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DOES USING DIFFERENT CONCEPT GENERATION TECHNIQUES CHANGE THE DESIGN COGNITION OF DESIGN STUDENTS?

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ABSTRACT

This paper presents the preliminary results of protocol studies to determine the effects of teaching different concept generation techniques to engineering students on their design cognition.

Twenty-two mechanical engineering students were given instructions in the three concept generation techniques of brainstorming, morphological analysis and TRIZ as part of their undergraduate education at a large land grant university. After the instruction for each concept generation technique, the students were formed into the same teams of two. Each team was given the same set of three design tasks, one for each concept generation technique, while their verbalization and gestures were videoed as they designed for a period of 45 minutes.

Students' design cognition was examined by protocol analysis using the FBS ontologically-based coding scheme. Preliminary results indicate that statistically significant differences in students' design cognition were observed when using different concept generation techniques.

1 INTRODUCTION

What is the effect of design education on students' design cognition? While most of the current design education research focuses on describing approaches to engineering design teaching [1, 2], there is little existing work that moves towards identifying the relationship between design curriculum, student learning, and student design behavior. To elucidate potential effects of engineering education on students' design cognition, the authors are engaged in a longitudinal study of students involved in curriculum centered on the study of design [3].

The scope of this study is targeted in the instruction, and resultant student implementation, of concept generation techniques. Specifically, the authors have conducted a series of experiments to examine how design students' design cognition is affected after receiving instruction in three concept generation techniques.

Creativity and concept generation techniques have been the focus of many studies recently. Most notable perhaps is the development of creativity metrics proposed by Shah and co-authors [4] (which has since been the subject of further development [5, 6]). Using these metrics, researchers have investigated how different concept generation techniques might affect the creativity and/or design fixation of a designer [7] and how a student's measured creativity changes over the course of their undergraduate studies [8]. However, no work has been done to evaluate how these differing techniques affect students' design cognition.

In this study, design cognition is determined using protocol analysis with the coding of the protocols based on a general design ontology, namely, the Function-Behavior-Structure (FBS) ontology as a principled coding scheme (as opposed to an ad hoc one). Four hypotheses are proposed to be tested:

1. engineering students' overall design cognition, measured by the distributions of design issues, is different when students design with different concept generation techniques;
2. engineering students' design cognition is different in the first half of their design sessions when using different concept generation techniques;
3. engineering students' design cognition is different in the second half of their design sessions when using different concept generation techniques; and

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4. the dynamics of design cognition for each of these three concept generation techniques (i.e., the cognitive changes between first and second halves of their design sessions) is different.

2 DESIGN EXPERIMENTS

In order to investigate the effect of different concept generation techniques on the design cognition of engineering students, three experiments were carried out.

2.1. Experimental Design

Twenty-two mechanical engineering students participated in this study voluntarily. They were formed into teams of two. Each team was given the same set of three design tasks, one for each concept generation technique. All design tasks were focused in designing an assistive technology device and were created to be similar in concept, context, and complexity. In the first session, students were asked to use brainstorming to design a device to help disabled users open a stuck double-hung window without relying on electric power. In the second session, students were asked to use morphological analysis to design a device to help stroke patients who are unable to perform bilateral tasks with opening doors. In the third session, students were asked to use TRIZ to design a device to add to an existing hand/arm-powered wheelchair that will allow paraplegic wheelchair users to traverse a standard roadside curb unassisted.

During the experimental sessions, the students were asked to collaborate with their team members. Then they were instructed to intentionally and actively use one of the concept generation techniques, and to come up with a design solution that meets the given design requirements within 45 minutes.

All the design sessions were audio and video recorded for later analysis. Specifically, two digital camcorders were used, one recording the whiteboard and the other recording the participants' gestures. Each participant had their own individual wireless lapel microphone to ensure a high recording quality of their conversation.

2.2. Participants and Design Course

Twenty-two participants were recruited from a capstone design course where they were taught three concept generation techniques (described below). The students' prior design education was a cornerstone experience in a first-year engineering program and in a sophomore-level course that focused in exposing students to engineering design and design methods at an early stage of their professional development. Students with significant design experience (either professionally or through prior academic experience), as identified through a preliminary interview, were not selected as participants for this study.

In the capstone sequence, student teams work with a faculty mentor on a year-long design project. In the second semester, the students work solely on their projects and are primarily focused in the latter stages of design including engineering analysis, prototype development, and detailed design. However, in the first semester, the students meet once a week in a classroom setting to discuss the early stages of the design process (problem definition, conceptual design), engineering ethics, and elements of engineering economics. The students' primary goal for this first semester is to scope their given design problem, generate several potential solutions, and select an alternative to embody during the second semester. It is in this semester that the students received instruction on the three concept generation techniques used in this study.

2.3. Three Concept Generation Techniques

Three concept generation techniques were taught in the course. Within a problem-based learning environment, the class is broken into teams of students who select an industry-based design problem provided by the industry participants.

Brainstorming. Brainstorming is a well-developed process and is widely used in industry. It involves having members of the design produce ideas without any concern for their viability and without any criticism of them during the production phase [9-12]. The notion is to produce as many ideas as possible. The ideas are then attempted to be linked, with judgment still deferred.

Morphological analysis. Morphological analysis is a well-developed process used in industry. It uses the concept of systematically structuring (shaping) a multi-dimensional problem through its relationships. It is based on bringing together two opposing notions: decomposition and forced associations [13-15]. Once the problem is decomposed, potential solutions for each sub-problem are ideated. These solutions are then organized in a morphological matrix. Potential solutions to the design task are generated by systematically combining concepts from each sub-problem.

TRIZ: TRIZ is the acronym in Russian for a system of inventive problem solving developed by G Altshuller. It a well-developed process and is very widely used in industry. It is a method founded on being directed to a set of fundamental physical principles through a process of resolving contradictions [16-21].

3 THE FBS ONTOLOGICALLY-BASED PROTOCOL ANALYSIS

Protocol analysis is a rigorous methodology for eliciting verbal reports of thought sequences as a valid source of data on thinking. It is a well-developed, validated method for the acquisition of data on thinking [22, 23]. It has been used extensively in design research to assist in the development of the understanding of the cognitive behavior of designers [24-27]. This paper uses a specific version of design protocol analysis method, applying the FBS ontologically-based coding scheme.

3.1. The FBS Ontology

The FBS ontology [28, 29] models designing in terms of three classes of ontological variables: function, behavior, and structure plus an external requirement and a design description,

Fig. 1. In this ontological view, the goal of designing is to transform a set of functions into a set of design descriptions (D). The *function* (F) of a designed object is defined as its teleology; the *behavior* (B) of that object is either derived (Bs) or expected (Be) from the structure, where *structure* (S) represents the components of an object and their relationships.

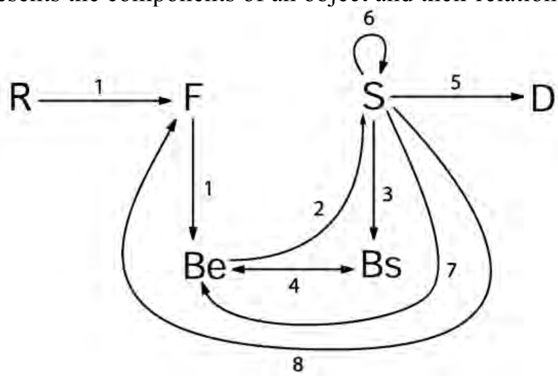

Figure 1. THE FBS ONTOLOGY

3.2. The FBS-based Coding Scheme

The FBS ontologically-based coding scheme is a principled coding scheme consisting of six pre-defined codes, Fig. 1 and Table 1. Application of this coding scheme [30] involves segmenting and coding transcripts of the experiment videos (i.e., design conversations and gestures, etc.) into a sequence of design issues denoted by semantic symbols, i.e., the FBS codes.

Table 1. THE FBS DESIGN ISSUES AND CODES

FBS design issue	Code
Requirement	R
Function	F
Expected behaviour	Be
Behavior from structure	Bs
Structure	S
Design description	D

Design conceptualization involves reasoning about the problem, ie, reasoning about requirement, function and expected behavior issues, while reasoning about structure and behavior derived from structure issue are related to artifacts as a solution to the design problem [25, 28].

The Delphi method [25, 31] was applied to increase the reliability of protocol segmentation and coding. It consists of two separate coding processes undertaken by two independent coders, and an arbitration session to resolve the coding disagreements identified in the previous coding results.

The arbitrated result, namely, a sequence of design issues, becomes the foundational data for subsequent analyses that characterize the design cognition of the participants.

4 ANALYSIS METHODS

A statistical software package, IBM SPSS v19, was utilized to identify statistically significant differences in the cognitive effort related to individual design issues between design sessions that were assigned to each of the three concept generation techniques. Statistically significant differences were assumed at a significance level (α) of 0.05. The normality assumption was tested for each design issue using the Shapiro-Wilk W test. Paired-samples t-test was used to examine the design issues for measurement distributions that were approximately normal. For non-normal distributions the Wilcoxon signed ranks test was used.

In addition to comparisons using the entire protocol, a fractioning technique [30] was applied to provide a more nuanced view that illuminates the dynamics of design cognition about how individual teams work through design problems across time. Here it is sued to divide the protocol into two halves with the same number of design issues.

5 RESULTS

The preliminary results of protocol studies are presented in five parts: (1) descriptive results of the FBS ontologically-based segmentation and coding, (2) overall comparisons of design cognition between three concept generation techniques, (3) comparisons between different techniques in the first half of the protocols, (4) comparisons between different techniques in the second half of the protocols, and (5) comparison between the first and second halves of protocols for each technique.

5.1. The FBS-based Segmentation and Coding

Utilizing the Delphi method, the typical inter-coder reliability reached 85~95%.

The total number of design issues for each design sessions varied, ranging from 213 to 874. The occurrence frequencies of design issues for each session were normalized by dividing them by the total number of design issues in that session. The normalized design issue distributions are shown in Table 2 and Fig. 2.

Table 2. FREQUENCY DISTRIBUTION OF DESIGN ISSUES OF THE EXPERIMENTS USING THREE CONCEPT GENERATION TECHNIQUES (%)

Design issues	Brainstorming Mean (SD)	Morphological analysis Mean (SD)	TRIZ Mean (SD)
Requirement	1.30 (0.42)	0.69 (0.28)	1.10 (0.91)
Function	4.39 (1.51)	6.59 (1.78)	10.12 (3.35)
Expect Behavior	7.21 (1.96)	11.86 (2.45)	16.73 (4.50)
Behavior from Structure	27.70 (2.78)	22.97 (3.26)	27.90 (3.71)
Structure	40.01 (4.79)	37.83 (4.1)	27.73 (5.23)
Description	19.38 (3.74)	20.05 (5.26)	16.42 (4.47)

In the three experiments, it is observed that students expended the majority of their cognitive effort focusing on design structure (approximately 28~40%), followed by behavior from structure (23~28%). The issues of requirement, function and expected behavior had relatively less cognitive focus. The cognitive effort spent on design descriptions seems to be not dependent on the concept generation technique used.

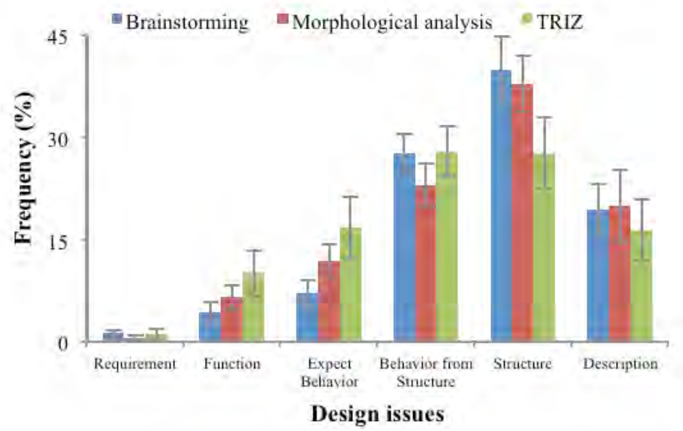

Figure 2. FREQUENCY DISTRIBUTION OF DESIGN ISSUES

5.2. Overall Comparison between Three Concept Generation Techniques

Brainstorming versus Morphological Analysis. Between the design sessions using brainstorming and morphological analysis, there are significant differences regarding the percentages of cognitive effort related to the four design issues of requirement, function, expected behavior and behavior from structure, Table 3. There is no statistically significant difference found for structure and description issues.

In particular, the students were more engaged in reasoning about function (approximately 7% vs 4%) and expected behaviors (12% vs 7%) when using morphological analysis. When designing using brainstorming, the students focused relatively more on behavior from structures (28% vs 23%). There was very cognitive focus on requirement in both design sessions. There was a marginally higher focus in the brainstorming sessions (approximately 1.3%) compared to the morphological analysis sessions (about 0.7%).

Table 3. COMPARISON OF DESIGN ISSUES BETWEEN BRAINSTORMING (BR) AND MORPHOLOGICAL ANALYSIS (MA) SESSIONS

Design issue	t statistics	p-value
Requirement	3.513	.007*
Function	-3.410	.008*
Expected Behavior	-5.543	.000**
Behavior from structure	6.770	.000**
Structure	1.663	.131
Description	-0.661	.525

* $p < 0.01$, ** $p < 0.001$

Brainstorming versus TRIZ. Designing using brainstorming and designing using TRIZ produced significantly different percentages of cognitive effort related to the three design issues of function, expected behavior and structure, Table 4. There is no statistically significant difference found for requirement, behavior from structure and description issues.

Table 4. COMPARISON OF DESIGN ISSUES BETWEEN BRAINSTORMING (BR) AND TRIZ (TRIZ) SESSIONS

Design issue	t (z) statistics	p-value
Requirement	-0.652[a]	.515
Function	-5.372[b]	.001*
Expected Behavior	-5.489[b]	.001*
Behavior from structure	-0.463[b]	.656
Structure	5.315[b]	.001*
Description	1.523[b]	.166

a Wilcoxon signed ranks test, b Paired-sample t-test
* $p < 0.01$

The students were relatively more concerned with the two problem-related issues of function (10% vs 4%) and expected behavior (17% vs 7%) when designing with TRIZ, while expending more cognitive effort discussing structure (40% vs 28%) in the brainstorming sessions.

Morphological Analysis versus TRIZ. There are four design issues of function, expected behavior, behavior from structure and structure have percentage occurrences that are significantly different between the sessions using morphological analysis and using TRIZ, Table 5.

The students spent more cognitive effort discussing function (10% vs 7%), expected behavior (17% vs 12%) and behavior from structure (28% vs 23%) when using TRIZ as the primary concept generation technique, whereas they focused more on structure (38% vs 28%) when designing using morphological analysis.

Table 5. COMPARISON OF DESIGN ISSUES BETWEEN MORPHOLOGICAL ANALYSIS (MA) AND TRIZ (TRIZ) SESSIONS

Design issue	t (z) statistics	p-value
Requirement	-1.070[a]	.285
Function	-3.021[b]	.014*
Expected Behavior	-3.348[b]	.009**
Behavior from structure	-3.771[b]	.004**
Structure	7.009[b]	.000***
Description	2.169[b]	.058

a Wilcoxon signed ranks test, b Paired-sample t-test
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

5.3. Comparison of First Half of Design Sessions' Protocols

The normalized frequency distributions of design issues in the first half of design sessions' protocols are illustrated in Fig. 3. The overall shape of Fig. 3 is similar to that of Fig. 2, which represents the design issue distributions of the entire sessions' protocols.

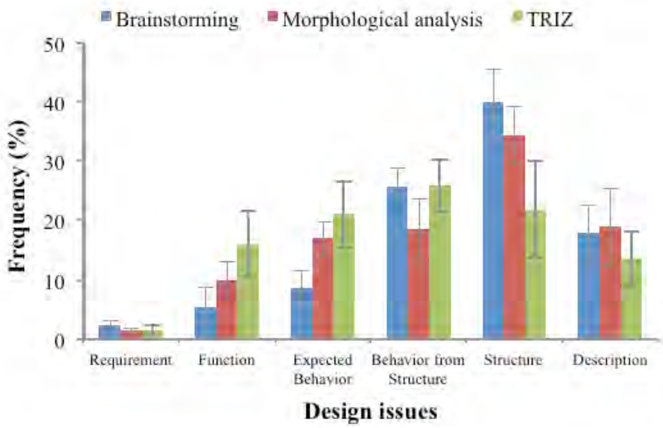

Figure 3. FREQUENCY DISTRIBUTION OF DESIGN ISSUES IN THE FIRST HALF OF DESIGN SESSIONS' PROTOCOLS

The inter-session comparisons of design cognition during the first half of design sessions were undertaken with the same method applied to the overall comparisons described in Section 5.2.

Table 6. COMPARISON OF DESIGN ISSUES BETWEEN THE FIRST HALF OF THE PROTOCOLS OF BRAINSTORMING (BR), MORPHOLOGICAL ANALYSIS (MA) AND TRIZ (TRIZ) SESSIONS

Design issue	BR vs MA		BR vs TRIZ		MA vs TRIZ	
	t statistics	p-value	t statistics	p-value	t statistics	p-value
Requirement	2.900	0.018*	1.910	0.092	-1.182	0.268
Function	-2.693	0.025*	-5.974	0.000***	-3.027	0.014*
Expected Behavior	-8.119	0.000***	-4.860	0.001**	-2.035	0.072
Behavior from structure	5.027	0.001**	-0.559	0.591	-3.763	0.004**
Structure	2.998	0.015*	5.831	0.000***	4.149	0.002**
Description	-0.752	0.471	1.900	0.094	1.957	0.082

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The percentages of cognitive effort spent discussing function and structure were found to be mutually different between the three concept generation techniques. The students were mostly focused on function in the TRIZ sessions (approximately 16%), followed by designing using morphological analysis (about 10%), and least concerned with in the brainstorming sessions (slight more than 5%).

The brainstorming sessions were found to have the highest percentage of structure issues (about 40%), followed by morphological analysis (35%). The students spent the least effort discussing structure in the TRIZ sessions (22%), among the three concept generation techniques.

The students were relatively less concerned with expected behaviors in the brainstorming sessions (9%) than designing with the other two techniques (17~21%), which were not statistically different.

In the morphological analysis sessions less cognitive effort was spent discussing behavior from structure (19%) than the brainstorming and TRIZ sessions (both about 26%).

No statistically significant difference was identified for description issues between the three concept generation techniques.

5.4. Comparison of Second Half of Design Sessions' Protocols

The design issues occurrence percentages in the second half of design sessions' protocols are illustrated in Fig. 4. The pairwise comparisons for each design issue are presented in Table 7. These results imply that as these designers move from the first half to the second half of their design sessions, the differences between designing using any of the three concept generation techniques decrease. The shapes of the three design issue distributions are similar to each other.

Pairwise comparisons of design issues indicate that, there are no pairs of design issues identified to have any statistically significant difference between the brainstorming and morphological analysis sessions. These two concept generation techniques have similar effects on the students' design cognition during the second half of their design sessions.

Designing with TRIZ was found to significantly differ from the other two methods in the cognitive effort related to expected behavior and structure. The students were relatively more focused on expected behavior in the TRIZ sessions (12%) than in the brainstorming (6%) and morphological analysis (7%) sessions. The TRIZ sessions showed a lower focus on structure issues (33%) than when using the other two techniques (approximately 40~41%).

There is no statistically significant differences in the other aspects of the students' design cognition in the second half of design sessions suggesting that these designers were unaffected by the different concept generation techniques they used.

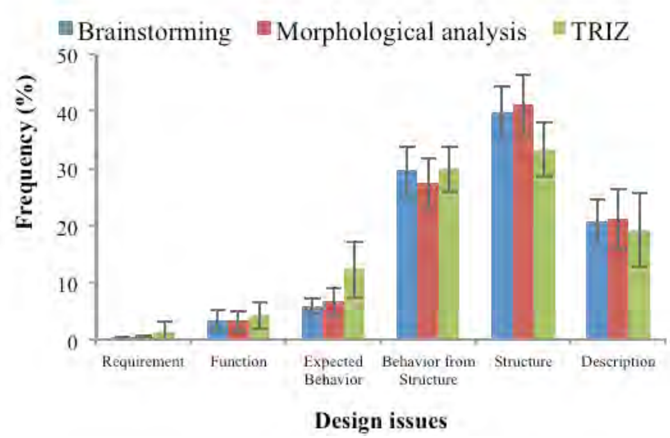

Figure 4. FREQUENCY DISTRIBUTION OF DESIGN ISSUES IN THE SECOND HALF OF DESIGN SESSIONS' PROTOCOLS

5.5. Comparison between First and Second Halves of Protocols

In addition to the inter-session comparisons of design cognition, this paper looks into the dynamics of design cognition using intra-session comparisons between the first and second halves of each design session, Table 7.

Table 7. COMPARISON OF DESIGN ISSUES BETWEEN THE FIRST HALF OF THE PROTOCOLS OF BRAINSTORMING (BR), MORPHOLOGICAL ANALYSIS (MA) AND TRIZ (TRIZ) SESSIONS

Design issue	BR vs MA		BR vs TRIZ		MA vs TRIZ	
	t (z) statistics	p-value	t (z) statistics	p-value	t (z) statistics	p-value
Requirement	0.807 [a]	.441	-0.805 [a]	.444	-1.309 [a]	.223
Function	0.011 [a]	.991	-1.120 [a]	.295	-1.160 [a]	.276
Expected Behavior	-0.877 [a]	.404	-4.812 [a]	.001**	-4.430 [a]	.002**
Behavior from structure	1.219 [a]	.254	-0.110 [a]	.915	-1.861 [a]	.096
Structure	-0.349 [a]	.735	2.073 [b]	.038*	2.701 [b]	.007**
Description	-0.372 [a]	.718	0.415 [b]	.678	0.968 [b]	.333

a Paired-sample t-test, b Wilcoxon signed ranks test
* $p < 0.05$, ** $p < 0.01$

It is observed that the first and second halves of the brainstorming sessions have similar design issue distributions, except that most of the requirement issues are in the first half of the design sessions, Fig. 5. Paired-samples t-tests, as shown in Table 8, indicate that the students are more focused on behavior from structure in the second half (30%) than the first half of the design sessions (26%). The cognitive effort related to expected behavior was more focused in the first half of the design sessions (9% vs 6%).

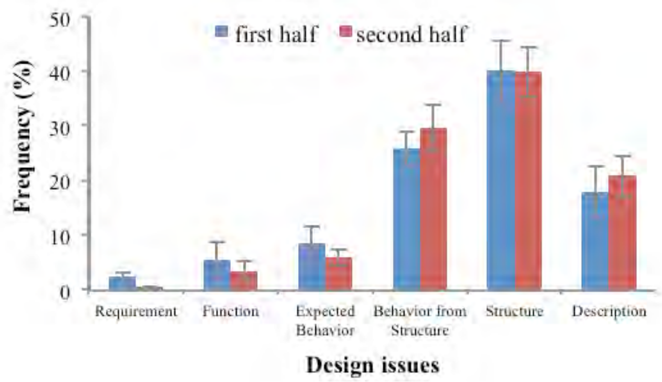

Figure 5. FREQUENCY DISTRIBUTIONS OF DESIGN ISSUES BETWEEN THE FIRST AND SECOND HALVES OF BRAINSTORMING SESSIONS

Table 8. COMPARISONS OF DESIGN ISSUES BETWEEN THE FIRST AND SECOND HALVES OF DESIGN SESSIONS' PROTOCOLS

Design issue	BR		MA		TRIZ	
	t statistics	p-value	t statistics	p-value	t (z) statistics	p-value
Requirement	6.439 [a]	.000***	4.497 [a]	.001**	1.826 [a]	.101
Function	1.358 [a]	.207	5.587 [a]	.000***	6.890 [a]	.000***
Expected Behavior	2.857 [a]	.019*	17.371 [a]	.000***	5.128 [a]	.001**
Behavior from structure	-2.452 [a]	.037*	-4.039 [a]	.002**	-3.325 [a]	.009**
Structure	0.130 [a]	.899	-3.777 [a]	.004**	-2.803 [b]	.005**
Description	-2.202 [a]	.055	-1.260 [a]	.236	-1.988 [b]	.047*

a Paired-sample t-test, b Wilcoxon signed ranks test
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Compared to the relatively homogenous organization of design cognition indicated in the brainstorming sessions, a much greater difference between the first and second halves of protocols was observed in the morphological analysis and TRIZ sessions, Fig. 6 and Fig. 7. The students spent more cognitive effort on two the problem-related issues of function and expected behavior, in the first half of the design session, while focusing more on the two solution-related issues of structure and behavior from structure in the second half of the morphological analysis and TRIZ sessions. The students were also found to generate more description issues in the second half of the TRIZ session (19%) than in the first half (14%).

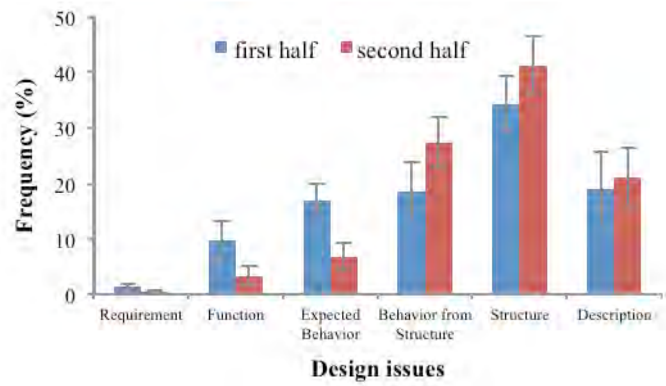

Figure 6. FREQUENCY DISTRIBUTIONS OF DESIGN ISSUES BETWEEN THE FIRST AND SECOND HALVES OF MORPHOLOGICAL ANALYSIS SESSIONS

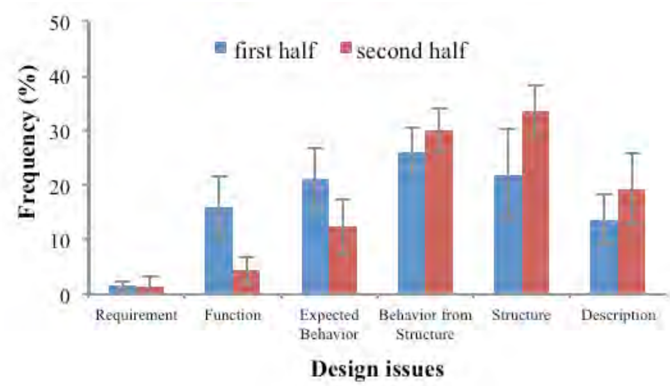

Figure 7. FREQUENCY DISTRIBUTIONS OF DESIGN ISSUES BETWEEN THE FIRST AND SECOND HALVES OF TRIZ SESSIONS

6 DISCUSSION

Four hypotheses were presented in the Introduction for which evidentiary support was sought through these experiments. Hypotheses 1 to 3 refer to the inter-session differences of design cognition caused by the three concept generation techniques that designers used. Hypothesis 4 refers to the cognition change within the design session using each of the concept generation techniques, i.e., the intra-session differences of design cognition across time.

6.1. Inter-session Differences of Design Cognition

The inter-session comparisons between the three concept generation techniques are summarized in Table 9.

Table 9. SUMMARY OF INTER-SESSION COMPARISONS OF THE PERCENTAGE OCCURRENCES OF DESIGN ISSUES

Design issues	Overall	First half	Second half
Requirement	TRIZ ≈ BR > MA	TRIZ ≈ BR > MA	TRIZ ≈ BR ≈ MA
Function	TRIZ > MA > BR	TRIZ > MA > BR	TRIZ ≈ BR ≈ MA
Expected Behavior	TRIZ > MA > BR	TRIZ ≈ MA > BR	TRIZ > MA ≈ BR
Behavior from structure	TRIZ ≈ BR > MA	TRIZ ≈ BR > MA	TRIZ ≈ BR ≈ MA
Structure	BR ≈ MA > TRIZ	BR > MA > TRIZ	MA ≈ BR > TRIZ
Description	TRIZ ≈ BR ≈ MA	TRIZ ≈ BR ≈ MA	TRIZ ≈ BR ≈ MA

≈ not significantly different
> significantly larger than

There is evidentiary support for Hypothesis 1 that engineering students' overall design cognition, measured by the distributions of design issues, is different when students design with different concept generation techniques as shown by the results in column 1 of Table 9.

There is evidentiary support for Hypothesis 2 that engineering students' design cognition is different in the first halves of their design sessions when using different concept generation techniques as shown in the results in column 2 of Table 9. These results are different to the overall results in column 1 indicating that the behaviors in the first halves of the design sessions of the different techniques are different to their overall behaviors.

There is evidentiary support for Hypothesis 3 that engineering students' design cognition is different in the second half of their design sessions when using different concept generation techniques as shown by the results in column 3 of Table 9. These results are different to the overall results in column 1 indicating that the behaviors in the second halves of the design sessions of the different techniques are different to their overall behaviors of their design sessions.

6.2. Intra-session Differences of Design Cognition

There is evidentiary support for Hypothesis 4 that the dynamics of design cognition for each of these three concept generation techniques (i.e., the cognitive changes between first and second halves of their design sessions) is different as shown in Table 10.

The intra-session differences are different when designing with the three concept generation techniques. A common trend of cognitive progress was only observed in the two behavioral issues. The students were relatively more engaged in discussing expected behavior in the first half of design sessions, and were more concerned with behavior from structure in the second half of the design sessions.

Table 10. SUMMARY OF INTRA-SESSION COMPARISONS OF THE PERCENTAGE OCCURRENCES OF DESIGN ISSUES IN THE FIRST AND SECOND HALVES

Design issues	BR	MA	TRIZ
Requirement	first > second	first > second	first ≈ second
Function	first ≈ second	first > second	first > second
Expected Behavior	first > second	first > second	first > second
Behavior from structure	first < second	first < second	first < second
Structure	first ≈ second	first < second	first < second
Description	first ≈ second	first ≈ second	first < second

≈ not significantly different
> significantly larger than
< significantly less than

7 CONCLUSIONS

This study provides the foundation for an understanding of students' design cognition during their application of different concept generation techniques to design problems. From this study it is found that the use of structured concept generation techniques (specifically morphological analysis and TRIZ) decreases the amount of cognitive effort students expend on the structure of a design solution, and instead increases the amount of cognitive effort they expend on expected behavior. This suggests that structured methods provide an appropriate framework for designers to think of solutions in an abstract sense before focusing on specific embodiments. This is corroborated by comparisons of students' utterances related to "expected behavior" across the protocols as well as in comparisons of the first halves of the protocols.

In addition to providing a better understanding of students' design cognition, the results of this study suggest that structured methods might be of value to design educators, as they provide frameworks that encourage more "expert-like" design behavior. Specifically, students' tendency to avoid abstraction, jump to a solution, and focus on the structure of a solution might be altered through the use of structured concept generation techniques such as morphological analysis and TRIZ.

The fractioning technique that divides the entire design sessions' protocol into two halves provides an approximate view about how design cognition changes across time. Future studies applying a finer grained fractioning (e.g. 10 sections per design session) are required to provide a more nuanced understanding of the dynamics of design cognition along the temporal dimension.

Further analyses of the current protocols will produce a more comprehensive understanding about the relationship between design cognition and concept generation techniques that designers used. Such analyses include examining design processes, transformations between different design issues and different processes, and determining the correlations between designers' cognitive behaviors with their design performance.

Future studies using a larger sample size are needed to generalize the effects observed in this study of using different concept generation techniques on the design cognition of designers.

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