Design cognition differences when using unstructured, partially structured and structured concept generation creativity techniques

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This paper presents an experimental study of measuring and comparing design cognition while using different concept generation creativity techniques in collaborative engineering design settings. Eleven design teams were given the same three design tasks, respectively using an unstructured concept generation technique (brainstorming), a partially structured technique (morphological analysis) and a structured technique (TRIZ). A protocol analysis was carried out using the Function-Behavior-Structure (FBS) ontologically-based coding scheme. This study showed that the students' design cognition was affected by the degree of structuredness of the concept generation creativity techniques they applied in their designing. The more structured a concept generation creativity technique is, the more likely that designers using this technique tend to focus more on problem-related aspects of designing, i.e., design goals and requirements. Results also indicate that the influence of the structuredness of concept generation creativity techniques mainly affects the early parts of the designing process, and differences between different design conditions exhibit an overall commonality of designing.

Keywords: concept generation technique; design cognition; FBS ontology; protocol analysis

Subject classification codes: include these here if the journal requires them

Introduction

In the conceptual design phase of the engineering design process, a design team embarks on creative activities to generate alternatives that meet the stated design requirements (French, 1999; Keinonen, 2006). A variety of concept generation techniques have been suggested in the literature that assist designers in exploring the entire design space, and that aid them in ideating as many different design alternatives as possible (Cross, 2008; Smith, 1998). These concept generation creativity techniques can be classified into two broad categories in terms of intuitiveness and structuredness

(Shah, Kulkarni & Vargas-Hernandez, 2000; Shah, Smith & Vargas-Hernandez, 2003; Moon, Moon, Ha & Yang, 2011). Unstructured/intuitive concept generation creativity techniques (e.g. brainstorming, 6-3-5 Method, Gallery Method, etc.) aim to increase the flow of intuitive thoughts and facilitate divergent thinking, and are mainly focused on the quantity of the solution proposals. Structured/logic concept generation creativity techniques (e.g., design by analogy, TRIZ, Advanced Systematic Inventive Thinking or ASIT, etc.) are the techniques that analyze functional requirements and generate solutions based on engineering principles and/or catalogued solutions from past experience. The boundary between unstructured and structured creativity techniques is not clearly defined. This paper does not conceptualize the degrees of structuredness of concept generation creativity techniques as a dichotomous scheme, but rather a continuum with two extremes of unstructured and structured techniques. Within this continuum there is a category of partially structured techniques that possess some of the characteristics of both unstructured and structured techniques.

Studying Creativity in Design

Creativity is a multi-faceted concept, referring to attributes or characteristics of a creative product, process, person/personality and/or place (Kozbelt, Beghetto & Runco, 2010; Taura & Nagai, 2010). The relationships between concept generation creativity techniques and four aspects of design creativity are illustrated in Figure 1. It is speculated that design cognition, i.e., mental mechanisms leading to designed outcome, is one pivot in the design creativity flow. Creativity techniques and other creativity aspects of personality and place do not cast direct impacts on the creativity of designed product; instead, their effects on the product's creativity require the mediation of design cognition.

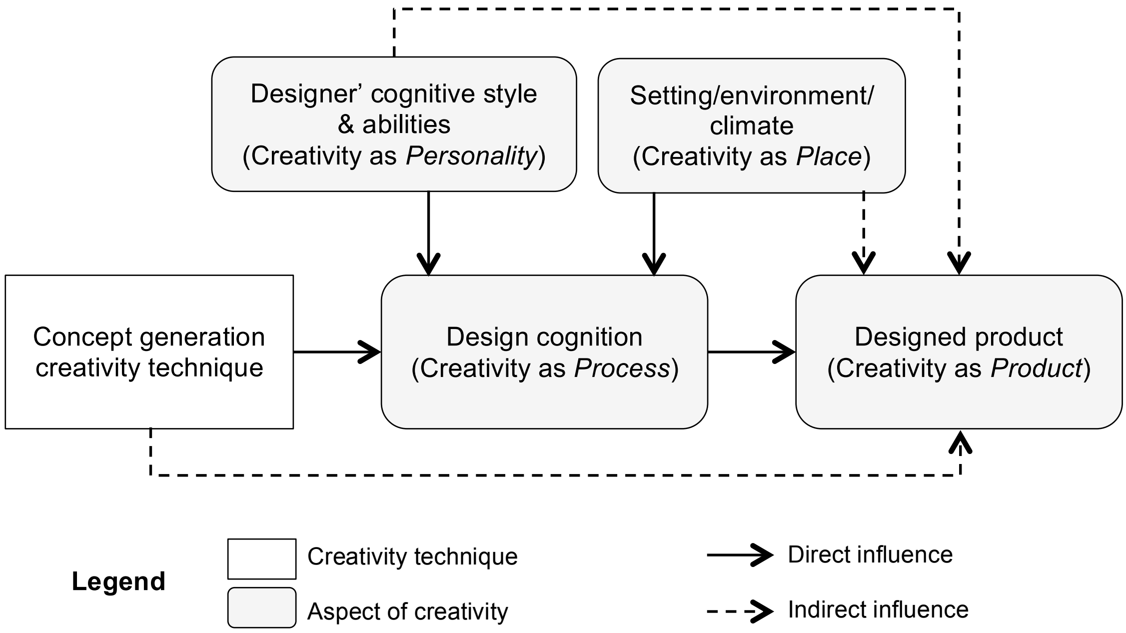

Figure 1. Effects of creativity techniques on aspects of design creativity

A review of design creativity literature shows that the majority of studies are focused on a single facet of design creativity, either prescribing a particular creativity technique (e.g., Shah, Vargas-Hernandez, Summers & Kulkarni, 2001), providing a descriptive model accounting for creative designing processes (e.g., Cross, 1997; Dorst & Cross, 2001), or proposing an objective creativity assessment for designing processes (e.g, Kan & Gero, 2008; Shah, Smith & Vargas-Hernandez, 2003) or designed outcomes (e.g., Demirkan & Afacan, 2012; Sarkar & Chakrabarti, 2011).

There is a comparative paucity of literature concerned with the interplay between different facets of design creativity. A few studies indicate that the degrees of creativity or originality in designed outcomes were to some extent related to the cognitive processes or mechanisms behind designing, without explicitly considering the influence of the techniques used (e.g., Kruger & Cross, 2006; Nagai, Taura & Mukai, 2009; Christiaans, 1992). An exploration of creativity techniques, products and processes showed that different degrees of structuredness of creativity techniques may lead designers to concentrate more on design problems or solutions during designing (Chulvi, Sonseca, Mulet & Chakrabarti, 2012) and affect the designed outcomes' emphasis on novelty or utility (Chulvi, Mulet, Chakrabarti, López-Mesa & González-Cruz, 2012). This particular study was however limited by its small sample size (n=4). The influences of different creativity techniques on the designers' cognition have been reported by Tang, Chen and Gero (2012), but without explicitly connecting them to the degree of structuredness of concept generation creativity techniques. Whether the design cognition is subject to the structuredness, or other attributes of creativity techniques remains unknown.

Hypotheses

Classification criteria of intuitiveness and structuredness have already implied that the degree of structuredness of the concept generation creativity technique would have some effects on the design cognition of designers, either promoting intuitive thoughts or removing incongruities/constraints through a more or less systematic approach. To gather evidences about this, the present paper examines and compares the design cognition of designers while using the three concept generation creativity techniques of brainstorming, morphological analysis and TRIZ as typical representatives of unstructured, partially structured and structured techniques. Possible effects of these concept generation creativity techniques on the design cognition are hypothesized as follows:

Hypothesis 1: Design Cognition Differences Dependent of Structuredness of Creativity Techniques

It is hypothesized that designers' design cognition when using these three concept generation creativity techniques would be significantly different, and the inter-technique differences should be ordinal along with the degrees of their structuredness.

Hypothesis 2: Design Cognition Exhibits a Commonality Independent of Specific Creativity Techniques

Design thinking theories usually assume that there is a regularity or commonality in designing that transcends any individual or situation (Gero, Kannengiesser & Pourmohamadi, 2012; Visser, 2009). In particular, the designing process generally commences with an articulation of design problems before moving to the generation and evaluation of solutions. Therefore, the second hypothesis paper is that designer's focus on scoping the problem would decrease along with the progress of designing, independent of which particular concept generation creativity technique was used.

Three Concept Generation Creativity Techniques

The three concept generation creativity techniques studied in this paper are brainstorming, morphological analysis and TRIZ, which have all been widely applied in industry. Brainstorming is a group concept generation creativity technique developed and popularized by Alex Osborn (1993). The essential principle underlying this technique is to remove mental blocks and increase the chance of producing creative ideas by suspending judgments and criticism during the concept generation process. The main objective of brainstorming is to produce as many ideas as possible. This technique can be considered as unstructured, as its idea generation process is achieved by randomly exploring a very large solution space without a predetermined direction. The solution space produced as a result of idea generation can be further expanded by amalgamating and refining the ideas while judgment is still deferred.

Morphological analysis is another well-known concept generation creativity technique designed for multi-dimensional, non-quantifiable problems (Zwicky, 1969). Shah et al. (2000) placed it in the same category with brainstorming, as both techniques are claimed to stimulate unconscious thought. This paper, however, considers it as partially structured. As opposed to brainstorming's random exploration of the solution space, morphological analysis provides a defined direction for the concept generation process: first abstracting the core of a product's functionality, and then systematically structuring (shaping) a complex problem through its internal relationships. It is based on bringing together two opposing notions: decomposition and forced associations (Ritchey, 2006; Ullman, 1992; Zwicky, 1969). Once the problem is decomposed, potential solutions for each sub-problem are ideated. These partial solutions are then organized in a morphological matrix, with a few potential solution concepts listed for each function. The overall solutions to the design task are generated by systematically combining concepts from each sub-problem. It is not considered as a structured technique, as the processes of generating sub-solutions are largely unstructured.

TRIZ, which is the acronym in Russian for the theory of inventive problem solving, was developed by Genrich Altshuller (1997, 1999). Based on critical analyses of historical inventions, a set of fundamental design principles was inductively derived aiming to discover and eliminate technical and physical contradictions in solutions (Silverstein, DeCarlo, & Slocum, 2007; Terninko, Zusman, & Zlotin, 1998). TRIZ is highly structured, with the procedures for applying it clearly defined and well elaborated.

Research Design

In order to investigate the potential effect of concept generation creativity techniques of different degrees of structuredness on designers' design cognition, three experiments were carried out in a collaborative engineering design setting. The experiments used a within-subject design; participants were asked to apply brainstorming, morphological analysis and TRIZ techniques respectively in three separate conceptual design tasks.

Participants

Twenty-two senior mechanical engineering students participated in this study voluntarily. They were recruited from the first semester of a capstone design course at a large land-grant university. As seniors, the students' prior design education was a cornerstone experience in a first-year engineering course and a sophomore-level course that focused on exposing students to engineering design and design methods at an early stage of their professional development. In this capstone sequence, student teams work with a faculty mentor on a year-long design project. 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 initial semester where the students received instruction on the different concept generation creativity techniques that are explored in this study.

Lectures of Concept Generation Creativity Techniques

Before each experiment, there was a lecture elucidating and detailing one of the creativity concept generation techniques. Each lecture was approximately 75 minutes in duration and was structured similarly: the instructor introduced a concept generation creativity technique, and would then provide the students with a sample design scenario to address using the new technique. As the class met once a week, the three concept generation techniques were presented sequentially over the course of three weeks: brainstorming, morphological analysis, and finally, TRIZ. Each lecture was given on a

Monday; the corresponding experiment was administered over the course of that week prior to the subsequent class meeting.

The brainstorming lecture covered the fundamental principles that contribute to intuitive concept generation, e.g., delaying judgment, production for quantity rather than quality of ideas, welcoming strange and unusual ideas, and inter-connection and cross-pollination on the basis of the generated ideas. The lecture on morphological analysis introduced the concepts of functional decomposition and the use of the morphological matrix. Students were engaged in discussions of how to functionally diagram a system, how to ideate design concepts within the bounds of a sub-function, and how to create full design alternatives via systemic combinations of concepts across the identified sub-functions. The TRIZ lecture focused on the concept of contradiction and a simplified TRIZ procedure. Hardcopies of the 40 inventive principles and contradiction matrix were provided during the lecture and design experiment.

Experiments

The twenty-two senior students were paired into eleven design teams of two persons. Each team was given the same three design tasks, whose complexities were set at the same level, as judged by design educators and expert designers. The first task was to design a device to help disabled users open a stuck double-hung window without relying on electric power, using the unstructured creativity technique of brainstorming. In the second session, students were asked to design a device to help stroke patients who are unable to perform bilateral tasks with opening doors, using the partially structured technique of morphological analysis. In the third session, students were asked 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, using the structured technique of TRIZ.

Each experiment was conducted prior to the lecture concerning the subsequent creativity technique to reduce possible experimental effects. The participants' ability to appropriately apply the various techniques was not formally assessed; however, participants had similar levels of design experience (as determined by interview prior to the experiments). Observation notes from the experimental sessions confirmed that the participants adequately applied the different techniques.

During each experimental session, the students were asked to collaborate with their team members to generate a design solution that meets the given design requirements within 45 minutes. All the design activities (including conversations, gestures and drawing) were audio and video recorded for later analysis. The experiment setting is shown in Figure 2. The participants were provided a computer with access to the internet, and a whiteboard with color markers for them to sketch or write notes.

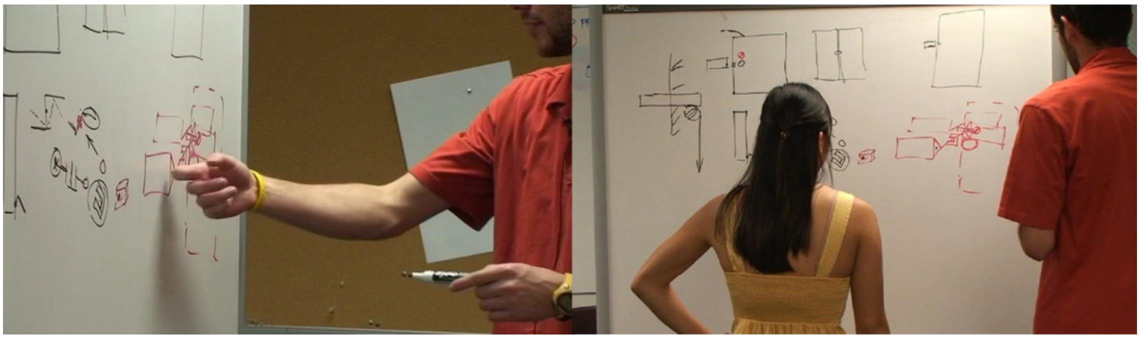

Figure 2. Experiment setting

Function-Behavior-Structure Ontologically-Based Protocol Analysis

The development of the results reported in this paper is guided by the Function-Behavior-Structure (FBS) design ontology, which models designing in terms of three classes of ontological variables that map onto design issues: function, behavior, and structure (Gero, 1990; Gero & Kannengiesser, 2004). 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 compositional relationships. These design issues are augmented by two further design issues: *requirements* (R) that come from outside the designer and *description* (D) that is the document of any aspect of designing, Figure 3.

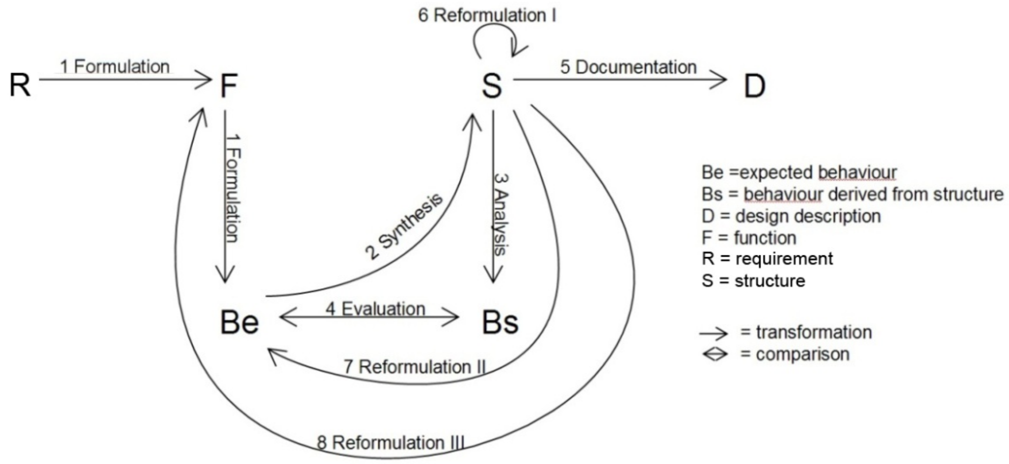

Figure 3. The FBS ontology (after Gero & Kannengiesser, 2004)

In this ontological view, the goal of designing is to transform a set of requirements and functions into a set of design descriptions. Eight design processes are defined as transformation between design issues, which are numbered in Figure 3.

The FBS Ontologically-Based Coding Scheme

The video records of design activities were analyzed using the FBS ontologically-based protocol segmentation and coding method (Gero, 2010; Pourmohamadi & Gero, 2011). The coding scheme applied is a principled coding scheme developed from the FBS ontology, consisting of six pre-defined codes that align with the six design issues, Table 1.

Table 1. The FBS ontologically-based coding scheme

FBS Design Issue	**Code**

Requirement	R
Function	F
Expected behavior	Be
Behavior from structure	Bs
Structure	S
Design description	D

Application of this coding scheme involves segmenting and encoding transcripts of the experiment videos. It follows the “one-segment-with-one-code” principle. Each segment is strictly assigned with one of the six design issue codes, based on the coders' critical judgment. If an utterance is identified to contain more than one issue, it will be further segmented. Those utterances that do not fit in any of six the design issue categories are marked as others (O). All the O-segments are removed before further analysis.

After the protocol segmentation and coding, a syntactic model can be applied to derive syntactic FBS design processes as transitional processes between pairs of design issues (Gero, 2010). The relationship between design issues and syntactic design processes is shown in Figure 3. The syntactic design processes are the consequence of the FBS ontologically-based coding scheme, rather than a separate conceptualization of protocol data.

Integration of the FBS-based Coding Scheme with Problem-Solution Division

The analyses reported in this paper are based on two novel measurements integrating the FBS ontologically-based coding scheme with a Problem-Solution (P-S) division (Jiang, Gero & Yen, 2012). The designing process is often viewed as constant interactions between two notional design “spaces” of the problem and the solution (Dorst & Cross, 2001; Maher & Tang, 2003). The original FBS-based measures of design issues and syntactic design processes can thus be reclassified into these two categories, as presented in Table 2. The FBS-based coding scheme does not specify description issues with the P-S division. Description issues and the process of "documentation" are thus excluded in the analyses using the P-S division.

Table 2. Mapping FBS design issues and processes onto problem and solution spaces

Problem/solution Space	**Design Issue**	**Syntactic Design Processes**
Reasoning about Problem	Requirement (R) Function (F) Expected Behavior (Be)	1 Formulation 7 Reformulation II 8 Reformulation III
Reasoning about Solution	Behavior from Structure (Bs) Structure (S)	2 Synthesis 3 Analysis 4 Evaluation 6 Reformulation I

Problem-Solution index as a single value

The P-S index, which helps to characterize the overall cognitive pattern of a design session, is calculated by computing the ratio of the sum of the design issues or processes concerned with the problem space to the sum of those related to the solution space, as shown in Equations (1) and (2). Compared with the original measures of design issues and syntactic processes using a set of measurements, the P-S indexes with a single value can facilitate comparisons across multiple sessions and across sessions involving different technique usage in an effective way.

$$\text{P-S index (design issue)} = \frac{\sum(\text{Problem-related issues})}{\sum(\text{Solution-related issues})} = \frac{\sum(R,F,Be)}{\sum(Bs,S)} \quad (1)$$

$$\text{P-S index (syntactic processes)} = \frac{\sum(\text{Problem-related syntactic processes})}{\sum(\text{Solution-related syntactic processes})} = \frac{\sum(1,7,8)}{\sum(2,3,4,6)} \quad (2)$$

Sequential Problem-Solution index as a time series

Designing is a dynamic process. A single-value P-S index for the entire design session collapses any time-based changes into that single value. This paper proposes a sequential P-S index across different parts of a design session. A fractioning technique

(Gero, 2010) was used to divide every design session into non-overlapping deciles each with an equal number of design issues or syntactic processes. The P-S index for each decile is calculated and used to generate a sequence of temporally ordered P-S indexes to represent the cognitive progress during the designing process.

To facilitate an intermediate granularity of analysis, these 10 deciles are re-aggregated into the two halves of a design session, i.e., deciles 1 to 5 as the first half of the design session and deciles 6 to 10 as the second half of the design session.

Analysis of Problem-Solution Indexes

This paper examines the students' design cognition from both a meta-level view (i.e., a single-value measurement) using statistical methods, and a dynamic view (i.e., taking the sequential order of design issues or processes into consideration) that mainly relies on qualitative assessments of sequential P-S indexes. Issue index and process index capture two orthogonal dimensions of design cognition, respectively responding to the content-oriented and process-oriented analyses.

As each team participated in all three experiments, the possible effect of the structuredness of concept generation creativity techniques was evaluated using one-way repeated-measures analysis of variance (ANOVA). Whether inter-technique differences of design cognition corresponded to the ordinal degree of techniques' structuredness was assessed by polynomial contrasts. Post-hoc tests applied three pairwise paired t-tests using Bonferroni correction; the achieved significance level (ASL) is set at 0.05/3=0.0167. If the assumption of normality is not met, tested by the Shapiro-Wilk test, Friedman's ANOVA, i.e., the nonparametric equivalent of one-way repeated-measures ANOVA, was applied instead. There is no nonparametric equivalent of polynomial contrasts in Friedman' test. The post-hoc test adopted three pairwise Wilcoxon Signed Rank tests using Bonferroni correction.

The commonality hypothesis of design cognition was tested by comparing the P-S indexes between the first and second halves of the design sessions, using paired t-test (if the normality assumption is met) or Wilcoxon test (if the normality assumption is not met). The line plot of sequential P-S indexes (mean only) also provides a qualitative trajectory of design cognition changing throughout the designing process.

Results

Descriptive Statistics of Coding Results

The Delphi method (Gero & McNeill 1998; Purcell et al. 1996) was applied to increase the reliability of the protocol segmentation and coding. It consisted 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 coders' agreement with the arbitrated version is approximately 90% (M=0.897, SD=0.039), which indicates the FBS ontologically-based coding result is statistically reliable.

After the protocol segmentation and coding, the video records of designing activities have been converted into sequences of design issues and, consequently, sequences of syntactic design processes. Due the varied lengths of design sessions, the occurrences of design issues and syntactic processes were respectively normalized as the percentages of the total issues or processes in each session, Figure 4.

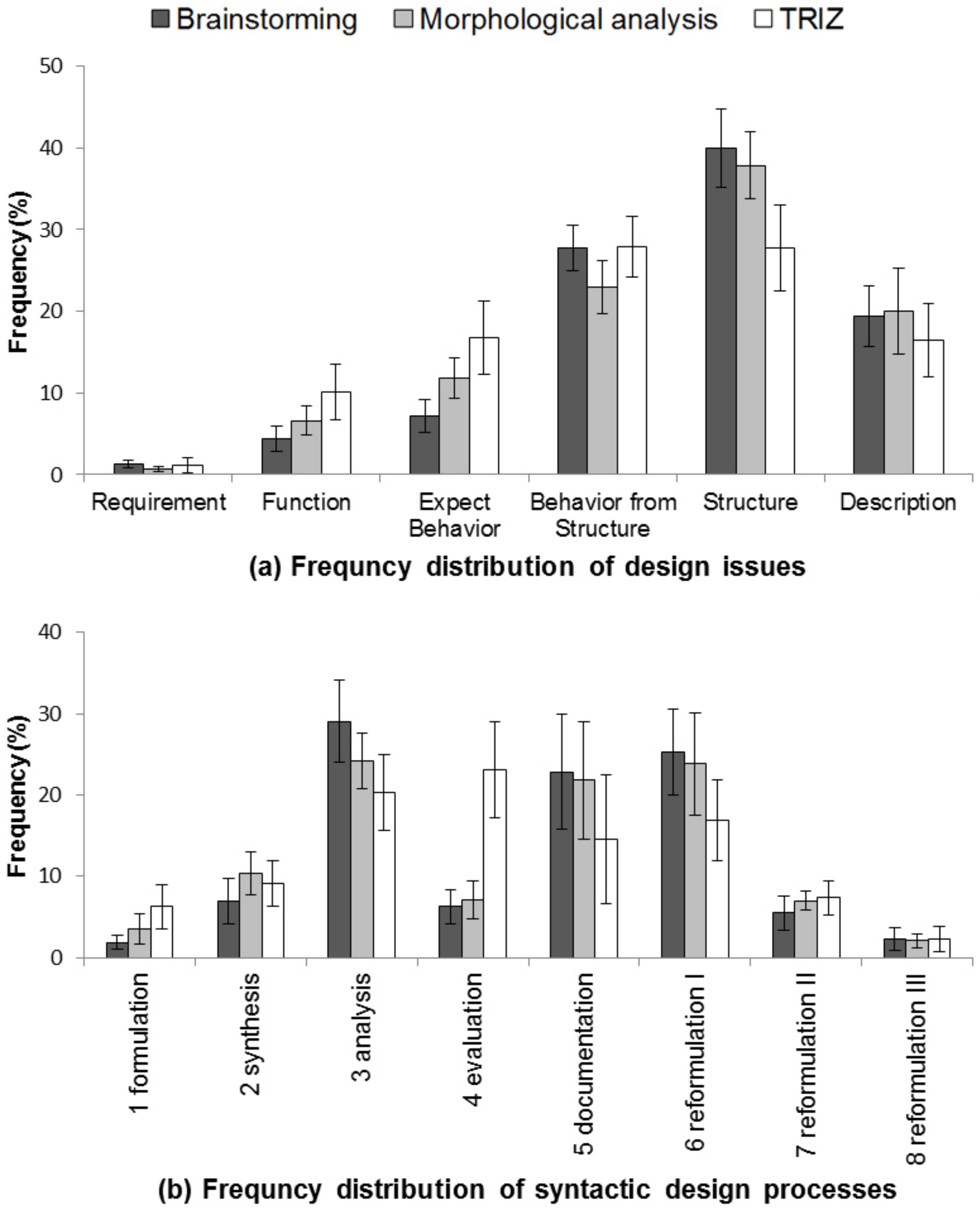

Figure 4. Frequency distribution of design issues and syntactic design processes (%)

In the three experiments, it was observed that students expended the majority of their cognitive effort discussing solution-related design issues, i.e., structure (approximately 28~40%) and behavior from structure (23~28%), as well as solution-related syntactic processes, i.e., analysis (17~32%) and reformulation I of structure

(12~34%). The problem-related aspects of design are relatively less focused on, as measured by low percentages of requirement, function and expected behavior issues and syntactic processes of formulation, reformulation II of expected behavior and reformulation III of function. These trends, in general, corroborate previous results of similar sample populations (Lee, Williams & Gero, 2012; Williams; Lee, Gero & Paretti, 2012).

Normality Test of Problem-Solution indexes

A summary of each experiment's P-S indexes is shown in Figure 5. The normality test results for each division of the designing process (i.e., the whole session and for the first and second halves of the design sessions) and for each concept generation creativity technique are presented in Table 3. It was found that the issue indexes of morphological analysis (second half), TRIZ (second half) and process indexes of brainstorming (full session, and first half), morphological analysis (full session) were not normally distributed (p<0.05). Hence the comparisons of issue indexes (full session, and first half) and process indexes (second half) used parametric statistical tests and the others applied the non-parametric equivalents.

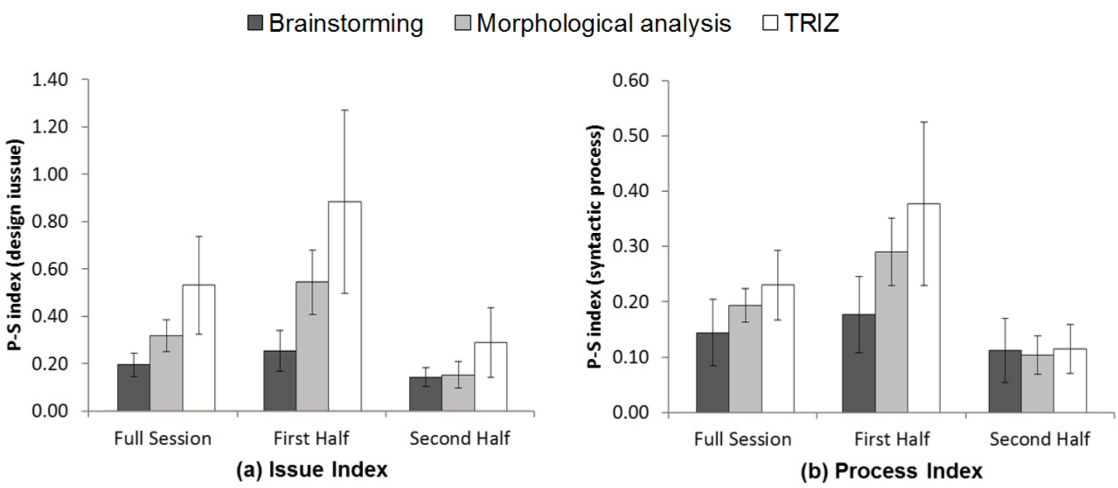

Figure 5. Problem-Solution (P-S) indexes

Table 3. Shapiro-Wilk test of normality

Experiment \ Fraction		Whole Session		First Half		Second Half	
		Statistic	Sig.	Statistic	Sig.	Statistic	Sig.
Brainstorming	Issue	0.940	0.579	0.943	0.614	0.945	0.630
	Process	0.824	0.038*	0.750	0.005*	0.903	0.270
Morphological Analysis	Issue	0.901	0.255	0.965	0.847	0.799	0.020*
	Process	0.814	0.028*	0.942	0.608	0.951	0.702
TRIZ	Issue	0.923	0.416	0.977	0.948	0.787	0.015*
	Process	0.926	0.447	0.887	0.187	0.938	0.557

* $p < 0.05$

Inter-Technique Comparisons

Overall Differences for the Whole Sessions

The effect of concept generation creativity techniques' structuredness on issue indexes of the whole design sessions was examined by one-way repeated-measures ANOVA. Mauchy's test indicated that the assumption of sphericity has been violated, $\chi^2(2)=11.62$, $p<0.05$, therefore Greenhouse-Geisser correction was applied for the main ANOVA test. ANOVA results showed that the differences of overall issue indexes between three experimental conditions were unlikely to have arisen by sampling error, $F(1.11,11.08)=17.76$, $p<0.005$. The effect size was large (partial eta^2 =0.689), indicating that nearly 70% of variation of overall issue indexes can be accounted for by different degrees of structuredness of concept generation techniques. Polynomial contrasts indicated that there was a significant linear trend along with the ordinal degrees of structuredness of creativity techniques, $F(1,10)=23.93$, $p<0.005$, partial eta^2=0.75. Post-hoc tests, shown in Table 4, confirmed that the issue indexes measured in three experiments are mutually different from each other. The more structured a concept generation technique was, the higher value of issue index was shown in the associated experiment.

Table 4. Post-hoc tests for the comparisons of full-length protocols

P-S Index \ Pairwise	BS vs MA [a]		BS vs TZ [a]		MA vs TZ [a]	
	t (z) statistic	Sig.[b]	t (z) statistic	Sig.[b]	t (z) statistic	Sig.[b]
Issue Index	5.574	0.000*	4.892	0.001*	3.292	0.009*
Process Index	1.580	0.114	2.547	0.011*	1.682	0.093

a BS=brainstorming; MA=morphological analysis; TZ=TRIZ

b Adjustment for multiple comparison: Bonferroni; ASL=0.05/3=0.0167

* p<ASL

Friedman's ANOVA showed that there is a significant inter-technique difference of overall process indexes between the three experiments, $\chi^2(2) = 8.00$, $p<0.05$. The results in Table 4 indicate that the process index measured in the brainstorming sessions was significantly lower than that in TRIZ sessions (p<ASL), while there was no significant difference between the conditions of morphological analysis and either of the other techniques.

First Half of Design Sessions (Deciles 1~5)

In order to gain a more detailed understanding of the design cognition of using these three creativity concept generation techniques, this paper divides the protocols of the whole design session into two halves of equal numbers of design issues or syntactic processes (deciles 1 to 5 and 6 to 10 respectively), and uses the first half of the design sessions to represent the early episodes of the designing process. Similar to the overall comparisons, issue indexes of the first half of design sessions were found to be significantly affected by different degrees of concept generation techniques' structuredness, $F(1.11,11.08) = 14.87$, $p<0.01$, partial eta^2 =0.650. The significance of linear trend of issue indexes was supported by polynomial contrasts, $F(1,10)=22.131$, $p<0.005$, partial eta^2=0.73. Pairwise comparisons, shown in Table 5, indicate that issue index of the brainstorming sessions was significantly lower than the other two conditions (d=2.03; 1.81), while the morphological analysis sessions tended to have a smaller issue index value than the TRIZ sessions, though it was not statistically significant.

Table 5. Post-hoc tests for comparisons based on the first half of protocols

Pairwise / P-S Index	BS vs MA [a]		BS vs TZ [a]		MA vs TZ [a]	
	t (z) statistic	Sig. [b]	t (z) statistic		t (z) statistic	Sig. [b]
Issue Index	6.146	0.000*	4.704	0.002*	2.704	0.024
Process Index	2.293	0.022	2.547	0.011*	1.599	0.110

a BS=brainstorming; MA=morphological analysis; TZ=TRIZ

b Adjustment for multiple comparison: Bonferroni; ASL=0.05/3=0.0167

* *p*<ASL

The effect of concept generation creativity techniques' structuredness on the process indexes of the first half of protocols was supported by the Friedman's ANOVA, $\chi^2(2) = 7.60$, $p<0.05$. The process index measured in the first half of brainstorming sessions was significantly lower than that of TRIZ sessions ($p<$ASL, shown in Table 5). It also tended to be lower than that of morphological sessions, Figure 5, though it was not significant using Bonferroni correction. There was no significant difference found between the conditions of morphological analysis and TRIZ.

Second Half of Design Sessions (Deciles 6~10)

The second half of a design session represents the later episodes of the designing process, in which designers elaborate and evaluate their design solutions. Friedman's test identified that issue indexes in the second half of protocols was significantly affected by the different concept generation techniques applied, $\chi^2(2)=10.89$, $p<0.01$. TRIZ sessions demonstrated a significantly higher value than the other two sessions using lesser structured techniques. There was no significant difference found between morphological analysis and brainstorming sessions.

The effect of different concept generation techniques on process indexes of the second half of design sessions was not supported, $F(2,20)=0.505$, $p>0.05$. The differences between three experiments' measurements were not statistically significant.

Dynamics of Design Cognition

Intra-session Comparisons between First and Second Halves of Design Sessions (Deciles 1~5 vs 6~10)

The dynamics of designing is explored by examining the sequential distributions of design issues and syntactic processes. A gross difference between design cognition focused on early and later episodes can be examined by comparing P-S indexes measured in the first and second halves of design sessions using one-tailed paired t-tests or Wilcoxon tests. In all conditions, the P-S indexes measured in the second half of design sessions are significantly smaller than their counterparts in the first half of design sessions, Table 6.

Table 6. Intra-session comparison between first and second halves of protocols (1-tailed)

Experiment	P-S Index	Difference (2^{nd} - 1^{st})		t (z) statistic	Sig.
		Mean	SD		
Brainstorming	Issue Index	-0.111	0.086	-4.100^{a}	0.005^{**}
	Process Index	-0.065	0.048	-2.599^{b}	0.018^{*}
Morphological analysis	Issue Index	-0.389	0.130	-2.934^{b}	0.006^{**}
	Process Index	-0.187	0.066	-9.351^{a}	0.000^{***}
TRIZ	Issue Index	-0.592	0.311	-2.803^{b}	0.009^{**}
	Process Index	-0.262	0.127	-6.485^{a}	0.000^{***}

a t score in paired t-test; b z score in Wilcoxon Signed Rank Tests
* $p<0.05$, ** $p<0.01$,*** $p<0.001$

Along with the commonality of decreasing focus on problem-related aspects of design cognition, the absolute amount of difference means of issue and process indexes (second half – first half) of the brainstorming session are much smaller than those of the other two experiments, roughly equal to 30% of the difference means of the morphological analysis sessions, and one fifth of those of the TRIZ sessions, Table 6.

Sequential P-S Index over Time

The evolving trajectory of design concepts are visualized in the form of line plots of sequential P-S indexes (mean only shown) against design sessions divided into deciles, Figures 6 and 7. The linear regression model of each session's sequential issue and process indexes for all design sessions in the three experiments show a negative slope for their best-fit line, Tables 7 and 8.

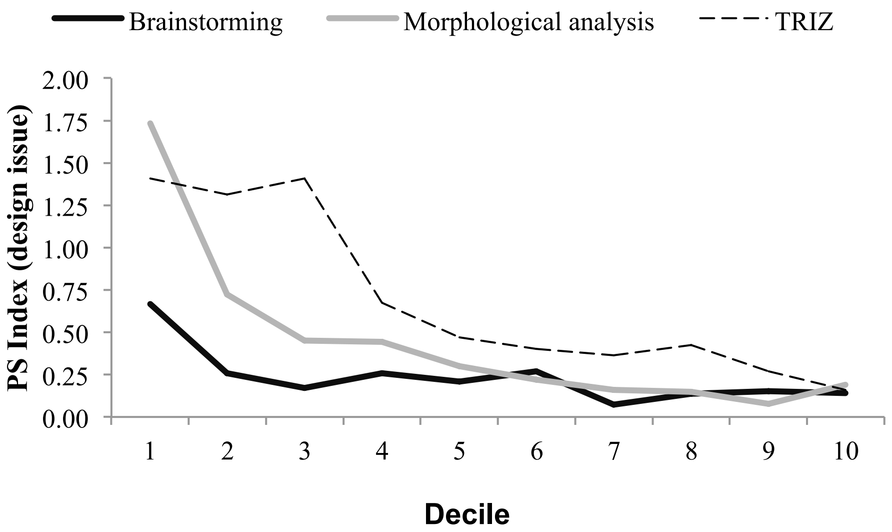

Figure 6. Sequential issue indexes (mean) in deciles of design sessions

Table 7. Slope of the best-fit line for each session's sequential issue index

Slope	Brainstorming	Morphological Analysis	TRIZ
Mean	-0.037	-0.126	-0.148
Std.Dev	0.031	0.069	0.080

The slopes of best-fit lines were examined using one-way repeated-measures ANOVA. For the issue index slopes, there is a significant effect of the different concept generation creativity techniques utilized in the three experiments, $F(2,20)=8.06$, $p<0.005$, partial eta^2=0.50. The inter-technique differences of issue index slopes demonstrate a significant linear trend along with increasing degrees of structuredness of the concept generation creativity techniques, shown in within-subject polynomial contrasts, $F(1,10)=76.23$, $p<0.001$, partial eta^2=0.91. Pairwise comparisons confirm that sequential issue indexes of brainstorming sessions have a significantly smaller decreasing rate than those of the sessions using more structured techniques, as brainstorming session started with a lesser focus on reasoning about problems than the other sessions.

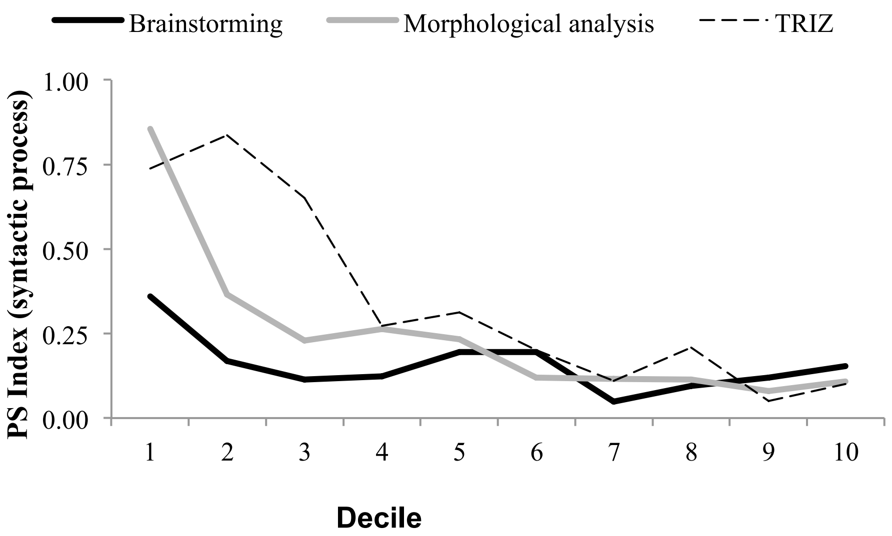

Figure 7. Sequential process indexes (mean) in deciles of design sessions

Similar to sequential issue indexes, best-fit lines' slopes of sequential process indexes are significantly different among the three experiments, $F(2,20)=6.64$, $p<0.01$, partial eta^2=0.45. A linear pattern of these slopes was found along with unstructured, partially structured and structured techniques, indicated by polynomial contrasts, $F(1,10)=17.89$, $p<0.005$, partial eta^2=0.69. Pairwise comparisons confirm that the decreasing slope in brainstorming sessions is significantly less than that of TRIZ sessions; however, the differences between morphological analysis and other sessions are not statistically significant.

Table 8. Slope of the best-fit line for each session's sequential process index

Slope	Brainstorming	Morphological Analysis	TRIZ
Mean	-0.015	-0.060	-0.085
Std.Dev	0.010	0.050	0.047

Discussions

This paper examines the effects of unstructured, partially structured and structured concept generation creativity techniques on the design cognition of senior mechanical engineering students in collaborative engineering design settings. The analyses and discussions are undertaken in response to two hypotheses presented in the Introduction.

(1) Structuredness-specific differences: the increasing degree of the structuredness of a concept generation creativity technique affects the design cognition when designers apply that concept generation creativity technique in the designing process; and

(2) Structuredness-independent commonality: designers commence with a relatively higher focus on the problem and this focus decreases as the design session progresses, independent of which particular concept generation creativity technique is used.

More Structuredness in the Creativity Technique Leads to More Focus on Reasoning about Problems

Results from this study support the first hypothesis that the structuredness of concept generation creativity techniques affects designers' relative focus on reasoning about design problems. Except the approximately equality of process index of the second half of design sessions, all other P-S indexes, as well as slopes of best-fit lines of sequential P-S indexes, were found to be significantly different between the three experiments, assessed using one-way repeated-measures ANOVA or Friedman's test; and the means of these measurements show a significantly linear trend along with the increasing structuredness of the associated techniques, as indicated by within-subject polynomial contrasts[1]. These findings suggest that the more structured a concept generation technique is, the more likely that designers applying this technique would spend more cognitive effort reasoning about the design problems rather than their solutions.

This cognitive difference corresponds to the manner in which these three concept generation creativity techniques are formalized. In order to use the TRIZ and its 40 inventive principles and contradiction matrix, a designer must first formulate the design problem into an abstract contradiction. This explicit, structured instruction requires designers to engage in cognitive exercises pertaining to the requirement, function and expected behavior of the design problem. Brainstorming, by contrast, offers no structured direction for the designer, thus designers tended to jump straight to activities related to solutions without fully scoping the design problem, which produces a low value for P-S indexes measured in the brainstorming sessions. This also explains the relatively homogeneous distributions of P-S indexes throughout the 10 deciles of design sessions (for both sequential issue and process indexes).

The blended characteristic of the partially structured technique of morphological analysis are revealed through dividing the whole session's protocols into the first and second halves. The first half tends to resemble the behavior of more structured techniques in early episodes of the designing process and the second half resembles the

[1] As there is no nonparametric equivalent in Friedman's ANOVA, within-subject polynomial contrasts were still calculated in those sessions that did not met normality assumption.

behavior of unstructured in later episodes. Both issue and process P-S indexes of morphological analysis experiment were not significantly different from those of TRIZ experiment in the first half of protocols, and those of brainstorming experiment in the second half of protocols. This may be because when designing using the morphological analysis technique, designers must first systematically decompose the design problem into sub-functions. As the problem decomposition process is rather structured, design cognition of the early stages of a morphological analysis session resembles many characteristics of designing activities using structured techniques, such as TRIZ. Morphological analysis does not specifically prescribe solution generation procedures for the decomposed problems; most students tended to revert to their default unstructured concept generation approach. As a result the latter part of a design session using morphological analysis resembles many characteristics of intuitive designing process using the unstructured brainstorming technique.

The structuredness specific findings in general support Chulvi, Sonseca et al.'s (2012) study that much more time was spent on problem analysis when using a structured logic technique of Functional Analysis than unstructured intuitive techniques of brainstorming and SCAMPER (partially-structured based on the present paper's classification). Some results of Tang, Chen, and Gero's (2012) experiment, where designers focused more on design problems when designing with the unstructured technique of brainstorming, and focused more on solutions when using the more structured technique of synectics, are not supported by the results of the experiment reported in this paper. It is noted that Tang et al.'s (2012) study did not explicitly investigate the structuredness of creativity techniques, and their participants (sophomore industrial design students) are less experienced than Chulvi, Sonseca et al.'s (2012) participants of PhD students and professional designers and engineers, and the participants (senior engineering students) in this study.

Focus on Reasoning about Problem Decreases while Designing Progresses

The second hypothesis concerning the commonality of design cognition, independent of any particular concept generation creativity technique used, is qualitatively supported by trajectories of sequential P-S indexes, Figures 6 and 7. It is quantitatively validated by intra-session comparisons of P-S indexes between the first and second halves of protocols, Table 6, and negative slopes of best-fit lines for each session's sequential P-S indexes, Tables 7 and 8. As all of three concept generation creativity techniques are oriented towards the goal of generating a solution to the design task, it is not unexpected that a design team shifts their focus to solution-aspects of design cognition towards the end of the designing process.

Conclusion and Future Studies

Various concept generation creativity techniques are used in industry and are taught during undergraduate and graduate engineering design education, with an expectation that such techniques could increase the fluency and potential creativity of resulting designs. There is both anecdotal and empirical evidence to support this premise. However, there is little or no evidence directly concerning the effects of concept generation creativity techniques on the cognitive process behind the designing process, which would provide a foundation for the differences of design outcomes. This paper compares senior mechanical engineering students' design cognition when designing with three concept generation creativity techniques of different degrees of structuredness. The protocol analyses reported here use two novel measurements based on the integration of the FBS ontologically-based coding scheme with a P-S division.

Findings indicate that the inter-technique differences correlate to the ordinal sequence of the concept generation creativity techniques' structuredness; increasing structuredness of a concept generation creativity technique leads designers to relatively focus more on the problem-related aspects of design cognition. This may be accounted for by the fact that structured concept generation creativity techniques usually prescribe a systematic problem decomposition process which is not in unstructured techniques. Results also reveal that the structuredness-specific effects take place within an overall commonality of designing. Independent of how structured a particular concept generation creativity technique is, designers' cognitive focus on reasoning about problems decreases along with the progression of the designing process.

The next step of this study aims to assess how using different concept generation creativity techniques affects the creativity of design outcomes, as well as whether the cognitive differences are correlated to the creativity difference of design outcomes. Understanding and measuring the design cognition of students and designers as they utilize different concept generation creativity techniques has the potential to provide a foundation for educational interventions that target desired design behaviors.

The findings of this paper are limited by the sample size of the experiments and the specifics related to the research setting, e.g., non-randomized matches of creativity techniques, experiment tasks and the order of experiments. Confirmative studies with a larger sample size, randomized matches of creativity techniques and experiment tasks, as well as including other types of designers and other concept generation creativity techniques, are needed to generalize the results of the influence of concept generation creativity techniques' structuredness presented here.

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