REPRESENTATIONS IN CIRCUIT DESIGN: A TEST OF GOEL'S THEORY OF NOTATIONALITY

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ABSTRACT
Vinod Goel [1] proposes a theory of notationality, derived from observations of interior designers, that distinguishes three classes of symbol systems: notational, non-notational, and discursive. He theorizes that design processes can be improved through the use of non-notational symbols. This paper presents the 2^3 factorial designed experiment used to test the applicability of this theory to electrical engineering. The results indicate that non-notational representations have a positive effect on designer productivity when complex design criteria are considered, but primarily if accompanied with discursive representations. Non-notational representations did not have a strong effect on number of ideas generated or quality of solution.

KEY WORDS
representation, electrical engineering design, design of experiment

1. Introduction

Design is an essential component of engineering firms and engineering education programs. As society continues to progress and global competition increases, there is greater pressure on engineering professionals to optimize the design process. Consequently, this creates a need to produce qualified engineers with the knowledge and skill in solving design problems [2]. Furthermore, tools aimed to support engineering design should facilitate rather than hinder creative design.

Design is often described as a process: a series of activities that converts an initial specification into a finished artifact that meets the requirements of the specification [3]. But this process is rarely straightforward. Frequently, initial specifications are ambiguous, causing the designer to explore specifications and pursue solutions for the problem simultaneously [4]. Gradual refinement of design concepts progressively adds constraints on the possible solution [5]. Design decisions can be difficult due to numerous interacting parameters, or ambiguity, or because future consequences are unforeseeable. To help deal with the complexity and ambiguity of design problems, engineers employ representations throughout the design process.

Researchers are becoming increasingly aware of the importance representation plays in engineering design. Vinod Goel [1] has developed a theory regarding the effect of representations on the outcomes of design processes in the domain of interior design. This paper presents a design of experiments that to tests the effect of Goel's three categories of representation on design outcomes in the electrical engineering domain. After presenting some background on Goel's theory, we describe the experimental design, then present the experimental results and discuss them. We conclude with some recommendations for electrical engineering design education.

2. Background

A representation is "something that stands for something else…some sort of model of the thing (or things) it represents" [6]. While representations can be internal, that is, present or created in the mind, we are concerned with so-called external representations that are present or created in the physical world and hence external to the mind. External representations are valuable to the designers because they serve as external storage of working memory [7,8], support communication [9,10], aid analysis and evaluation [11,12], and assist idea generation [13,14].

Vinod Goel emphasizes the importance of external representations to the design process in his theory of notationality [1]. As part of this theory, Goel categorizes external representations into three classifications of symbol systems of significance to design (see Table 1). Notational symbol systems are structured, well defined, and specific representations that correspond closely to artifacts in the physical world without ambiguity; for example, ZIP codes and musical scores. Discursive symbol systems are also structured, well defined, and specific representations; however, their associativity with physical artifacts is not always clear, but can be determined from context. Examples of discursive systems include natural and artificial languages such as English, French, Latin, and predicate calculus. In contrast, non-notational systems are not structured, well defined, or specific and therefore their connection to physical artifacts is even more ambiguous; for example, paintings and sketches. Non-notational systems are difficult to interpret even with the knowledge of the context.

	Notational System	Discursive System	Non-Notational System
Definition	• Structured • Well defined • Specific • Unambiguous	• Structured • Well defined • Specific • Ambiguous	• Unstructured • Unclear • Vague • Ambiguous
Examples	ZIP code Telephone number Musical score	Natural languages Predicate calculus	Sketches Sculpture Seismograph readout

Table 1: Goel's Classification of Symbol Systems

Goel describes the design process as a manipulation of representations of the world. Designers manipulate representations to transform an input into an output. As shown in Figure 1, inputs are often presented using a representation from the discursive symbol system, such as a design brief, while outputs are usually in the form of a notational representation, such as an engineering drawing. The process that transforms the inputs into outputs involves representations from all three categories.

According to Goel, non-notational symbol systems are central to innovative design because their ambiguous characteristic encourages creativity. This ambiguity allows for multiple interpretations, which in turn facilitates transformations between different ideas. It simultaneously encourages divergence and discourages premature convergence. The design theory literature widely recognizes that "good" design processes involve exploration of multiple ideas. Hence, the theory of notationality implies that use of non-notational systems can lead to better design outcomes: more ideas generated, higher quality solutions, and better designer productivity.

Goel developed his general theory based on interior and graphic designers; however, it has yet to be tested in any other domain. There are significant differences between interior or graphic design and engineering design; for example, the role and prevalence of mathematical analysis. So does Goel's theory hold true for engineering design? Can we improve engineering design processes through the use of non-notational representations? If so, this could have important implications for how we teach engineering design.

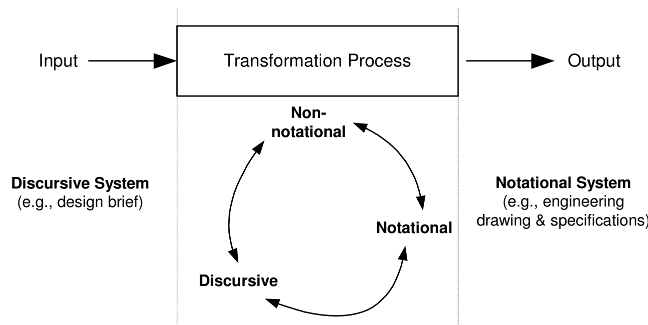

Figure 1: Design as a Process of Transforming Representations

3. Experimental Design

In order to gain some insight into these questions, we conducted a design of experiment using electrical engineering juniors and seniors as subjects and a circuit design problem as a test case [15]. The subjects for the experiment were students from EE 391: Electrical Engineering Senior Design I in Spring 2004 semester. The course instructor incorporated the "mini-design" problem as an assignment for the course.

The class make-up was typical for a junior/senior level EE course at Montana State University. Two of the 31 participants were female. None of the students had any formal training in design processes prior to taking this course, but all had taken and passed the prerequisite courses: circuits, electronics, digital logic, signal systems, and microprocessors. The design problem used was as follows:

> *Design a system (analog, digital, or mixed) to distinguish between two different ranges of frequency. Light an LED whenever the incoming signal frequency is below 600 Hz, and light a different LED whenever the incoming signal frequency is above 12 kHz. Only one LED is to be lit up at a time, but one LED must be lit at all times whenever there is an incoming signal. You are free to choose the switching point. Produce a circuit diagram for your design by following the specific instructions presented to you, and label the circuit diagram with all the relevant information including the 600 Hz LED and 12 kHz LED.*

The participants' solutions were evaluated for functionality and for complexity as measured by number and complexity of components used. Thus, participants would need to engage creative problem solving to achieve the required functionality while minimizing complexity and number of parts.

In order to test Goel's theory for EE, we analyzed student design journals from a prior semester and made a comprehensive list of all representations either included or referred to in the journal entries. The list of electrical engineering representations were then categorized according to the three symbol systems described earlier (see Table 2).

Notational Systems	Discursive Systems	Non-notational Systems
• Circuit diagrams • Equations • Technical jargon • Component pin out • Computer/pseudo code	• Languages • Software flow chart	• Block diagrams • Response curves (graphs)

Table 2: Electrical Engineering Representations

Each electrical engineering representation system under notational is quite specific and interpretation is unambiguous. The symbol for a resistor is not going to be interpreted as something other than a resistor, for example. Under discursive systems, software flow charts are fairly specific (e.g., where a loop or call instruction should be placed in the sequence of operations), but often the elements can often be implemented in different ways. Finally, the non-notational elements are not specific and have multiple possible interpretations. In a block diagram, for example, a line connecting two blocks could be a control signal or power, a digital or analog signal, and so an; often only the originator of the diagram knows what is meant by the specific symbol.

The experiment was a simple 2^3 factorial design: three factors at two levels in the basic design. The factors were electrical engineering representations grouped according to Goel's three classifications of symbol systems: A) non-notational, B) discursive, and C) notational. Factor level high corresponded to designing a circuit using the representations listed for that symbol system, while low corresponded to designing a circuit without those representations.

The 2^3 factorial design requires a minimum of three replications in order to obtain statistical validity. The experimental design used here had four replications resulting in 32 total observations (4 replicates * 8 runs per replicate). Each replicate occurred in a different day because running all thirty-two runs in one day was infeasible. Day of the week was treated as a nuisance factor, and because the effect of days on outcome variables was not of interest, blocking was used to reduce or eliminate the variability transmitted from days. In this experiment, each replicate was completed in a single day resulting in a total of four blocks. Randomization occurred within blocks, not between blocks.

In order to minimize the effect of different problem solving methods, all subjects followed the same design process steps: problem definition, preliminary idea generation, research, idea development, and analysis. Then, specific instructions were developed for each treatment condition, directing the subject to execute activities within each step using a particular set of representations. In some cases, subjects were required to execute design steps without any external representations; in others, they were required to use the full slate of representations. For ease of evaluation, the outputs of the transformation process were all in one representation type, a circuit diagram.

The experiment took place in a laboratory setting. Subjects had available pencil and paper, a calculator, two textbooks [16,17], and a computer with circuit simulation software. Upon arrival, the subjects randomly selected their treatment condition out of a hat, then signed a non-disclosure agreement to not share any information regarding the experiment to anyone until after all individuals completed the experiment. The investigator then explained the rules of conduct for the experiment, asked if there were any questions, and set the subject to work.

Upon completion of the experiment, the final circuit designs were evaluated for solution quality as measured by two scores: functionality and component score. The functionality score measured the solution's conformance to three design specifications, receiving ten points for meeting an objective and zero if not. Thus the maximum score was 30. The component score was tabulated based on a point scheme previously developed by the EE 391 instructor. Electrical components were assigned points according to the complexity/cost of the component; for example, a resistor (a two-pin part) received one point while a more complex transistor (a three-pin part) was assigned six points. The component score serves as a surrogate measure of reliability, manufacturability, and cost of the design. A smaller number of components in a device means fewer electrical connections, which not only simplifies manufacturing process and reduces cost, it improves reliability because fewer devices and connections can fail. The component score, then, enables us to assess design quality at a more advanced level that just pure functionality.

Two electrical engineering professors independently evaluated the subjects' solutions. They received photocopies of only the solution page together with evaluation forms for scoring the circuit designs. The correlations of the evaluators' functionality and component scores were 0.66 and 0.99 respectively. Once the evaluations were complete, functionality and component scores from the evaluators were averaged, then normalized to a scale of 0-1. Finally, the quality score was computed by taking a weighted average of the normalized functionality and component scores. The weights varied by intervals of 25%: 100% and 0%, 75% and 25%, 50% and 50%, and 25% and 75% for the functional and component scores respectively.

In addition, we calculated the productivity of each subject by dividing the quality score by the total time spent on the design process, and used that as an outcome variable. We also tabulated the number of different ideas generated by every subject as an additional outcome variable.

The data were analyzed using analysis of variance (ANOVA). ANOVA models are statistical tools for studying the relation between a response variable and one or more factors or independent variables. For this study, the three qualitative factors were electrical engineering representations categorized in non-notational, discursive, and notational symbol systems, while the response variables were quality and productivity (four weight combinations each), and the number of ideas generated. We had one missing observation due to a student failing to show up at his appointed time; its value was estimated using an averaging technique considered reasonable by Montgomery [18]. For this analysis, the level of significance was set at 10% for all outcome variables, with 15% indicating possible significance. Fairly high significance levels were chosen because of the heavy dependence on human subjects and evaluators.

4. Results and Discussion

The first analysis concerns whether representation affects the number of different ideas generated during the course of design. The ANOVA results (see Table 3) indicate that factor C, notational systems, is significant at $p \leq 0.10$ in the positive direction, while factor A (non-notational) and factor B (discursive) are not significant. Of the interaction effects, only AC is significant at $p \leq 0.10$, and in the negative direction. Day of the week also has a significant effect.

These results do not support Goel's theory, even providing some contraindication. Subjects using notational systems (standard representations such as circuit diagrams and mathematical equations) generated more alternative design solutions, unless they also used non-notational systems (block diagrams and response curves) which seemed to dampen their idea generation ability! A possible explanation is that students have not been trained in non-notational representations. From their first EE course, students see and use circuit diagrams in analysis and design. At no point in their curriculum do they receive formal training in block diagrams or response curves, though they have been exposed. Thus, these results could simply indicate that students are more adept with notational representations by virtue of prior training.

Source of Variance	**Factor Effects**
	Number of Ideas
Blocks	**
A	0.56
B	0.94
C	2.31 **
AB	0.19
AC	-1.19 **
BC	-0.31
ABC	0.19

* $p \leq 0.15$, ** $p \leq 0.10$

Table 3: ANOVA Results for Number of Ideas as Response Variable

The ANOVA results for quality are displayed in Table 4. Four quality scores were used as the response variable, varying by the proportional weight given to functionality versus component score. They range from 100% functionality and 0% component score to 25% functionality and 75% component score. This approximates the range of design priorities common in industry, from total focus on the design's functionality without regard to manufacturability or cost, to a strong focus on cost with functionality being less important.

As Table 4 indicates, no factors or interactions were significantly associated with quality at a significance level of $p \leq 0.10$. Factor A and interaction AB show possible slight significance, with p-values of 0.14 and 0.11 respectively, when component score is heavily weighted. Thus it appears that use of notational versus discursive or non-notational representations has little effect on solution quality in circuit design, at least among this group of students.

These results are rather surprising. Not only does use or non-use of non-notational representations seem to have little effect on quality, use or non-use of the other representational systems apparently also has little effect (similarly for interactions)! Goel's theory of notationality says that the design process involves manipulations and transformations among all three classes of representations, so one might expect the interaction ABC to be significant; yet, it is not. Similarly, one might expect that students allowed use of equations or the computer simulation program (both notational representations) to evaluate their designs would outperform those students not allowed to use them; yet, they do not. A possible explanation may simply be the lack of robustness in the evaluation measure. This will be discussed more later.

Source of Variance	Factor Effects			
	100:0 Quality	*75:25 Quality*	*50:50 Quality*	*25:75 Quality*
Blocks				
A	0.35	-1.81	-3.96	-6.12
B	-12.15	-4.92	2.31	9.55 *
C	12.15	10.66	9.17	7.68
AB	-2.43	1.85	6.12	10.40 *
AC	10.76	9.86	8.95	8.05
BC	2.43	1.28	0.13	-1.03
ABC	3.82	-0.16	-4.14	-8.11

* $p \leq 0.15$, ** $p \leq 0.10$

Table 4: ANOVA Results for Quality as Response Variable

Table 5 below displays the ANOVA results for productivity. Since productivity was calculated by dividing the quality score by the amount of time the student spent working on the design problem, we can compare, for example, students that spent much time to get a good quality solution versus those that spent quite a bit less time to get a slightly lower quality solution.

Source of Variance	Factor Effects			
	100:0 Prod.	*75:25 Prod.*	*50:50 Prod.*	*25:75 Prod.*
Blocks				
A	-4.34	-9.73	-15.12 *	-20.51 *
B	-16.74 *	-10.95	-5.16	0.64
C	9.58	7.36	5.14	2.92
AB	5.54	12.29	19.02 **	25.77 **
AC	2.02	0.09	-1.84	-3.77
BC	11.05	10.61	10.17	9.73
ABC	8.72	4.19	-0.35	-4.88

* $p \leq 0.15$, ** $p \leq 0.10$

Table 5: ANOVA Results for Productivity as Response Variable

As Table 5 indicates, when functionality is more important than component score, none of the factors significantly affect productivity at $p \leq 0.10$. However, when component score is equally or more heavily weighted than functionality, interaction AB becomes significant and has a positive association. Thus, it appears that using non-notational representations together with discursive representations has a significant positive impact on designer productivity. In addition, factor A may have a small negative effect ($p = 0.12$).

This is an interesting result. It appears that we can help EE designers reach good design solutions faster when more complex design criteria are at play (e.g., functionality and manufacturing cost, rather than just functionality, as in this case). We do this by getting them to use non-notational representations throughout the design process along with written interpretations of what those representations mean. This is particularly significant because EE textbooks rely almost exclusively on notational and discursive symbols to represent or describe electrical systems and phenomena, and rarely if at all use non-notational representations. These findings suggest a possible improvement.

These results must be interpreted cautiously, however, and need to be affirmed by additional studies. For one, human subjects are notorious for their variability. Statistically insignificant results in many cases may be human subjects' variability masking the effect. Secondly, as already mentioned, most if not all of the students had little to no training in how to use non-notational representations. Providing training may change the results. Thirdly, the evaluation of solution quality was not as robust as we would like. The two evaluators (both with Ph.D.'s in EE) did not strongly agree in the functionality score (correlation coefficient = 0.66). This was due in part to the nature of the task—evaluating a circuit design on paper is complicated and not totally objective—and in part to the binary nature of the scoring convention. It is possible, for example, to have a design where current will flow through an LED, but without enough current to light the LED brightly. One evaluator may judge the dimly light LED as meeting the design criterion and give it 10 points; they other may judge this as not meeting the criterion and give it zero points. The correlation between evaluators is marginally acceptable, so developing a more robust quality measurement is the subject of future work.

5. Summary and Implications

We have used Goel's theory of notationality to categorize electrical engineering representations into notational, discursive, and non-notational symbol systems. Goel's theory suggests that non-notational representations are particularly useful for design because they enable lateral transformations; EE uses notational and discursive systems quite heavily, but not non-notational representations. Thus a controlled experiment was designed and conducted to determine what effect, if any, the three classes of representation might have on the number of ideas generated, the quality of design solutions, and designer productivity.

The results indicate that only notational representations had a positive effect on number of ideas generated, and that using non-notational representations along with notational seemed to have a mild negative effect. The results also indicate that non-notational representations used in conjunction with discursive (primarily text-based representations such as describing how a given concept with work) has a significantly positive effect on productivity and a positive though less significant effect on solution quality when the quality measure included more advanced criteria captured in a component score. Using non-notational representations alone seemed to have a mild negative effect. While the first result would seem to counter Goel's theory, the other results seem to provide some evidence in support and suggest that his theory may have applicability to the electrical engineering domain and that additional studies should be done.

If these results hold, the implications for EE design instruction are several. First, they suggest that instructors should include block diagrams and response curves more pervasively in the EE curriculum. Even without proper training, these representations appear as significantly affecting quality and productivity, so additional instruction may improve the results even more. Although, additional studies are needed to confirm this. Second, instructors may want to modify their selection criteria for textbook and other course materials. A textbook that uses multiple external representations, not just circuit diagrams, equations and text, may lead to better representation use by students and may ultimately improve their design ability.

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