEL 5 PLAN VIEW	CU BOULDER	DATE: 8/14/2013 SCALE: 3/8"=1'-0" SHEET: S.7

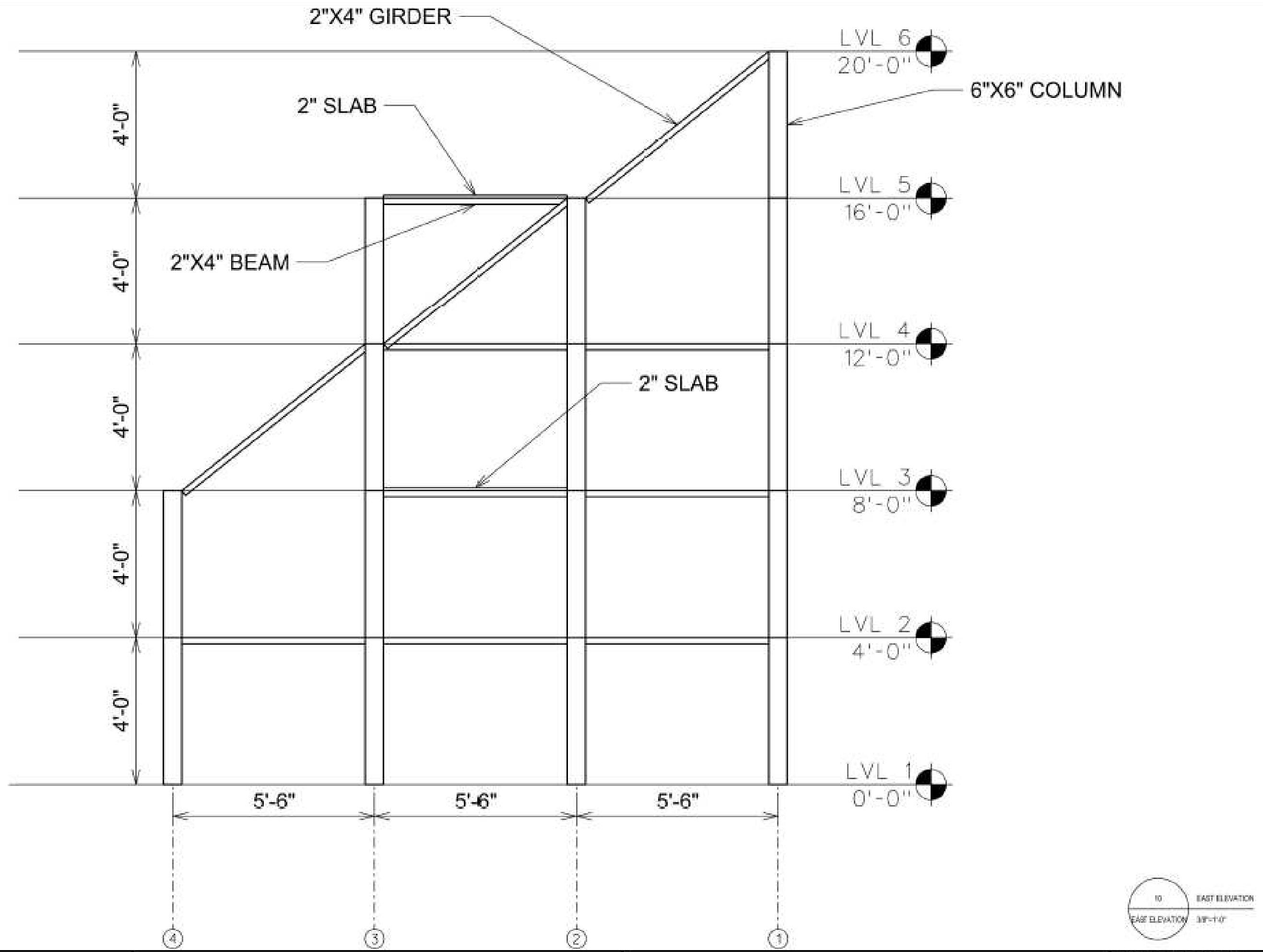

2"X4" BEAM
6"X6" COLUMN
N
2"X4" GIRDER TO LVL 5 COLUMN C2
2"X4" GIRDER TO LVL 5 COLUMN D2
A
B
C
D
1
2
3
4
5'-6"
5'-6"
5'-6"
5'-6"
5'-6"
5'-6"
SLOPE OFFICE
LEVEL 6 PLAN VIEW
CU BOULDER
DATE: 8/14/2013
SCALE: 3/8"=1'-0"
SHEET: S.8



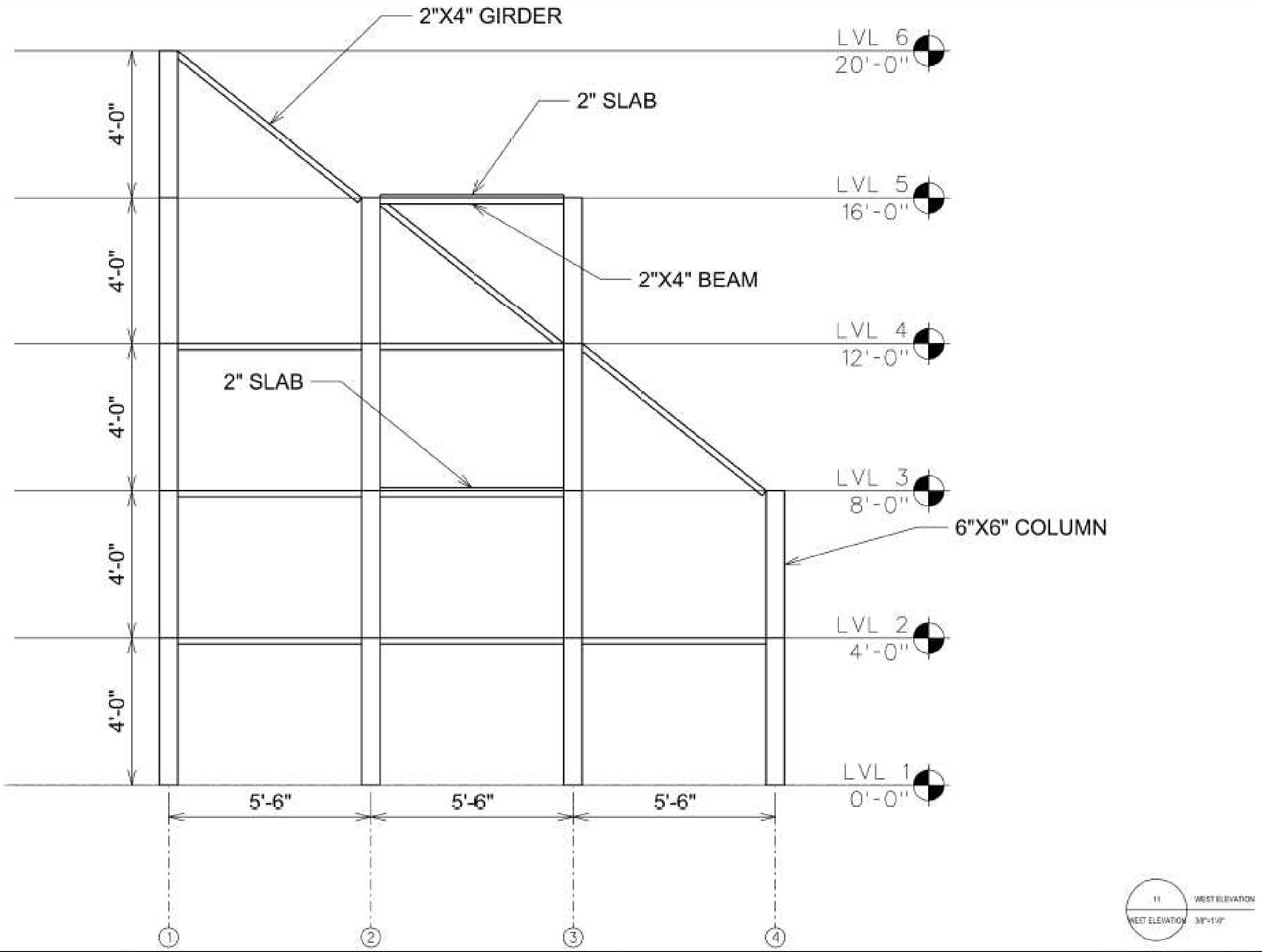
SLOPE OFFICE	NORTH ELEVATION	CU BOULDER	DATE: 8/14/2013 SCALE: 3/8"=1'-0" SHEET: S.9



SLOPE OFFICE	SOUTH ELEVATION	CU BOULDER	DATE: 8/14/2013 SCALE: 3/8"=1'-0" SHEET: S.10



SLOPE OFFICE	EAST ELEVATION	CU BOULDER	DATE: 8/14/2013 SCALE: 3/8"=1'-0" SHEET: S.11



SLOPE OFFICE	WEST ELEVATION	CU BOULDER	DATE: 8/14/2013 SCALE: 3/8"=1'-0" SHEET: S.12

C. 5 Minute Rating Form

Date	PIN
8/1/2014	000

Totals	Office	Bridge	Shelter
Units	21	13	12
Direct	14	10	10
Indirect	6	2	2
Rework	1	1	0

Percent	Office	Bridge	Shelter
Units	21	13	12
Direct	66.67%	76.92%	83.33%
Indirect	28.57%	15.38%	16.67%
Rework	4.76%	7.69%	0.00%

Notes: Field Trials

Total Time: ________

Assembly #: ________

	Direct Work	Indirect Work	Rework
0:30		X	
1:00		X	
1:30		X	
2:00	X		
2:30	X		
3:00	X		
3:30	X		
4:00	X		
4:30	X		
5:00	X		
5:30	X		
6:00	X		
6:30	X		
7:00	X		
7:30	X		
8:00	X		
8:30	X		
9:00		X	
9:30			X
10:00		X	
10:30		X	
11:00			
11:30			
12:00			
12:30			
13:00			
13:30			
14:00			
14:30			
15:00			
Total	14	6	1

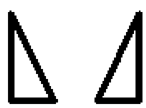
PIN:________

D. Card Rotation Test

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.

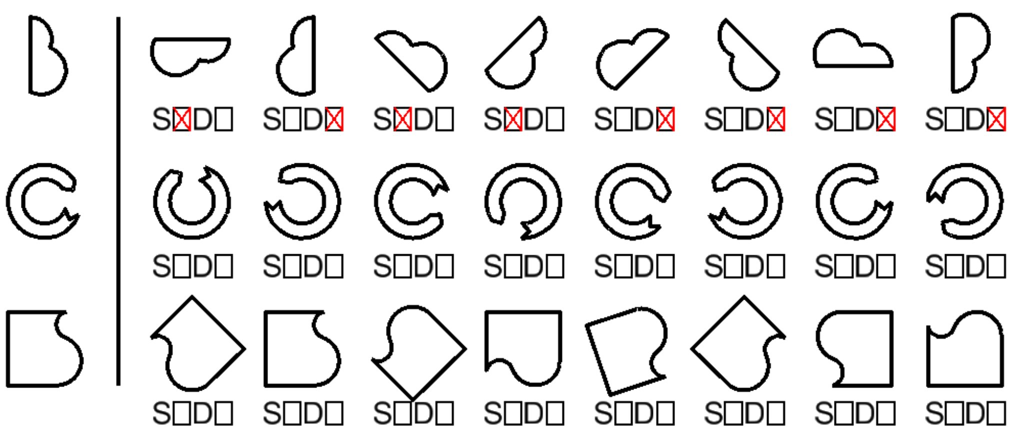
Now look at the 2 cards below:



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 left of a vertical line and eight cards on the right. You are to decide wether each of the eight cards on the right is the **same as** or **different from** the card at the left. Mark the box besides the S if it the **same as** the one at the beginning of the row. Mark the box beside the D if it is **different from** the one at the beginning of the row.

Practice on the following rows. The first row has been correctly marked for you.



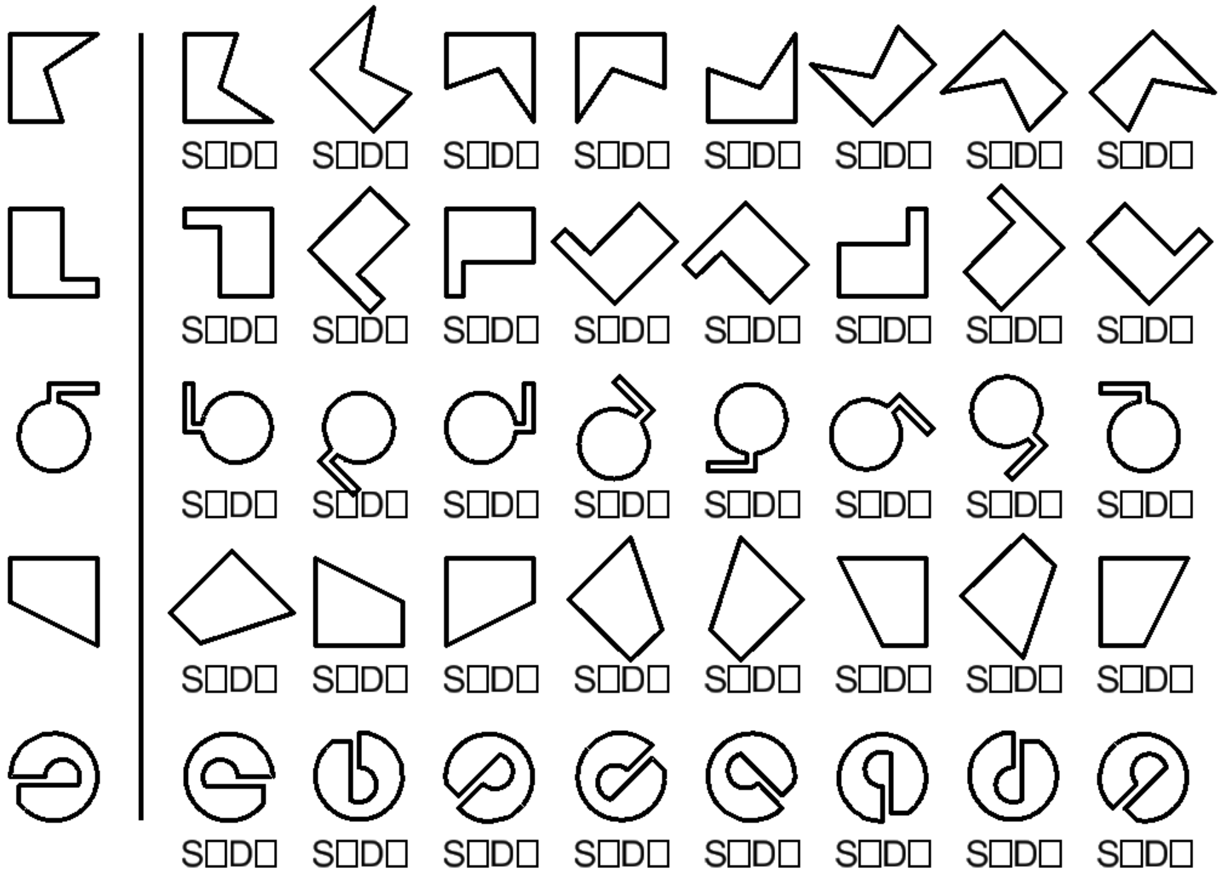
Your score on this test will be the number of items answered correctly minus the number answered incorrectly. Therefore, it will **not** be to your advantage to guess, unless you have some idea whether the card is the same of different. Work as quickly as you can without sacrificing accuracy.

You will have **1.5 minutes** for this test. When you have finished this test, STOP.

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO

Card Rotation Test (1.5 minutes)

S = same (only rotated)
D = different (flipped and/or rotated)



_____________ – _______________ = __________ / 40

Correct Answers – Incorrect Answers = Total Score

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO

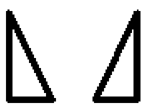
PIN:________

E. Card Rotation Test Answers

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.

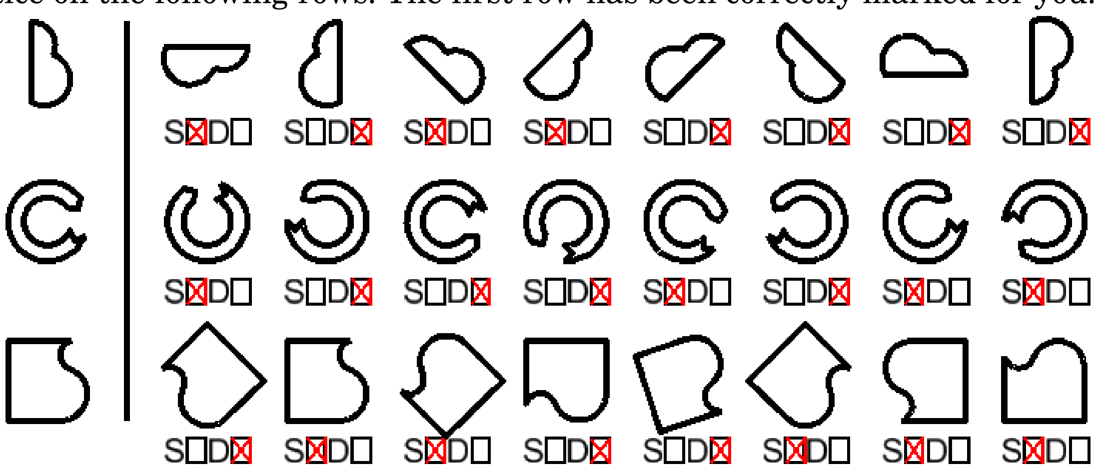
Now look at the 2 cards below:



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 left of a vertical line and eight cards on the right. You are to decide wether each of the eight cards on the right is the **same as** or **different from** the card at the left. Mark the box besides the S if it the **same as** the one at the beginning of the row. Mark the box beside the D if it is **different from** the one at the beginning of the row.

Practice on the following rows. The first row has been correctly marked for you.



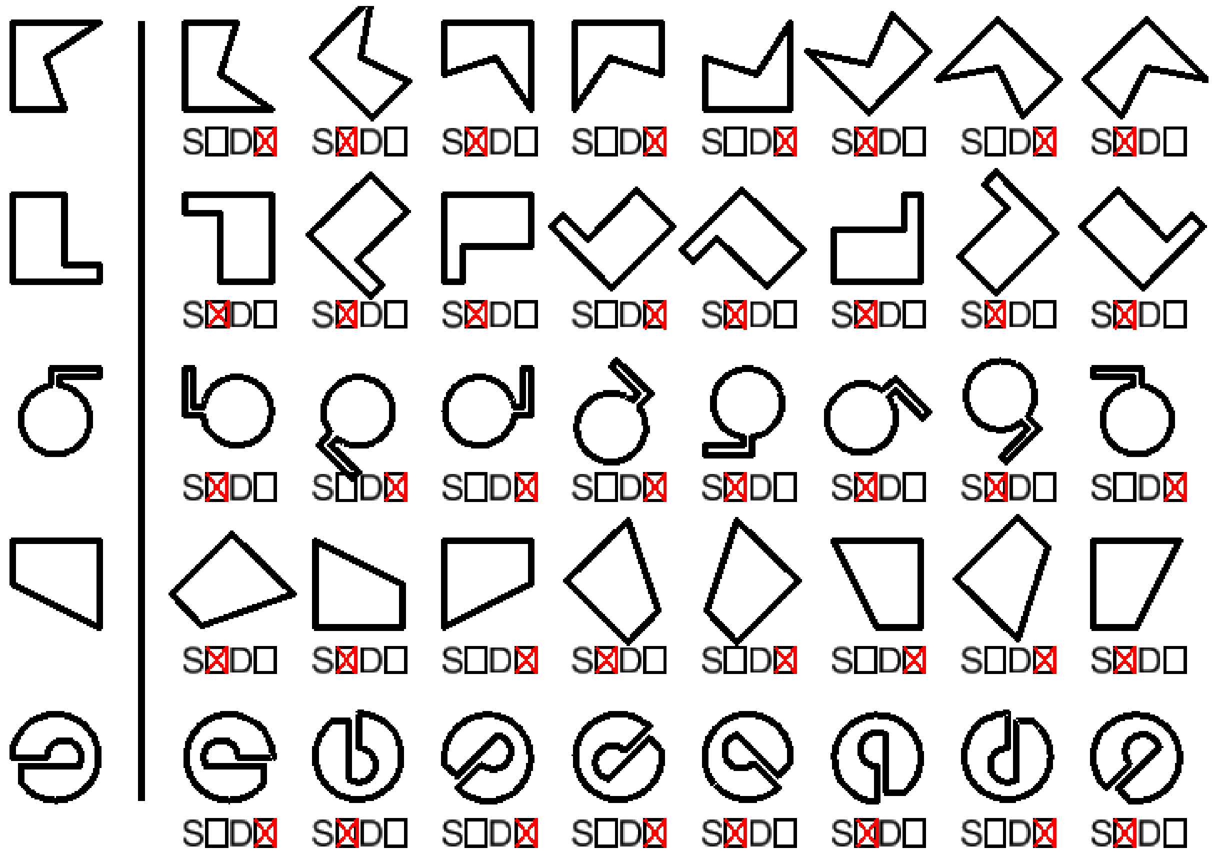
Your score on this test will be the number of items answered correctly minus the number answered incorrectly. Therefore, it will **not** be to your advantage to guess, unless you have some idea whether the card is the same of different. Work as quickly as you can without sacrificing accuracy.

You will have **1.5 minutes** for this test. When you have finished this test, STOP.

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO

Card Rotation Test Answers (1.5 minutes)

S = same (only rotated)
D = different (flipped and/or rotated)



_____________ – _______________ = __________ / 40

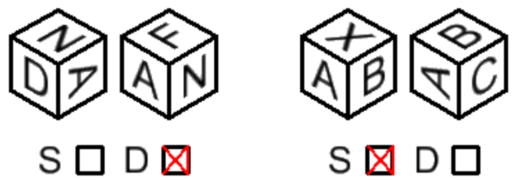
Correct Answers – Incorrect Answers = Total Score

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO

PIN:________

F. Cube Comparison Test

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 a drawing 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 maked D because they must be drawings of **different** 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 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.
Note: No letters appear on more than one face of a given cube. Except for that, any letter can be on the hidden faces of a cube.

Work the three examples below.

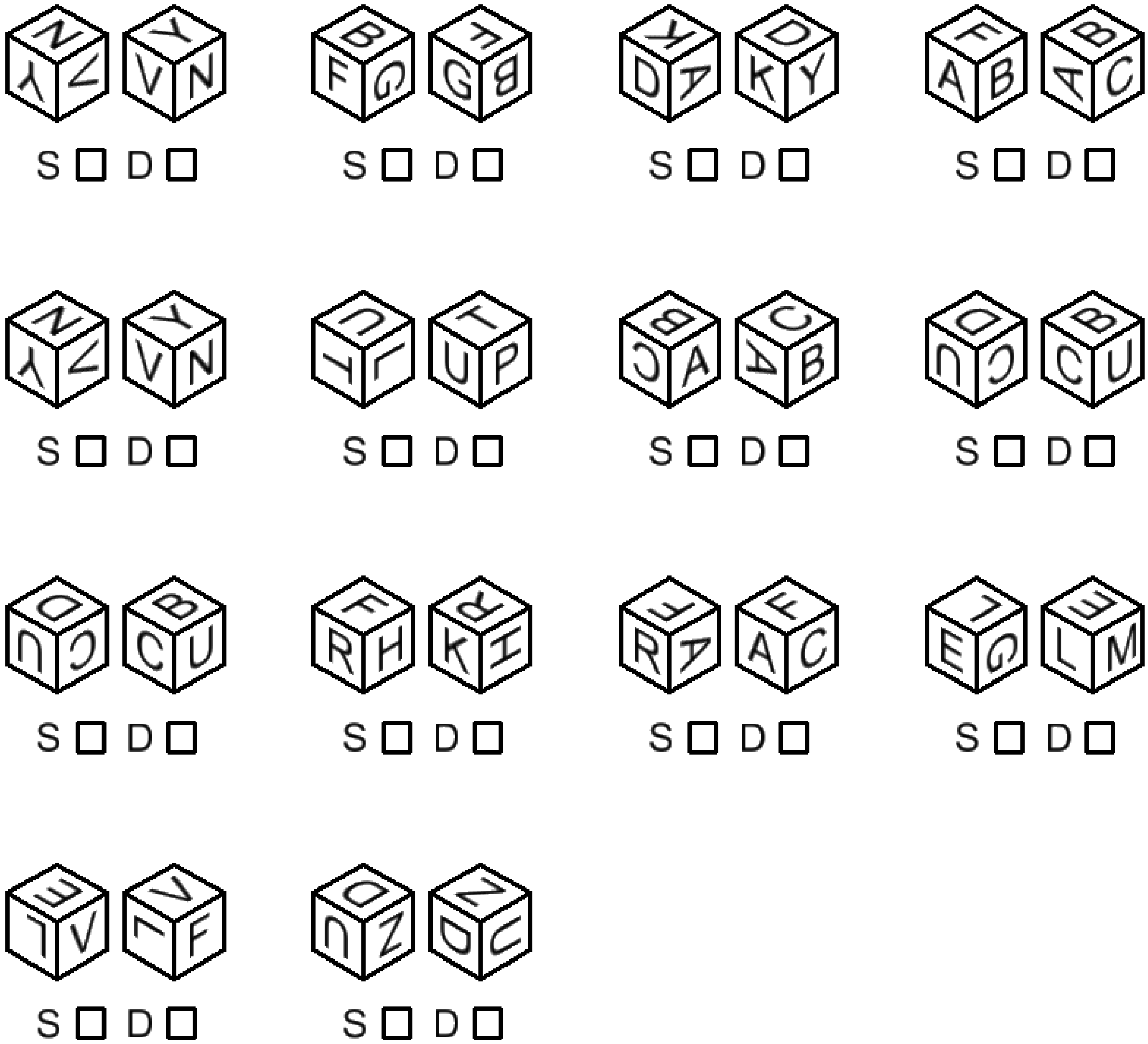
The first pair immediately above should be marked D because the X cannot be at the top of the A on the left hand drawing and at the base of the A on the right hand drawing. The second pair is "different" because P has its side next to G on the left hand cube but its top next to G on the right hand cube. 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 **2 minutes** for this test. When you have finished this test, STOP.

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO

Cube Comparison Test (2 minutes)

S = same (same cube)
D = different (different cubes)



______________ – ________________ = __________ / 14

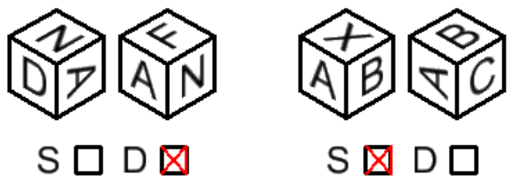
Correct Answers – Incorrect Answers = Total Score

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO

PIN:________

G. Cube Comparison Test Answers

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 a drawing 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 maked D because they must be drawings of **different** 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 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.

Note: No letters appear on more than one face of a given cube. Except for that, any letter 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 top 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.

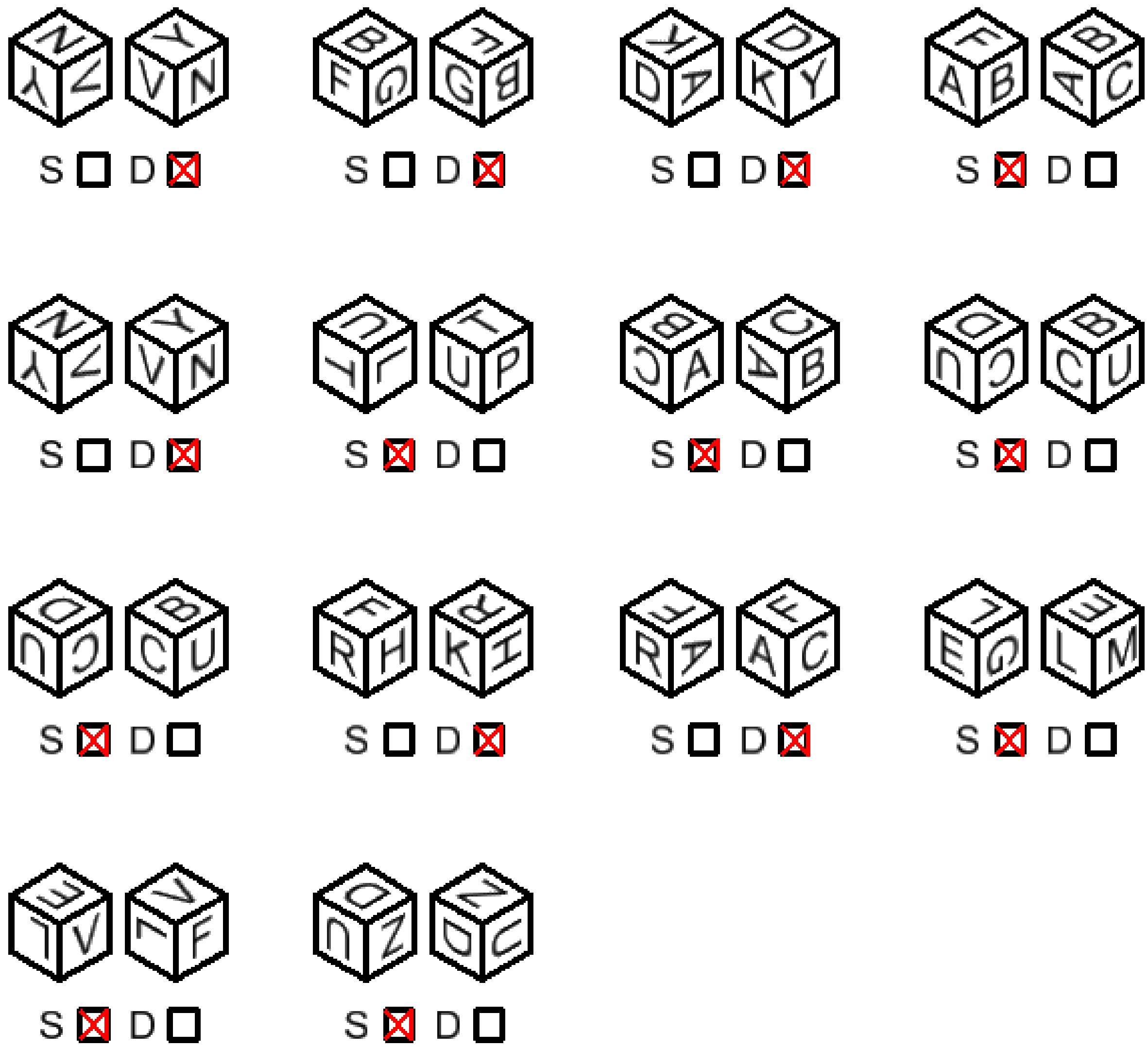
Your score on this test will be the number marked correctly minus the number marked incorrectly. Therefore, it will **not** be to your advantage to guess unless you have some idea which choice is correct. Work as quickly as you can without sacrificing accuracy.

You will have **2 minutes** for this test. When you have finished this test, STOP.

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO

Cube Comparison Test Answers (2 minutes)

S = same (same cube)
D = different (different cubes)



______________ – ________________ = __________ / 14

Correct Answers – Incorrect Answers = Total Score

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO

H. Demographics Questionnaire

I have signed the Informed Consent Form agreeing to participate in this study, "Tangible and Adaptive Engineering Instructions for Developing Societies", that has been approved by the Office of Research Integrity (ORI) at the University of Colorado Boulder. I understand that my responses to this questionnaire are voluntary and that I can choose not to answer certain questions. Furthermore, I understand that I will not be identified by name in any research or publications resulting from this study.

Personal Identification Number (PIN): ________________

Demographic Information
Age: ________________
Gender:
_____ Male
_____ Female

Educational Background
Total years of education (e.g. grade school through high school = 12 years): _______________
Please select your highest level of education:
_____ Less than a high school diploma
_____ High school diploma
_____ Some college no degree
_____ Bachelor's Degree
_____ Master's Degree
_____ Professional Degree
Have you had any formal training in engineering drawings/blueprint reading:
_____ Yes _____ No

Work Experience
Current Occupation: ________________
Years of Engineering Industry Work Experience): ________________
Type of Engineering Industry Work Experience (check all that apply):
_____ None
_____ Design
_____ Construction
_____ Internship or Co-op
_____ Field Inspector
_____ Estimator
_____ Project Engineer
_____ Project Manager
_____ Craft Worker
_____ Foreman
_____ Superintendent
_____ Owner's Representative
_____ Other: ________________

I. Post Assembly Questionnaire

I have signed the Informed Consent Form agreeing to participate in this study, "Tangible and Adaptive Engineering Instructions for Developing Societies", that has been approved by the Office of Research Integrity (ORI) at the University of Colorado Boulder. I understand that my responses to this questionnaire are voluntary and that I can choose not to answer certain questions. Furthermore, I understand that I will not be identified by name in any research or publications resulting from this study.

Personal Identification Number (PIN): ________________

Information Delivery Formats

What was the greatest challenge from the type of information delivery format you received (2D, 3D Interface, Physical Model)?

If you are a structural steel subcontractor and need to plan and present an erection sequence, which information delivery format would you use to complete the task (2D, 3D Interface, Physical Model) and why (you may suggest a combination)?

If you are calculating the necessary cubic yards of concrete for an upcoming slab pour, which information delivery format would you use to complete the task (2D, 3D Interface, Physical Model) and why (you may suggest a combination)?

If you are a mechanical, electrical, or plumbing engineer and need to design piping runs with sufficient access space, which information delivery format would you use to complete the task (2D, 3D Interface, Physical Model) and why (you may suggest a combination)?

If you are estimating the quantity of earthwork that will have to be cut and/or filled on a project, which information delivery format would you use to complete the task (2D, 3D Interface, Physical Model) and why (you may suggest a combination)?

J. Raw Data Baseline Testing

PIN	Cognitive Tests		Time to Completion			Number of Errors			Direct Work			Indirect Work			Rework		
	Card	**Cube**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
008	0	0	07:32	12:00	09:48	0	0	2	75.0%	66.7%	73.7%	25.0%	25.0%	21.1%	0.0%	8.3%	5.3%
009	0	0	10:34	09:22	11:51	0	0	0	76.2%	68.4%	75.0%	14.3%	26.3%	20.8%	9.5%	5.3%	4.2%
010	31	6	07:41	09:18	09:40	10	0	0	73.3%	63.2%	70.0%	26.7%	26.3%	25.0%	0.0%	10.5%	5.0%
011	32	12	11:21	10:57	12:11	0	0	0	69.6%	68.2%	75.0%	30.4%	22.7%	20.8%	0.0%	9.1%	4.2%
012	33	12	09:31	08:52	09:35	0	0	0	75.0%	73.7%	70.0%	20.0%	26.3%	25.0%	5.0%	0.0%	5.0%
013	23	10	09:31	11:31	09:30	0	0	0	80.0%	73.9%	89.5%	20.0%	21.7%	10.5%	0.0%	4.3%	0.0%
014	40	12	07:01	08:58	07:41	0	0	0	86.7%	77.8%	73.3%	13.3%	22.2%	26.7%	0.0%	0.0%	0.0%
015	34	14	05:17	05:58	06:21	0	0	0	90.9%	76.9%	84.6%	0.0%	7.7%	7.7%	9.1%	15.4%	7.7%
016	12	6	15:55	13:40	13:10	0	0	2	43.8%	51.9%	55.6%	34.4%	37.0%	25.9%	21.9%	11.1%	18.5%
017	39	8	07:58	08:47	09:13	0	0	1	75.0%	70.0%	75.0%	25.0%	30.0%	25.0%	0.0%	0.0%	0.0%

PIN	Age	Gender	Years Edu	Highest Level Edu	Formal Drawing Training?	Current Occupation	Years Work Experience	Type Work Experience
008	31	Male	20	Master's degree	No	Student	2	Internship or Co-op, Project Engineer
009	45	Male	19	Master's degree	Yes	Student	18	Design, Construction, Estimator, Project Engineer, Project Manager, Craft Worker, Foreman, Superintendent
010	22	Male	17	High school diploma	Yes	Student	1	Construction, Internship or Co-op
011	22	Male	16	Some college, no degree	No	Student	1	Construction, Internship or Co-op, Field Inspector
012	19	Female	14	Some college, no degree	Yes	Student	0	None
013	20	Female	16	Some college, no degree	Yes	Student	0	None
014	20	Female	15	Some college, no degree	Yes	Student	0	None
015	19	Male	14	Some college, no degree	Yes	Student	0	None
016	21	Female	17	High school diploma	Yes	Student	0	None
017	22	Male	17	Some college, no degree	Yes	Student	0	None

K. Raw Data Field Testing

PIN	Cognitive		Time to Completion			Number of Errors			Direct Work			Indirect Work			Rework		
	Card	Cube	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
018	35	12	20:40	10:44	08:59	5	2	0	60.5%	78.3%	88.9%	32.6%	21.7%	11.1%	7.0%	0.0%	0.0%
019	32	13	09:20	10:45	08:32	1	0	0	68.4%	61.9%	76.5%	26.3%	28.6%	23.5%	5.3%	9.5%	0.0%
020	40	14	13:41	12:34	09:08	0	0	0	73.3%	72.2%	88.9%	26.7%	22.2%	11.1%	0.0%	5.6%	0.0%
021	35	10	11:55	09:25	06:51	0	0	0	70.8%	68.4%	87.5%	29.2%	31.6%	12.5%	0.0%	0.0%	0.0%
022	24	-3	09:13	08:53	07:24	2	1	0	68.4%	77.8%	87.5%	31.6%	22.2%	12.5%	0.0%	0.0%	0.0%
023	27	3	13:45	10:29	08:25	2	1	0	64.3%	71.4%	82.4%	28.6%	28.6%	17.6%	7.1%	0.0%	0.0%
024	28	6	14:52	10:47	07:31	3	0	2	56.7%	85.7%	86.7%	36.7%	14.3%	13.3%	6.7%	0.0%	0.0%
025	26	6	15:31	13:42	10:54	0	0	1	80.6%	60.7%	90.9%	16.1%	35.7%	9.1%	3.2%	3.6%	0.0%
026	33	2	11:37	10:12	07:24	0	0	0	70.8%	76.2%	80.0%	29.2%	14.3%	20.0%	0.0%	9.5%	0.0%
027	36	12	10:52	09:11	08:46	0	0	0	63.6%	83.3%	88.9%	36.4%	16.7%	11.1%	0.0%	0.0%	0.0%
028	37	7	12:16	11:24	10:31	1	0	2	75.0%	69.6%	85.7%	25.0%	30.4%	14.3%	0.0%	0.0%	0.0%
029	37	2	17:42	12:34	08:21	2	0	0	68.6%	69.2%	75.0%	25.7%	30.8%	25.0%	5.7%	0.0%	0.0%
030	38	14	19:52	10:09	06:53	3	0	0	50.0%	70.0%	78.6%	42.5%	30.0%	21.4%	7.5%	0.0%	0.0%
031	34	6	13:07	11:14	12:06	1	0	4	65.4%	72.7%	76.0%	30.8%	27.3%	16.0%	3.8%	0.0%	8.0%
032	24	11	08:02	07:58	06:49	0	0	0	70.6%	75.0%	85.7%	29.4%	25.0%	14.3%	0.0%	0.0%	0.0%
033	16	0	20:49	15:39	10:45	0	0	0	44.4%	67.7%	90.9%	51.1%	29.0%	9.1%	4.4%	3.2%	0.0%
034	24	11	09:47	11:58	03:14	0	0	0	68.2%	70.8%	81.8%	31.8%	29.2%	18.2%	0.0%	0.0%	0.0%
035	37	14	10:29	06:20	05:27	0	0	0	66.7%	76.9%	83.3%	28.6%	15.4%	16.7%	4.8%	7.7%	0.0%
036	23	2	13:25	11:41	08:53	1	0	2	70.0%	72.7%	76.0%	25.0%	27.3%	16.0%	5.0%	0.0%	8.0%
037	31	10	11:28	10:56	09:31	0	0	0	73.9%	77.3%	84.2%	21.7%	22.7%	15.8%	4.3%	0.0%	0.0%

PIN	Age	Gender	Years Edu	Highest Level Edu	Formal Drawing Training ?	Current Occupation	Years Work Experience	Type Work Experience
018	29	Male	18	Bachelor's degree	No	Project Engineer	2	Construction, Internship or Co-op, Project Engineer
019	24	Female	18	Bachelor's degree	Yes	Field Engineer	4	Construction, Internship or Co-op, Estimator, Project Engineer
020	23	Female	20	Bachelor's degree	Yes	Field Engineer	1	Construction, Internship or Co-op, Field Engineer
021	24	Male	17	Bachelor's degree	Yes	Project Engineer	3	Construction, Project Engineer, Craft Worker
022	23	Male	19	Bachelor's degree	Yes	Engineering Intern	3	Design, Construction, Internship or Co-op, Estimator
023	33	Male	17	Bachelor's degree	Yes	Construction Management	10	Construction, Superintendent
024	22	Male	17	Bachelor's degree	Yes	Intern	1	Construction, Internship or Co-op
025	22	Male	17	Bachelor's degree	Yes	Field Engineer with Mortenson	1	Project Engineer
026	23	Female	13	Bachelor's degree	Yes	Field Engineer	1	Internship or Co-op, Project Engineer
027	40	Male	18	Bachelor's degree	Yes	Construction Management	15	Construction, Internship or Co-op, Estimator, Project Engineer, Project Manager, Craft Worker, Foreman
028	32	Male	18	Bachelor's degree	Yes	Senior Surveyor	12	Construction, Craft Worker, Foreman, survey
029	28	Male	17	Some college, no degree	Yes	Surveyor	10	Construction, Craft Worker, Foreman, Survey
030	32	Male	16	Some college, no degree	Yes	surveyor	13	Construction, Craft Worker, Foreman, survey
031	29	Male	17	Bachelor's degree	No	Assistant Project Manager	7	Construction, Internship or Co-op, Estimator, Project Engineer, Project Manager
032	35	Male	17	Bachelor's degree	Yes	superintendent	12	Construction, Field Inspector, Project Engineer, Superintendent
033	33	Female	18	Bachelor's degree	No	Project Engineer	3	Project Engineer
034	42	Female	17	Bachelor's degree	Yes	Quality Manager	17	Construction, Project Engineer, Project Manager
035	39	Male	20	Bachelor's degree	No	Sr ICC	12	Design, Construction, Project Manager, Owner's Representative
036	28	Male	18	Bachelor's degree	Yes	Project Engineer	6	Construction, Internship or Co-op, Project Engineer, Craft Worker, Asst. Superintendent
037	27	Male	17	Bachelor's degree	Yes	Project Engineer	5	Construction, Internship or Co-op, Field Inspector, Project Engineer

L. SPSS Outputs

L1. ANOVA Results 1: Performance Metrics by Model Number

		Sum of Squares	df	Mean Square	F	Sig.
Time To Completion	Between Groups	11260.467	2	5630.233	.267	.768
	Within Groups	569139.000	27	21079.222		
	Total	580399.467	29			
Number of Errors	Between Groups	5.000	2	2.500	.699	.506
	Within Groups	96.500	27	3.574		
	Total	101.500	29			
Direct Work	Between Groups	.019	2	.009	.948	.400
	Within Groups	.267	27	.010		
	Total	.286	29			
Indirect Work	Between Groups	.009	2	.004	.681	.515
	Within Groups	.177	27	.007		
	Total	.185	29			
Rework	Between Groups	.002	2	.001	.256	.776
	Within Groups	.100	27	.004		
	Total	.101	29			

L2. ANOVA Results 2: Performance Metrics by Information Type

		Sum of Squares	df	Mean Square	F	Sig.
Time to Completion	Between Groups	936132.433	2	468066.217	17.158	.000
	Within Groups	1554923.500	57	27279.360		
	Total	2491055.933	59			
Number of Errors	Between Groups	7.300	2	3.650	3.196	.048
	Within Groups	65.100	57	1.142		
	Total	72.400	59			
Direct Work	Between Groups	.305	2	.152	33.202	.000
	Within Groups	.262	57	.005		
	Total	.566	59			
Indirect Work	Between Groups	.227	2	.113	29.561	.000
	Within Groups	.219	57	.004		
	Total	.445	59			
Rework	Between Groups	.005	2	.003	2.574	.085
	Within Groups	.056	57	.001		

Total	.061	59			

L3. ANOVA Results 3: Performance Metrics by Card Rotation Score (Information Type)

		Sum of Squares	df	Mean Square	F	Sig.
Time to Completion 2D Plans	Between Groups	45984.050	1	45984.050	.873	.363
	Within Groups	948600.500	18	52700.028		
	Total	994584.550	19			
Time to Completion 3D CAD	Between Groups	14634.050	1	14634.050	.991	.333
	Within Groups	265929.700	18	14773.872		
	Total	280563.750	19			
Time to Completion 3D Physical	Between Groups	1095.200	1	1095.200	.071	.793
	Within Groups	278680.000	18	15482.222		
	Total	279775.200	19			
Number of Errors 2D Plans	Between Groups	.450	1	.450	.222	.643
	Within Groups	36.500	18	2.028		
	Total	36.950	19			
Number of Errors 3D CAD	Between Groups	.000	1	.000	.000	1.000
	Within Groups	5.200	18	.289		
	Total	5.200	19			
Number of Errors 3D Physical	Between Groups	.050	1	.050	.039	.845
	Within Groups	22.900	18	1.272		
	Total	22.950	19			
Direct Work 2D Plans	Between Groups	.000	1	.000	.000	.984
	Within Groups	.136	18	.008		
	Total	.136	19			
Direct Work 3D CAD	Between Groups	.001	1	.001	.312	.583
	Within Groups	.072	18	.004		
	Total	.073	19			
Direct Work 3D Physical	Between Groups	.000	1	.000	.167	.688
	Within Groups	.052	18	.003		
	Total	.052	19			
Indirect Work 2D Plans	Between Groups	.000	1	.000	.060	.809
	Within Groups	.106	18	.006		
	Total	.106	19			
Indirect Work 3D CAD	Between Groups	.002	1	.002	.622	.440

	Within Groups	.071	18	.004		
	Total	.074	19			
Indirect Work 3D Physical	Between Groups	.000	1	.000	.225	.641
	Within Groups	.038	18	.002		
	Total	.039	19			
Rework 2D Plans	Between Groups	.000	1	.000	.293	.595
	Within Groups	.016	18	.001		
	Total	.016	19			
Rework 3D CAD	Between Groups	.000	1	.000	.176	.680
	Within Groups	.022	18	.001		
	Total	.022	19			
Rework 3D Physical	Between Groups	.000	1	.000	.000	1.000
	Within Groups	.012	18	.001		
	Total	.012	19			

L4. ANOVA Results 4: Performance Metrics by Cube Comparison Score (Information Type)

		Sum of Squares	df	Mean Square	F	Sig.
Time to Completion 2D Plans	Between Groups	47142.050	1	47142.050	.896	.356
	Within Groups	947442.500	18	52635.694		
	Total	994584.550	19			
Time to Completion 3D CAD	Between Groups	49501.250	1	49501.250	3.856	.065
	Within Groups	231062.500	18	12836.806		
	Total	280563.750	19			
Time to Completion 3D Physical	Between Groups	58752.800	1	58752.800	4.785	.042
	Within Groups	221022.400	18	12279.022		
	Total	279775.200	19			
Number of Errors 2D Plans	Between Groups	.450	1	.450	.222	.643
	Within Groups	36.500	18	2.028		
	Total	36.950	19			
Number of Errors 3D CAD	Between Groups	.000	1	.000	.000	1.000
	Within Groups	5.200	18	.289		
	Total	5.200	19			
Number of Errors 3D Physical	Between Groups	6.050	1	6.050	6.444	.021
	Within Groups	16.900	18	.939		
	Total	22.950	19			

Direct Work 2D Plans	Between Groups	.000	1	.000	.002	.964
	Within Groups	.136	18	.008		
	Total	.136	19			
Direct Work 3D CAD	Between Groups	.001	1	.001	.134	.719
	Within Groups	.073	18	.004		
	Total	.073	19			
Direct Work 3D Physical	Between Groups	.001	1	.001	.305	.587
	Within Groups	.051	18	.003		
	Total	.052	19			
Indirect Work 2D Plans	Between Groups	.000	1	.000	.025	.877
	Within Groups	.106	18	.006		
	Total	.106	19			
Indirect Work 3D CAD	Between Groups	.001	1	.001	.351	.561
	Within Groups	.072	18	.004		
	Total	.074	19			
Indirect Work 3D Physical	Between Groups	.000	1	.000	.018	.894
	Within Groups	.039	18	.002		
	Total	.039	19			
Rework 2D Plans	Between Groups	.000	1	.000	.277	.605
	Within Groups	.016	18	.001		
	Total	.016	19			
Rework 3D CAD	Between Groups	.000	1	.000	.176	.680
	Within Groups	.022	18	.001		
	Total	.022	19			
Rework 3D Physical	Between Groups	.001	1	.001	2.250	.151
	Within Groups	.010	18	.001		
	Total	.012	19			

L5. ANOVA Results 5: Performance Metrics by Information Type (Card Rotation)

High Card Rotation Score

		Sum of Squares	df	Mean Square	F	Sig.
Time to Completion	Between Groups	622085.400	2	311042.700	12.149	.000
	Within Groups	691253.400	27	25601.978		
	Total	1313338.800	29			
Number of Errors	Between Groups	5.067	2	2.533	1.500	.241
	Within Groups	45.600	27	1.689		
	Total	50.667	29			

Direct Work	Between Groups	.142	2	.071	19.954	.000
	Within Groups	.096	27	.004		
	Total	.238	29			
Indirect Work	Between Groups	.109	2	.055	16.497	.000
	Within Groups	.089	27	.003		
	Total	.198	29			
Rework	Between Groups	.002	2	.001	.800	.460
	Within Groups	.031	27	.001		
	Total	.033	29			

Low Card Rotation Score

		Sum of Squares	df	Mean Square	F	Sig.
Time to Completion	Between Groups	370421.067	2	185210.533	6.236	.006
	Within Groups	801956.800	27	29702.104		
	Total	1172377.867	29			
Number of Errors	Between Groups	2.467	2	1.233	1.753	.192
	Within Groups	19.000	27	.704		
	Total	21.467	29			
Direct Work	Between Groups	.164	2	.082	13.546	.000
	Within Groups	.164	27	.006		
	Total	.328	29			
Indirect Work	Between Groups	.121	2	.060	12.951	.000
	Within Groups	.126	27	.005		
	Total	.247	29			
Rework	Between Groups	.004	2	.002	2.038	.150
	Within Groups	.024	27	.001		
	Total	.028	29			

L6. ANOVA Results 6: Performance Metrics by Information Type (Cube Comparison)

High Cube Comparison Score

		Sum of Squares	df	Mean Square	F	Sig.
Time to Completion	Between Groups	485477.067	2	242738.533	7.780	.002
	Within Groups	842376.400	27	31199.126		
	Total	1327853.467	29			
Number of Errors	Between Groups	4.467	2	2.233	1.977	.158
	Within Groups	30.500	27	1.130		

		Sum of Squares	df	Mean Square	F	Sig.
	Total	34.967	29			
Direct Work	Between Groups	.162	2	.081	22.661	.000
	Within Groups	.096	27	.004		
	Total	.258	29			
Indirect Work	Between Groups	.113	2	.056	20.133	.000
	Within Groups	.076	27	.003		
	Total	.188	29			
Rework	Between Groups	.005	2	.002	2.844	.076
	Within Groups	.022	27	.001		
	Total	.027	29			

Low Cube Comparison Score

		Sum of Squares	df	Mean Square	F	Sig.
Time to Completion	Between Groups	451009.800	2	225504.900	10.928	.000
	Within Groups	557151.000	27	20635.222		
	Total	1008160.800	29			
Number of Errors	Between Groups	6.067	2	3.033	2.915	.071
	Within Groups	28.100	27	1.041		
	Total	34.167	29			
Direct Work	Between Groups	.143	2	.072	11.807	.000
	Within Groups	.164	27	.006		
	Total	.307	29			
Indirect Work	Between Groups	.115	2	.058	11.021	.000
	Within Groups	.141	27	.005		
	Total	.257	29			
Rework	Between Groups	.002	2	.001	.930	.407
	Within Groups	.031	27	.001		
	Total	.034	29			

L7. ANOVA Results 7: Indirect Work by Drawing Training

		Sum of Squares	df	Mean Square	F	Sig.
Indirect Work 2D Plans	Between Groups	.015	1	.015	3.028	.099
	Within Groups	.091	18	.005		
	Total	.106	19			
Indirect Work 3D CAD	Between Groups	.002	1	.002	.404	.533
	Within Groups	.072	18	.004		
	Total	.074	19			

Indirect Work 3D Physical	Between Groups	.002	1	.002	1.201	.288
	Within Groups	.036	18	.002		
	Total	.039	19			

L8. ANOVA Results 8: Direct Work by Age

		Sum of Squares	df	Mean Square	F	Sig.
Direct Work 2D Plans	Between Groups	.000	1	.000	.019	.891
	Within Groups	.136	18	.008		
	Total	.136	19			
Direct Work 3D CAD	Between Groups	.000	1	.000	.036	.852
	Within Groups	.073	18	.004		
	Total	.073	19			
Direct Work 3D Physical	Between Groups	.012	1	.012	5.262	.034
	Within Groups	.040	18	.002		
	Total	.052	19			

L9. ANOVA Results 9: Direct Work and Indirect Work by Years of Industry Experience

		Sum of Squares	df	Mean Square	F	Sig.
Direct Work 2D Plans	Between Groups	.026	1	.026	4.357	.051
	Within Groups	.109	18	.006		
	Total	.136	19			
Direct Work 3D CAD	Between Groups	.001	1	.001	.230	.637
	Within Groups	.072	18	.004		
	Total	.073	19			
Direct Work 3D Physical	Between Groups	.000	1	.000	.141	.712
	Within Groups	.052	18	.003		
	Total	.052	19			
Indirect Work 2D Plans	Between Groups	.024	1	.024	5.136	.036
	Within Groups	.082	18	.005		
	Total	.106	19			
Indirect Work 3D CAD	Between Groups	.000	1	.000	.016	.901
	Within Groups	.074	18	.004		
	Total	.074	19			
Indirect Work 3D Physical	Between Groups	.000	1	.000	.190	.668

	Within Groups	.038	18	.002		
	Total	.039	19			

L10. Two-Way ANOVA Results 1: Time to Completion by Cube Comparison Score and Age

2D Plans

Between-Subjects Factors

		N
Cube Comparison Score	1	10
	2	10
Age	1	10
	2	10

Tests of Between-Subjects Effects

Dependent Variable: Time to Completion 2D Plans

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	85456.467[a]	3	28485.489	.501	.687
Intercept	37177782691.408	1	37177782691.408	654302.220	.000
Cube2nd	63250.208	1	63250.208	1.113	.307
Age2nd	37559.408	1	37559.408	.661	.428
Cube2nd * Age2nd	755.008	1	755.008	.013	.910
Error	909128.083	16	56820.505		
Total	38730059115.000	20			
Corrected Total	994584.550	19			

a. R Squared = .086 (Adjusted R Squared = -.085)

3D CAD

Between-Subjects Factors

		N
Cube Comparison Score	1	10
	2	10
Age	1	10
	2	10

Tests of Between-Subjects Effects

Dependent Variable: Time to Completion 3D CAD

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	76494.583[a]	3	25498.194	1.999	.155
Intercept	36929979820.800	1	36929979820.800	2895487.284	.000
Cube2nd	43930.133	1	43930.133	3.444	.082
Age2nd	1763.333	1	1763.333	.138	.715
Cube2nd * Age2nd	25230.000	1	25230.000	1.978	.179
Error	204069.167	16	12754.323		
Total	38456292065.000	20			
Corrected Total	280563.750	19			

a. R Squared = .273 (Adjusted R Squared = .136)

3D Physical

Between-Subjects Factors

		N
Cube Comparison Score	1	10
	2	10
Age	1	10
	2	10

Tests of Between-Subjects Effects

Dependent Variable: Time to Completion 3D Physical

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	123222.617[a]	3	41074.206	4.198	.023
Intercept	36684124547.408	1	36684124547.408	3749193.915	.000
Cube2nd	57772.408	1	57772.408	5.904	.027
Age2nd	205.408	1	205.408	.021	.887
Cube2nd * Age2nd	64264.408	1	64264.408	6.568	.021
Error	156552.583	16	9784.536		
Total	38192681388.000	20			
Corrected Total	279775.200	19			

a. R Squared = .440 (Adjusted R Squared = .336)