

## Effects of Thinking Style on Design Strategies: Using Bridge Construction Simulation Programs

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### ABSTRACT

Computer simulation users can freely control operational factors and simulation results, repeat processes, make changes, and learn from simulation environment feedback. The focus of this paper is on simulation-based design tools and their effects on student learning processes in a group of 101 Taiwanese senior high school students. Participants identified as having executive, legislative, judicial, global or local thinking style tendencies were asked to design bridges using WPBD2007 computer simulation freeware. Design strategies and design tool usage were video recorded and analyzed. Results indicate a positive correlation between judicial thinking style and frequency of substantial change in structure and goal strategy; a negative correlation between local thinking style and frequency of component tool list usage; a negative correlation between use of top-down strategies and frequency of using two types of assistance tools; a positive correlation between the use of bottom-up strategies and frequency of using both tool types; a positive correlation between the use of a substantial change strategy and frequency of using the graphical interface only; and positive correlations between total construction costs and the frequencies of using the substantial change strategy and component list tool.

### Keywords

Simulation, Design strategy, Thinking styles, Constructionism

### Introduction

Researchers have reported mixed results regarding the effects of instructional technology and daily life technology on learning (see, for example, Greenhow, Robelia, & Hughes, 2009; McLoughlin & Lee, 2007; Spotts, 1999; Ting & Tai, 2010; Zimmerman & Bell, 2008). Various information tools associated with the Web 2.0 model of co-creation and learning are providing teachers with curriculum design and instructional tools such as readily available slides and simulation programs (Ajjana & Hartshorne, 2008; Franklin & Van Harmelen, 2007; Greenhow, 2007; McLoughlin & Lee, 2010). These tools can be introduced into learning processes in a natural manner, with or without active promotion by instructors. However, many of them are designed for specific purposes that do not directly match instructional goals or reflect an accurate understanding of learning processes. For instance, search engines may help learners find information, but their use does not necessarily result in learning if students cannot identify information that is accurate or appropriate for their assigned tasks. In other cases, design assistance tools that are not developed for learning purposes require advanced theoretical foundations and/or practical experience. Modifying them to assist learning may produce mixed results—perhaps encouraging experimentation, but possibly increasing reliance on support mechanisms and reducing motivation for creative thinking. Thus, there is a growing body of research on the best uses of multi-faceted information tools in classrooms (Bransford, Vye, Stevens, Kuhl, Schwartz, Bell et al., 2005).

For this project we investigated the effects of simulation-based design assistance tools on learning processes for a group of Taiwanese senior high school freshmen. Taiwanese students must cope with the stress of various entrance examinations, therefore their efforts are primarily focused on attaining high test scores. As a result, quick fixes and useful formulas are deeply rooted in their learning. Emphases on “the only right answer” and “give me the key point, not the reason” have undermined the development of observation, comprehension, and creativity skills in the country’s education system. Simulation tools can be used to address this problem by facilitating exploratory and constructive learning. Instead of forcing students to find “right answers,” simulation programs can give them opportunities to experiment and to develop trial-and-error skills for optimizing the results of their efforts.

Simulation-based design programs can help students perform complex experiments and use acquired knowledge to predict results and modify simulations (Gredler, 2003). Past experience with simulation-based instruction indicates that students with similar knowledge backgrounds have varying preferences for design tools, rules, and strategies, produce a broad range of results, and benefit from a number of concept development processes. We will use Sternberg's (1997) thinking style theory as part of our effort to explain these differences from a non-ability perspective, based on the assumption that thinking style determines how individuals express their abilities. For our experiment, participants were asked to use a simulation program to design truss bridges. We used the results to determine how thinking style, design behaviors, and design tool preferences affect simulation-based design performance.

## Literature review

### Simulation and learning

High-quality simulations give learners more detailed information than printed texts, and their game-like experiences have the secondary advantage of enhancing learning motivation (Cottrell, 2002). Today's computer simulation products can be used to introduce information on natural phenomena, repetitive processes, and processing procedures—for example, global weather patterns, biology research procedures, chemistry lab experiments, and modeling human behavior (Alessi & Trollip, 2001). In product design, simulations are often applied to test or predict product performance, thus reducing costs. They are also increasingly being used to facilitate trial-and-error experimentation and knowledge construction, with learners adjusting design variables and working with simulation results in real time. Users can fine-tune directions and strategies to close the gap between design results and goal expectations. These processes involve a combination of existing and new knowledge. Alessi's (2000) depiction of the relationship between simulation fidelity and learning transfer is shown in Figure 1.

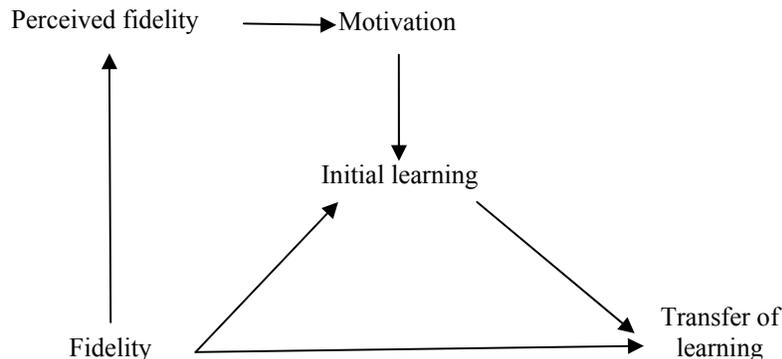


Figure 1. Simulation of fidelity-transfer of learning relationship

In educational contexts, computer simulations can help instructors simplify the operations and output methods of complex systems, and help learners present simulation results that match a range of cognitive abilities. Computer simulations allow learners to perform experiments that cannot be done in the physical world, yet enjoy a sense of achievement similar to that experienced by professional designers (Hwang & Esquembre, 2003). Constructionists support the use of simulations by students to engage in learning through production or design (Papert, 1991), creating sharable products such as computer programs, machines, and games with no cost overruns or risks tied to experimental failure. Such products require students to learn design principles, skills, and strategies.

### Design strategies in simulations

According to Kafai (1996), most professional design activities concentrate on the final product as the central outcome, whereas in education the central concern is learning process. Thus, students can have effective learning experiences even if they do not create good products. It is important to remember that in simulation design environments that are not intended for learning, students may be misled by a strong product orientation. In some

cases, learners may rely too much on system prompts that are meant to support professional design efficiency, and therefore miss opportunities for independent thinking practice.

The two most common problem-solving strategies associated with classroom design projects are top-down and bottom-up (Kafai, 1996). The first consists of breaking down a problem into meaningful sub-problems, while the second consists of finding solutions from a convergence of ideas during the process of idea implementation. These strategies have been extensively applied to analyses of cognitive control of operational transfer (Schoelles & Gray, 2003), software design procedures (Jeffries, Turner, Polson, & Atwood, 1981), visual search strategies (Wolfe, Butcher, Lee, & Hyle, 2003), and Web searches (Navarro-Prieto, Scaife, & Rogers, 1999). Using computer programming as an example, many researchers believe that a top-down strategy is more effective, since long, complex programs can be divided into a series of smaller, more manageable tasks. However, Kafai (1996) has observed that some students approach problem solving as a “conversation with a situation,” with appropriate designs emerging through a process of implementation—a bottom-up strategy. Kafai also found that the large majority of students in his study used a combination of the two strategies, with various degrees of overlap.

Both strategies have advantages and disadvantages. Simulation environments generally encourage the kinds of bottom-up strategies that are hard to teach and practice in classroom instruction. In contrast, top-down design strategies encourage systematic approaches in which learners plan or choose a structure and then deconstruct it into modules. After establishing details for each module, they must test module integration—an example of a thinking-oriented approach in which all product details must be addressed before completion. Bottom-up design strategies are action-oriented. Simulation software programs consist of numerous components that can be executed individually or in combination, therefore learners can work on understanding the function of each component before searching for feasible mixes. Learners who use bottom-up strategies must be careful to avoid spending so much time on details that they lose sight of the overall goal in the local optimization process. In contrast, learners who use top-down strategies may suffer from limited creativity due to their reliance on conventional thinking models. In this project our concern is whether simulation systems provide learners with excessive guidance for bottom-up design approaches, which are most effective when they balance or supplement top-down approaches.

### **Thinking styles**

Sternberg (1994) defines thinking style as an individual’s preferred way of using personal abilities when dealing with life problems. Thinking style represents individual habits rather than intelligence or ability, with ability defined as the extent to which one is capable of accomplishing a certain task, and style defined as the way one prefers getting the task done. In Taiwan, all students must take an entrance examination to attend senior high school; therefore students in any high school class generally share a similar level of academic achievement. In such environments, students’ habits are central to learning performance, and thinking style—as a habit of thought—exerts considerable influence on learning outcomes (Sternberg, 1997). In the context of the present study, it is an important factor influencing the simulation design process.

Sternberg identified 13 styles of mental self-government in the five categories of function, form, level, scope, and leaning. Since our focus is on the effects of thinking style on learning processes and strategies, we will emphasize the function and scope categories. Characteristics of each thinking style are shown in Table 1.

Links between thinking style and design behavior have been examined in studies conducted in countries all over the world, with researchers identifying correlations between such factors as creative ideas and peer feedback (Boden, 2004; Kristensson, Gustafsson, & Archer, 2004; Lin, Liu, & Yuan, 2001; O’Hara & Sternberg, 2001; Wolfradt & Pretz, 2001). Hilton (2002) is among those scholars describing a relationship between thinking style and incentive to implement design products among students in a design department. Our goal is to investigate potential associations between student design processes/learning outcomes and thinking style in a sample of Taiwanese high school freshmen, and the impact of thinking style on differences among students with similar prior knowledge and competencies using simulation software.

According to Sternberg (1994), individuals who use an executive learning style favor fixed and predefined procedures. These learners may rely heavily on instructions provided by simulation software, and approach all tasks in terms of a fixed number of steps. In contrast, learners who follow a legislative thinking style prefer having more

freedom to put together different combinations of components. They are likely to prefer object-oriented design interfaces that support the development of creative ideas. Judicial thinking style is characterized by multiple trials and comparisons, which is a key characteristic of simulation systems. In the scope category, a global thinking style is characterized by greater attention given to the aggregate properties of a design, including asymmetry, aesthetics, and overall costs, while a local thinking style is characterized by greater attention to design weaknesses.

Table 1. Function- and scope-category thinking styles

Category	Item	Behavioral Characteristics
Function	Legislative	Prefer creating their own ways of doing things and deciding for themselves what they will do and how they will do it. Like to create their own rules, and prefer problems that are neither pre-structured nor prefabricated.
	Executive	Prefer pre-structured or prefabricated rules and problems. Like filling in gaps within existing structures rather than creating the structures themselves.
	Judicial	Like to evaluate rules and procedures. Prefer problems involving analyses and evaluations of existing objects and ideas.
Scope	Global	Prefer dealing with relatively larger and more abstract issues. Tend to ignore or dislike details in favor of “seeing the forest rather than the trees.”
	Local	Like concrete problems rich in detail. More oriented toward pragmatics, and prefer “seeing trees rather than the forest.”

## Method

Our motivation was to investigate relationships among thinking styles, design strategies, and design tool preferences for a group of students with similar prior knowledge who were asked to achieve the same goal using a simulation-based bridge design program. We will emphasize the relationship between design tool preference and design strategy, with a secondary emphasis on connections between design outcome and both design strategy and design tool usage. Our research framework is shown in Figure 2.

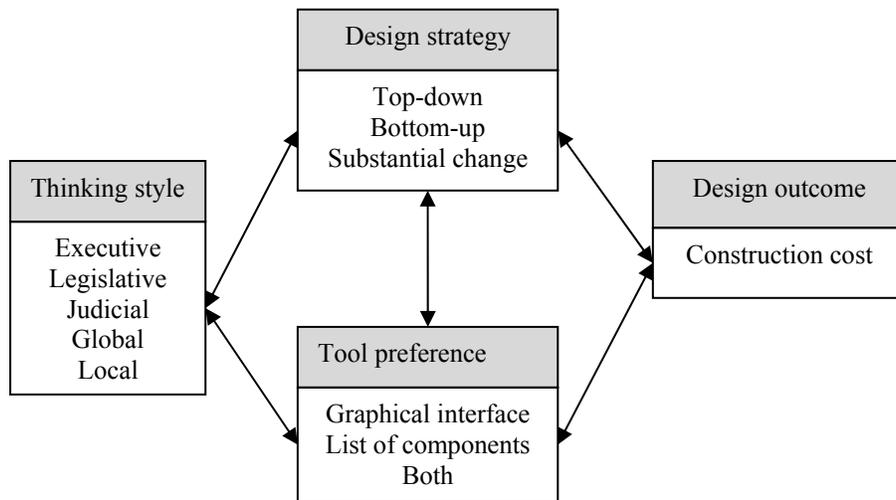


Figure 2. Research framework

## Data sources

The construction simulation program used in this study was the West Point Bridge Designer 2007 (WPBD2007), developed by Colonel Stephen Ressler of the United States Military Academy at West Point (<http://bridgecontest.usma.edu/download2007.htm>). WPBD2007 is at the center of an annual international competition for junior high school students, the West Point Bridge Design Contest (<http://bridgecontest.usma.edu/>). Students from any country can register and send their designs to the Academy, and a small number are invited to

West Point for the final round. This version of the program, which was originally designed to train military engineers, was developed for use by middle school students. The software is regularly updated; the 2007 version was current when this article was being written. WPBD2007 has a simple interface and uses animation, color marks, and graphs to present the results of semi-finished bridge designs. The goal is to design a truss bridge that meets specified loading requirements at the lowest possible cost. As shown in Figure 3, WPBD2007 has an intuitive interface that lets learners draw bridge designs using computer click-and-drag functions. Tool descriptions are given in Table 2.

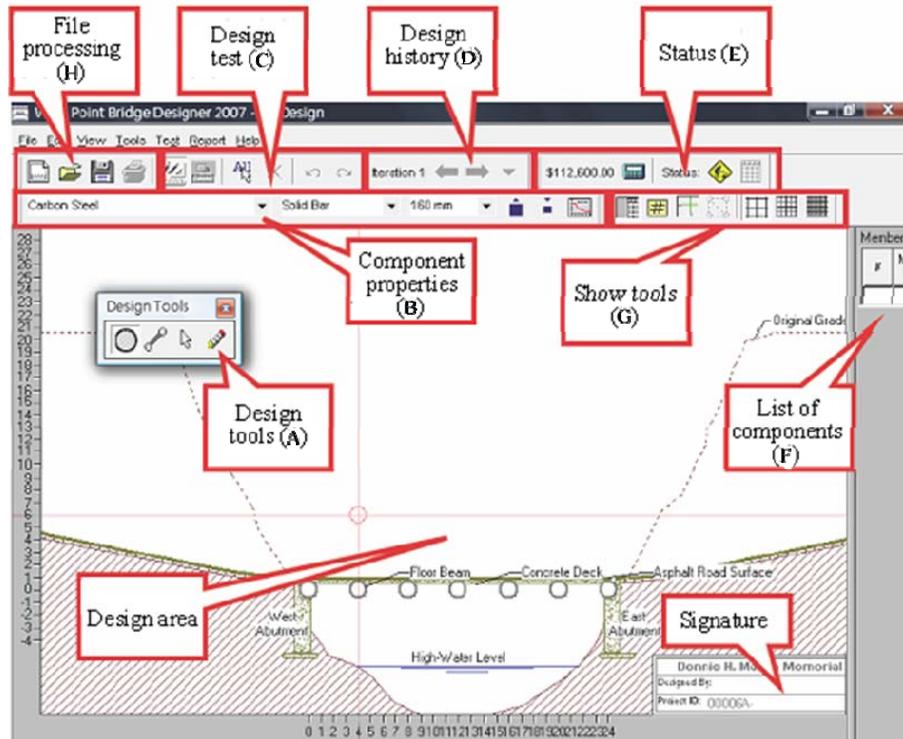
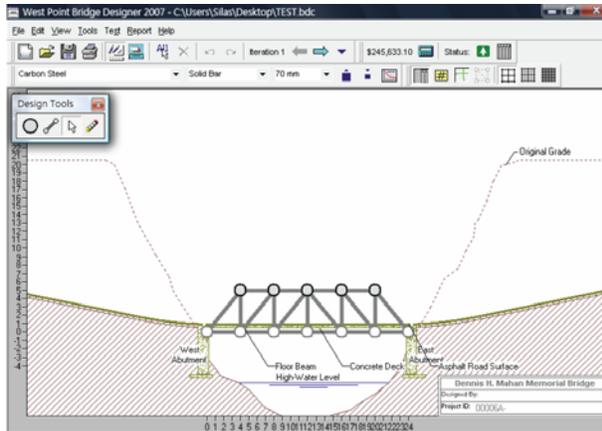


Figure 3. WPBD2007 design interface

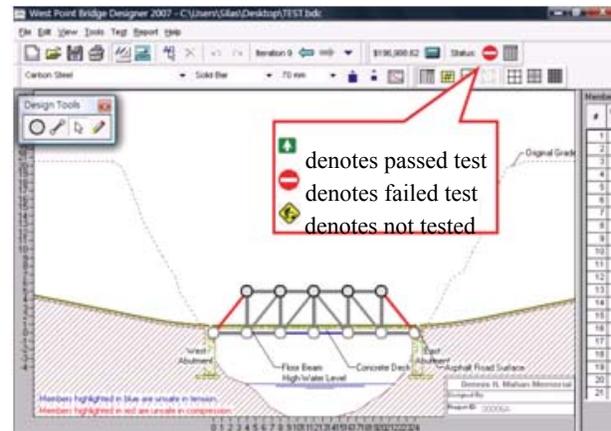
Table 2. WPBD2007 tool descriptions

Tool Type	Function
Design	Placing bridge components and connection points.
Component properties	To show the properties of selected components, including loading-length relationships and cost.
Design test	To test loading capacity.
Design history	To record all tested designs.
Status	To show current design cost, simulation test results, and loading test report.
Component list	Show all component properties and indicate failed components.
Show tools	Display/hide component list, component number, and design assistance grid.
File processing	Execute build/open/save/print functions.

WPBD2007 users manipulate design tools to place bridge components and connection points, and then use various tools to check component properties such as load capacity, length, and cost. A design example is shown as Figure 4a. Other tools are available to test preliminary bridge designs. After each loading test, bridge components that are subject to compression are marked in red, and those subject to tension are marked in blue. The difference between an external force and component limit is marked by color intensity—the darker the color, the closer the force to the maximum tolerance limit (Figure 4b). An example of a design that passes the loading test is shown in Figure 5a; one that fails is shown in Figure 5b. The color-marking feature helps users focus on components that need modification. The current bridge design cost is indicated in the status area.

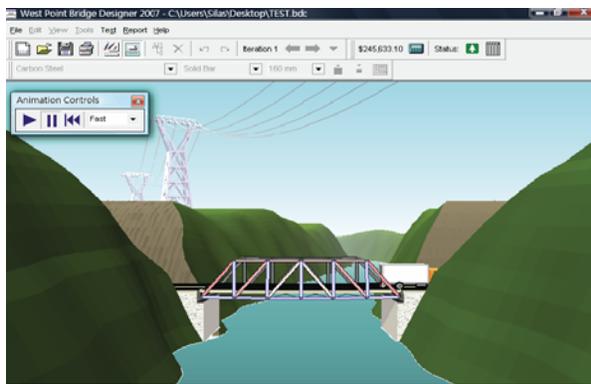


(a) Tentative design for testing.

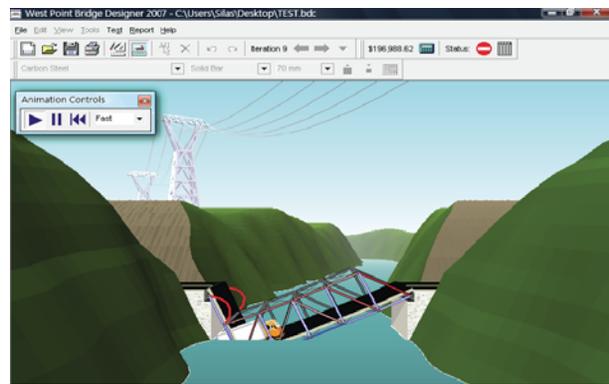


(b) Example of a failed design.

Figure 4. Two screen shots of West Point Bridge Designer (WPBD) projects



(a) Image of a bridge that passes a loading test.



(b) Image of a bridge that fails a loading test.

Figure 5. Two bridge design results

We used a 55-item questionnaire to identify the study participants' thinking styles—11 items each for executive, legislative, judicial, global and local. Responses were recorded along a 5-point scale (1 = “strongly disagree” to 5 = “strongly agree”). Internal consistency coefficients ( $\alpha$ ) for the five dimensions were measured as 0.71 for legislative, 0.61 executive, 0.63 judicial, 0.65 global, and 0.45 local. Thinking style tendency refers to the mean score per thinking style obtained by each participant; higher scores indicate stronger tendencies toward a specific style.

Design strategy preference indicates the frequency of using each strategy type over a fixed number of design steps. We considered three design strategies in this project: top-down, bottom-up, and substantial change in design structure and goals. Kafai (1994) discusses the first two strategies in the context of digital games designed for elementary school students. The third strategy, which can be described as “starting from scratch,” cannot be used in conjunction with the other two. Participant design strategy preference scores represent the means of scores given by three raters familiar with engineering design principles. Rater agreement was calculated using Kendall's coefficient of concordance; coefficients for top-down, bottom-up, and substantial change were .945 ( $p < .001$ ), .933 ( $p < .001$ ), and .886 ( $p < .001$ ) respectively, indicating high levels of agreement.

Design tool preference refers to the frequency of using each design tool over a fixed number of WPBD2007 design steps. The most commonly used design tools are graphical interfaces and component lists. Accordingly, we established three tool usage behavior types: graphical interface only, component list only, and combined use of graphical interface and component list (Figure 6). Design tool preference is directly observable in terms of usage behavior; therefore one member of the research team was responsible for quantifying tool usage behaviors.

Design outcome refers to the cost of a design, as calculated by WPBD2007. To motivate the study participants to achieve this goal, we conducted our experiment as a competition.

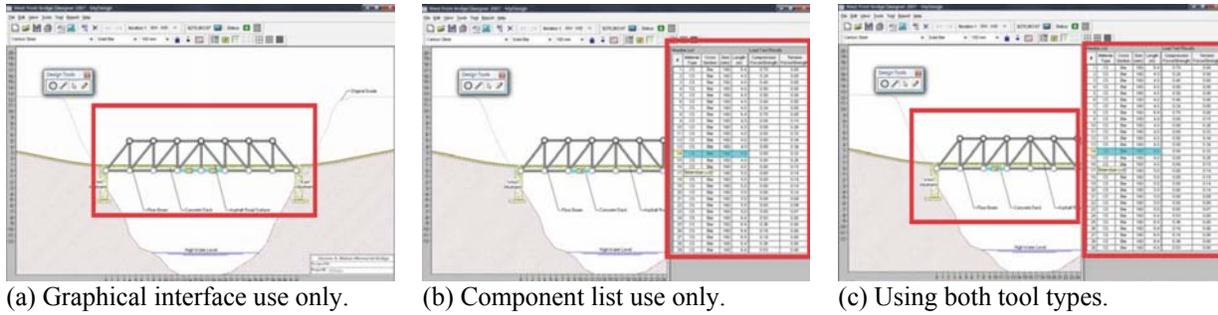


Figure 6. Examples of three design tool usage behaviors

## Participants

The sample consisted of 101 freshmen students (58 males and 43 females) attending a senior high school in Hsinchu County, Taiwan. Students were identified and recruited by convenience sampling. Taiwanese students do not study mechanics at all in junior high school; they receive some basic instruction in one-dimensional mechanics in their freshman year of senior high school. Overall, the participants had almost no training in bridge design, either direct or indirect; therefore all of their knowledge during this project came from their experience with WPBD2007. There was little likelihood of knowledge from other science classes affecting their performance.

## Procedure

The thinking style questionnaire was administered during the first week of the two-week experiment. During the second week, all participants were given 35 minutes of training on the functions of the simulation software and basic knowledge about truss bridges and construction materials. They were given handouts for reference during the 50-minute design activity. Design actions were recorded using screen capture software for later analysis of design strategies and tool preferences.

## Results and discussion

### Descriptive analysis

Descriptive statistics on thinking styles, design strategies, and tool preferences are presented in Table 3. As shown, the mean scores for participant legislative, executive, judicial, global and local style tendencies were 3.68, 3.34, 3.81, 3.16 and 3.03, respectively. As noted above, all Taiwanese students must take an entrance exam that determines which senior high school they are assigned to. All of the participants had recently taken that entrance examination, which is composed by a large number of multiple-choice questions, and it is possibility that preparation for that test supported a tendency toward a judicial thinking style, which favors analysis and comparison.

As shown in Table 3, the participants used top-down strategies an average of 12.3 times and bottom-up strategies an average of 16.3 times during the first 30 design steps. Both were used much more than the substantial change strategy, with a near-normal distribution of frequency values. In terms of design tool preference, the participants used the graphical interface more frequently, but further analysis of the associated distribution reveals that 22.7% of the participants never used the tool and 35.6% used it exclusively. Usage frequencies were lower for both the component list and component list-plus-graphical interface tools—67.3% and 40.6% of the participants never used this tool or tool combination, respectively.

Table 3. Descriptive statistics for measured variables

Variable	Min	Max	Mean	Std. value	Std. deviation
Function of thinking style					
Legislative	2.00	5.00	3.68	0.06	0.60
Executive	1.00	4.67	3.34	0.08	0.76
Judicial	2.60	4.80	3.81	0.05	0.50

Scope of thinking style						
Global	1.00	5.00	3.16	0.08	0.80	
Local	1.00	4.33	3.03	0.06	0.63	
Design strategy						
Top-down	0.00	26.67	12.37	0.58	5.88	
Bottom-up	2.33	30.00	16.38	0.58	5.84	
Substantial change	0.00	10.00	1.21	0.20	2.00	
Design tool						
Graphical interface	0.00	30.00	17.30	1.19	11.99	
Component list	0.00	28.00	4.44	0.74	7.44	
Both	0.00	30.00	8.28	0.89	8.89	

Note. N = 10

### Correlation analysis: Thinking style and design strategy/tool preferences

Pearson analyses were performed to identify correlations between thinking styles and design strategies. As shown in Table 4, among the three thinking styles in the functions category, judicial was positively correlated with the frequency of the substantial change of structure and goals strategy. WPBD2007 users can produce several designs quickly, with large amounts of information shown in real time during design tests (e.g., deformations under compression, component properties at various forces, and colors denoting those forces). This platform presents sufficient information and immediate feedback for fine-tuning bridge designs, allowing judicial style learners to react to all possible design ideas, analyze weaknesses and advantages, and revise their designs multiple times. This encourages students to think independently, and complements conventional teaching/learning approaches that are considered more passive.

Table 4. Correlations among thinking styles, design strategies and design tools

Thinking style	Design Strategy			Design Tool		
	Top-down	Bottom-up	Substantial change	Graphical interface	Component list	Both
Legislative	-0.036	-0.016	0.116	0.050	-0.109	0.022
Executive	0.016	-0.006	0.014	0.009	-0.108	0.079
Judicial	-0.167	0.085	0.214*	-0.027	0.054	-0.011
Global	-0.104	0.087	0.046	-0.082	0.117	0.011
Local	-0.013	0.055	-0.107	0.059	-0.213*	0.098

\* $p < .05$

Between the two thinking styles in the scope category, a statistically significant and negative correlation was observed between local style and usage frequency for the component tool list, which presents component parameters so that designers can make more comprehensive design assessments. It is generally more difficult for beginners to grasp and use this kind of information; therefore a low usage frequency for this tool was expected. We examined our collection of screen shots to analyze the design actions of participants with strong tendencies toward a local thinking style, and found that while they seldom used the tool, their cursors were never far from the parameter adjustment buttons, perhaps indicating a preference for the pop-up display of the selected component properties. In addition to adjusting individual properties, users can use this tool to read detailed data for each component. The tool is considered helpful for professional designers who favor a local thinking style because it provides them with in-depth information, but for inexperienced learners it may provide excessive information, and therefore encourage them to concentrate on local problems only. Thus, the tool might exert negative effects on learning among younger students.

### Design strategy and design tool preference

Correlations between the three design strategies and three design tools were examined using Pearson's correlation analyses. According to the results shown in Table 5, the usage frequency of top-down strategies was significantly and negatively correlated with the frequencies of using both tools; the usage frequency of bottom-up strategies was significantly and positively correlated with the frequencies of using both tools; and the usage frequency of the substantial change strategy was significantly and negatively correlated with the frequencies of using both tools.

Table 5. Correlations between design strategy and design tool preference (N=101)

		Design Tool		
		Graphical Interface	Component List	Both
Design strategy	Top-down	0.091	0.100	- 0.206*
	Bottom-up	- 0.194	- 0.048	0.300**
	Substantial change	0.286**	- 0.149	- 0.260**

\* $p < .05$ , \*\* $p < .01$

In WPBD2007, design information is presented in the central graphical interface, and the list of components is shown along the right panel. They present useful information for learners who favor either top-down or bottom-up strategies. According to our video recordings, participants who preferred top-down strategies tended to focus on the graphical interface or configuration of multiple components (i.e., sub-problems) using the components list. When the list of components is launched, the pop-up display blocks part of the design interface (i.e., the component selection or bridge structure change tools). This might not be a problem for professional designers, but could be a barrier for inexperienced learners.

The video recordings also show that participants who preferred bottom-up strategies tended to launch the component list to gather information in the form of statistics and individual component status. In these cases, the component list serves a debugging function and does not interfere with user operations associated with the design interface. Likewise, participants who preferred the substantial change strategy had to use the graphical design interface to revise their designs. Since the pop-up list of components along the right panel might interfere with their design operations, they may have purposefully avoided using it.

### Design outcomes and design strategy/tool preferences

Among the study participants, the minimum bridge cost was \$144,923.78 and maximum \$241,705.72 (mean = \$166,144.21; SD = \$13,214.65). When graphed, the range of costs produced an approximately normal distribution. Correlations between construction cost and the three design strategies and three tool preferences were examined using Pearson's analyses. According to the results shown in Table 6, the usage frequency of the substantial change strategy was significantly and positively correlated with total construction cost, and the usage frequency of the component list-only strategy was significantly and negatively correlated with total construction cost.

Table 6. Correlations between bridge construction cost and both design strategy and design tool preference

	Design Strategy			Design Tool		
	Top-down	Bottom-up	Substantial change	Graphical interface	Component list	Both
Construction cost	-0.124	0.017	0.332**	0.132	-0.215*	0.002

\* $p < .05$ , \*\* $p < .01$

Due to the fixed time allotment for the assignment, participants who preferred the substantial change strategy spent most of their time on comparing all possible structures, which reduced the available time for fine-tuning their designs and decreasing construction costs. Our results also suggest that students who made greater use of the component list produced less costly designs. According to our video analysis, participants who made frequent use of the component list were more likely to benefit from information on component specifications and properties, thus creating cheaper and more efficient bridge designs. Additional research is required to determine whether cost information exerts an impact on student learning.

### Gender and design strategy, tool preference, and outcomes

As stated earlier, the sample consisted of 58 male and 43 female freshmen students. Results from independent-samples t-tests for thinking style indicate that male students had a significantly stronger tendency than female students toward a judicial thinking style (Mean=3.91 versus Mean=3.67;  $t_{(99)}=2.501$ ,  $p < .05$ ), but no other significant differences between genders were noted for the other thinking styles. Furthermore, we failed to find any significant

differences between genders in terms of design strategy, tool preference, or outcome (Table 7). According to these data, gender did not affect simulation learning processes or outcomes in our experiments.

Table 7. Descriptive statistics and t-test results for differences between male and female study participants in terms of thinking style, design strategy, design tool preference, and design outcome.

Measure	Male (N=58)		Female (N=43)		t (99)
	Mean	SD	Mean	SD	
Thinking Style					
Legislative	3.764	.617	3.558	.551	1.736
Executive	3.264	.804	3.442	.693	-1.162
Judicial	3.910	.473	3.665	.507	2.501*
Global	3.198	.868	3.111	.706	.543
Local	2.960	.670	3.124	.578	-1.291
Design strategy					
Top-down	11.997	5.961	12.899	5.791	-.778
Bottom-up	16.747	6.014	15.891	5.626	.726
Substantial change	1.220	1.675	1.210	2.387	.022
Design tool					
Graphical interface	15.740	12.489	19.400	11.084	-1.524
Component list	5.520	8.103	2.980	6.228	1.714
Both	8.740	9.475	7.650	8.106	.607
Construction cost	1.6E5	9.9E3	1.7E5	1.6E4	-1.763

\* $p < .05$

## Conclusion

A well-designed simulation program can help learners predict the results of certain actions, understand processes underlying observed events, explore the implications of conclusions, evaluate ideas, and develop critical thinking skills (Lunce, 2006). It can also motivate learners to engage in problem solving, hypothesis testing, experiential learning, schema construction, and mental model development (Duffy & Cunningham, 1996). The list of researchers presenting evidence shows that educational simulations with scaffolding, coaching, and feedback features can facilitate the transfer of knowledge from simulation to real-world situations includes Alessi and Trollip (2001), Duffy and Cunningham (1996), and Leemkuil, de Jong, de Hoog and Christoph (2003). In addition to simulation functions, simulation systems also come with numerous assistive tools that utilize the power of modern computer systems for real-time design purposes (e.g., highlighting design weaknesses in various color intensities). These tools are very helpful for experienced designers, but for learners with little or no professional knowledge, they may exert very different effects on learning. For example, local error messages may encourage learners to find quick fixes rather than analyze multiple aspects of their designs or reject original plans.

To identify learner-simulation relationships, we considered learner personalities and thinking style, and observed design strategy and tool preferences. Specifically, our results indicate that students with strong judicial thinking style tendencies were more likely to use system-generated messages to quickly identify design flaws and make adjustments. Note also that the system's pop-up displays of selected component properties are well-suited to users who tend toward a local thinking style. Sternberg and Spear-Swerling (1996) suggest that teachers should utilize more than one teaching method so as to avoid favoring students with a particular thinking style. This is especially true in learning environments that are heavily reliant on traditional expository teaching methods, in which students are expected to passively take in information. While such a learning model is suitable for executive students, it does not serve the needs of legislative students. The simulation software used in this study represents a new approach, one that allows students to learn according to their preferred thinking styles. The software's emphasis on more-than-one possible result supports the need of legislative students to establish their own design rules through multiple tests. In addition, since each bridge component has some property limitations (e.g., the relationship between component length and capacity is characterized by fixed tension and stress curves), executive students can refer to specifications when selecting components. During the simulation process, judicial students can use system-generated messages to analyze and evaluate their designs. The needs of global and local thinking style students are met because some of these messages focus on the entire design and others on individual components. In short, the "learning-by-doing"

aspect of the program satisfies the needs of students who have a variety of thinking styles, allowing them to demonstrate their abilities in their preferred ways.

Participants who used top-down strategies tended to avoid using the two types of available tools at the same time. We believe the main reason is that they preferred working with a design interface that was neither blocked nor otherwise disturbed. Participants who preferred bottom-up strategies were much more likely to use both available tools to facilitate fast access to the results of design adjustments. Using both tools reduced the potential for becoming mired in local optimization. Participants who favored a substantial change strategy tended to use the graphical design interface only, a preference that prevented them from identifying core problems. Consequently, they occasionally had to make major design revisions that added to construction costs.

Simulation software is characterized by a graphical design interface containing a variety of real-time statistics plus a list of components that support top-down strategies. In addition, parameter adjustment tools and the color marking of problematic components support bottom-up strategies. According to our findings, design strategy is strongly associated with design tool preference and design outcome. In addition, simulation software functions considered appropriate for professionals accustomed to using bottom-up strategies will not cause problems for non-professional learners, thus making simulation-based learning suitable for classroom instruction.

We used video screen recordings to study participant design actions, including mouse movements, clicks, and drag-and-drops. Obviously we could not directly observe their responses, mental states, or emotions, thereby limiting our ability to address factors such as flow, playfulness, professionalism, and enjoyment. We suggest that researchers use instruments such as eye-trackers to observe other behaviors in order to better capture the benefits of this and other simulation systems for learning. Furthermore, since our experiment had the form of a competition, there is a need to determine how learners use simulation platforms and tools in the absence of prize incentives.

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