The Effect of Design Education on Creative Design Cognition of High School Students

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Abstract: This paper presents results from a study exploring the relationship between design education and creative design cognition in high school students. Data from coded protocols of high school students with and without design education serve as the source. Audio/video recordings of student pairs engaged in a design task captured both their design approach and their concurrent design conversation. Following a verbal protocol methodology, videos were coded using the Function-Behaviour-Structure ontology coding scheme. This coding scheme was augmented by two further codes "new" and "surprising" as the basis for measuring design creativity. Results revealed significant differences between the two cohorts in creative design cognition, while no significant differences in general design cognition were found.

Keywords: Creative design cognition, protocol analysis, creative codes, FBS ontology

1. Introduction

1.1 Motivation

Fostering the capacity for design thinking within high school students is essential to imparting the 21st century skills they need as creative problem solvers (Dede, 2010, p. 21). Research regarding the preparation of students with the ability to design creatively has become a critical issue in design education. Researchers discuss creativity usually from four perspectives: creative process, creative outcome, creative individuals, and interactions between creative individual and the context/environment (Said-Metwaly, Noortgate, & Kyndt, 2017). In a survey of 152 creativity studies Said-Metwaly et al. (2017) found that the process approach was the most commonly used approach to measure creativity (52.58% of all studies surveyed) followed by the person approach (28.87%), the product approach (14.43%)

and interaction approach (4.12%). Other studies have focused on the evaluation of the design product (Runco & Pritzker, 1999; Torrance, 1966) with a variety of evaluating criteria used of which novelty, surprise and value are the most commonly applied (Hayes, 1978; Maher, 2010; Nguyen & Shanks, 2009). Some formal methods for evaluating creativity have been developed, such as Creative Product Semantic Scale (CPSS) (Besemer & O'Quin, 1993) and the Consensual Assessment Technique (CAT) (Amabile, 1982). Others suggest exploring creativity during the design process (Rosenman & Gero, 1993; Suwa, Gero, & Purcell, 1999). Kan and Gero (2008) proposed the idea that a reformulation process is beneficial to creative thinking by introducing new variables or new directions, which potentially lead to creative results. An underlying assumption within such studies is adequate preparation in design and creative design cognition. However, there is insufficient empirical evidence supporting the assumption that design education is effective in helping students develop creative design cognition. The study reported in this paper is a first step in filling this gap in our knowledge.

1.2. Aims and objectives.

This study aims to explore the relationship between design education and the demonstration of creative design cognition by high school students. The research focuses on exploring creativity in design processes rather than outcomes. The objectives of this study are:

1. To test a novel coding scheme for its ability to distinguish design cognition between students with and without design education.
2. To determine whether there is a temporal aspect to creative design cognition.
3. To test whether there are temporal differences in creative design cognition between students with and without design cognition.

The research described in this paper is a significant extension of a previously reported study on design cognition (Wells et al., 2016) . That study was a protocol analysis of a two-by-two factorial investigation across two exogenous variables, design experience (formal pre-engineering coursework) and maturity (time between data collected in junior and senior years of high school). A subset of data collected in Year 2 of the original research from that study is used to investigate creative design cognition by recoding the protocol data using two new codes that allow the assessment of creative design cognition. This dataset allows the comparison of the creative cognitive behaviour of high school students with and without design education without the need to collect further data.

2. Measuring Creativity

Hocevar (1981) and many later researchers state that defining and measuring creativity is complicated. Sarkar and Chakrabarti (2008) argue that measuring creativity is essential to select innovative products and to evaluate the degree of innovation taking place. However, creativity is not only exhibited in design products, but also in design processes. The research aims to measure high school students' creative design processes and compare them under conditions of with and without engineering training. To better understand and distinguish creativity in the design process from the product, the next section presents definitions and measurements of both creative design product and design process.

2.1. Measuring creativity of design product

Researchers from psychology, social science, architecture, engineering and industrial design have offered various definitions of creativity. According to psychologists Runco and Prizker (1999) the creativity of a product is characterised by its aesthetic appeal, novelty, quality, unexpectedness, uncommonness, peer-recognition, influence, intelligence, learning and popularity. The measurement of an artefact to determine whether it is creative is an important issue for researchers, designers and educators. Kaufman and Sternberg (2006) claim that “creativity can be measured, at least in some degree”. However, the evaluation of creativity can be subjective, and evaluation standards are not easily defined (Jordanous, 2011). A step in attempting to measure creativity is establishing evaluation criteria. Cropley and Cropley (2005) propose a four-dimensional, hierarchical model for measuring creative product that exhibits relevance and effectiveness, novelty, elegance, and generalizability. Rosenman and Gero (1993) define the criteria of a creative product as including “having richness of interpretation”. Richness of interpretation refers to the way that a design can be interpreted in multiple ways, and which to some extent represents the potential for future development. Amabile (1983) states that novelty and appropriateness should be the criteria for accessing creative product. Ritchie (2007) and Oman and Tumer (2009) suggest that novelty and quality are the criteria to evaluate creative design products. Similarly many other researchers (Aldous, 2005; Boden, 2004; Cropley, 1999; Oman & Tumer, 2009; Ritchie, 2007; Weisberg, 1993; Wiggins, 2006) list novelty/originality and usefulness/value/utility as the criteria to assess creativity. Sarkar and Chakrabati (2008) conclude that most definitions will list Novelty and Usefulness in definitions of creativity.

Creativity in design may be a phenomenon that shares common characteristics with creativity in psychology, social psychology, and cognition. Whilst many researchers use the two criteria of novelty and usefulness, other researchers argue that these two may be insufficient and must be augmented by a third criterion, “surprise”, necessary to measure the unexpectedness of a novel design (Brown, 2012; Bruner, 1962; Gero, 1996; Maher, Poon, & Boulanger, 1996a). For example, Hayes (1978) and Nguyen and Shanks (2009) define valuable, novel and surprising as the key criteria of creativity. Maher (2010) suggests value, novelty and unexpectedness are the important features of creative design and has proposed formal methods to measure surprise. Brown (2012) proposes a framework to consider various situations where designers/evaluators might be surprised.

For assessing creative design products, some formal methods have been developed. A well-known method for evaluating creative outcomes is the Creative Product Semantic Scale (CPSS) (Besemer & O'Quin, 1993). Evaluation criteria for the CPSS are novelty (original and surprising), product resolution (valuable, logical, useful and understandable), and elaboration and synthesis (organic, elegant and well-crafted). Similarly, the Consensual Assessment Technique (CAT) (Amabile, 1982) also uses novelty and valuable as evaluation criteria for creative outcomes. The CAT approaches assessment of creativity through the subjective evaluation by expert judges. Sarkar and Chakrabarti (2011) proposed a method for assessing the degree of creativity of design products based on their novelty and usefulness. Their methods employ FBS and Sapphire models. Using the FBS model, it is possible to test if the produce is novel or not; While the SAPPHIRE model is used to assess relative degree of novelty of a product. Jagtap (2018) further develops Sarkar and Chakrabarti's method by proposing four modifications, which was evaluated by benchmarking them against the collective, intuitive assessment of novelty by experienced designers.

2.2. Measuring creativity of design process

Researchers have studied the design processes involved in the production of creative design products and recognize that evaluating the creativity expressed within design processes is a complex issue (Lawson, 1997). Fundamental to better understanding the role of creativity in designing is determining if there are specific processes that produce creative outcomes that would then be recognized as creative processes. A creative process has been defined in a variety of ways. One common definition is that "Creativity occurs through a process by which an agent uses its ability to generate ideas, solutions or products that are novel and valuable" (Sarkar & Chakrabarti, 2011). Sarkar and Chakrabarti's definition of creativity represents the idea that a creative process is the one which can produce a creative outcome.

However, sometimes a creative process does not necessarily produce a creative design product. Thus, many researchers define creative process in a different way. For example, Wallas (1926) argues that there are four stages of creative design processes: preparation, incubation, illumination and verification. These four stages have been applied in various research (Dewett, 2003; Kristensen, 2004; Rastogi & Sharma, 2010). As (Runco, 2004, p 665) states, Wallas' four stage creativity model has "shown its usefulness through years".

For measuring a creative design process, Guilford (1975) proposed that divergent thinking is the most relevant to creative design process. Divergent thinking tests have been most widely used for measuring creative processes or creativity-relevant skills (Kaufman & Sternberg, 2006).

Another measurement method is to calculate the design co-evolution process (Yu, Gu, Ostwald, & Gero, 2015). Designing can be analysed through the way cognitive effort shifts between the consideration of problems and solutions (Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996b). Many scholars state that a creative design process is related to problem-finding, idea finding and problems-solving process (Osborn, 1963; Parnes, 1981). The co-evolution model of design (Maher & Poon, 1996) recognizes that it is during this process where designers formulate critical questions and explore answers to establish a relationship between the "problem space" and the "solution space". Maher and Poon (1996) and later Dorst and Cross (2001) each suggest that the co-evolution of design problem and solution spaces has a close correlation with the occurrence of design creativity.

Hasirci and Demirkan (2007) apply observation, protocol analysis and rating scales to assess creativity during the design process. Their study shows that creative design product and process are highly correlated. Toh and Miller (2015) evaluate creativity from the perspective of concept selection in a teamwork design context. Results of their study suggest that creative concept selection can be related to discussions on the decomposition of generated ideas. D'Souza and Dastmalchi (2016) evaluate creative design processes by applying the CAT method (Amabile, 1982). Results of the study suggest that design processes do not follow patterns of linear periods of incubation followed by creative leaps and the expertise and background of designers are critical for creative design idea generation. Other creative process measurement methods include the Wallach-Kogan Creativity Tests (WKCT) (Wallach & Kogan, 1965) and Structure of the Intellect Divergent Production Tests (SOI) (Guilford, 1967).

From a cognitive perspective, Bruner (1962) defined creativity as an act that results in “effective surprise” (Bruner, 1962, p. 3). Within the specific context of design cognition, Gero (2000) builds on this in defining creativity as “the designing activity that occurs when one or more new variables are introduced into the design”. “New variables” refers to ideas introduced for the first time.

The current study is based on a blend of these concepts and seeks to measure creative design by re-examining design cognition through the lens of “new” variables introduced by the students engaged in the design process which account for “effective surprise” on their part (Bruner, 1957; Grace & Maher, 2015; Grace, Maher, Fisher, & Brady, 2015; Maher, Fisher, & Brady, 2013; Maher & Fisher, 2012), where “effective surprise” is defined as the production of novelty, which “takes one beyond common ways of experiencing the world” (Bruner, 1979, p22). In the current study, both “New” variable and “Surprising” are coded within the context: “New” is relative to previous utterance; while “Surprising” is dependent on the design situation/context. In the coding process this is accomplished by identifying the new variables introduced and then assessing whether they constitute effective surprise within that context. Although creative design processes cannot guarantee creative outcomes, their likelihood is increased by introducing new variables. For the current research, the introduction of new variables is an important benchmark for measuring a creative design process.

3. Empirical Measurement in Protocol Analysis

A protocol is the record of behaviours exhibited by designers as captured in sketches, notes, or audio/video recordings (Akin, 1986). Protocol analysis, a method of converting qualitative verbal and gestural utterances into quantitative data (Ericsson & Simon, 1993; Gero & McNeill, 1998), is conducted through the application of coding schemes used to categorise unique variables within the data. The strength of such an analysis for providing a detailed study of the design process in any given design environment has resulted in protocol analysis becoming the prevailing experimental technique used in exploring and understanding the process of design (Atman et al., 2007).

There are several common procedures for applying the protocol analysis method. According to Ericsson and Simon (1993), the general procedures include: proposing a hypothesis or direction of observation; experimental design and subject recruitment; conducting experiments; transcribing protocols and materials generated in the design process; devising a coding scheme; segmenting and encoding protocols; quantitative and qualitative comparison of encoded protocols; and proposing results. There are several alternative methods to segment data, such as dividing by a fixed time duration, on individual sentences or on the meanings. During the encoding process the current research segments the transcribed data based on the meaning of the utterance and then categorises each segment using an existing, commensurable coding scheme.

4. Augmenting the FBS Coding Scheme

Gero's Function-Behaviour-Structure (FBS) ontology (1990) has been applied in many cognitive studies (Gero & Tang, 1999; Kan & Gero, 2005; Lammi, 2011; Song, 2014) because it is capable of capturing most of the meaningful design processes and the transitions between design issues are clearly classified into eight design processes. The FBS ontology contains three classes of variables: Function (F), Behaviour (B) and Structure (S). Function (F) represents the design intentions or purposes; behaviour (B) represents the artefact's derived (Bs) or expected behaviour from the structure (Be); and structure (S) represents the components that make up an artefact and their relationships. The model is completed by two external design factors: requirements (R) and descriptions (D). The first of these represents requirements from outside the design and the second, descriptions, meaning the documentation of the design. Both R and D are expressible in F, B or S so do not require an extension of the ontology. From the FBS ontology there are eight design processes—formulation, analysis, evaluation, synthesis, and reformulation I, II, and III, Figure 1. The FBS ontology describes generic design processes. Howard, Culley, and Dekoninck (2008) argue that there is no link to what is referred to as the creative design output, and therefore do not differentiate between a process leading to a creative design over one leading to a routine design.

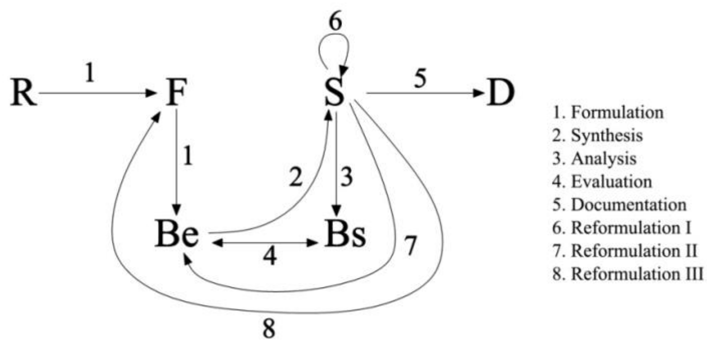

Figure 1. The FBS ontology of variables and processes (Gero & Kannengiesser, 2004)

The coding scheme derived from the FBS ontology consists of six codes that map onto the ontology: R, F, Be, Bs, S and D (Kan & Gero, 2017). This coding scheme is augmented by two further codes used to tag New and Surprising segments that have already been segmented and coded using the FBS coding scheme. “New” means that design issue is introduced for the first time in that particular context of the design session; while “Surprising” means unexpected within the context of the design being proposed. Further explanation regarding “New” and “Surprising” are provided in Section 6. The current research adopted the augmented FBS coding scheme to explore creative design processes.

5. Experiment Design

The following summarizes the method used in data collection and analyses.

5.1. Participants

Forty participants were drawn from a convenience sample of high school students in their senior (12th) year at mid-Atlantic US high schools of similar population size offering the same Project Lead the Way – PLTW (PLTW, 2017) pre-engineering program where students engage in design-based learning intended to foster critical and creative thinking. The PLTW Engineering program is comprised of a sequence of nine courses beginning with Introduction to Engineering and progressing to the Engineering Design and Development capstone course.

Purposeful selection from the convenience sample, whereby participants are selected because they are “information rich” (Patton, 1990, p. 169) with respect to understanding the phenomenon under study, was used in assigning students to experiment and control groups (those with and without formal pre-engineering course experience respectively). For participants in the experiment group, prior course experience in the PLTW Engineering program ranged from one to two full years. Participants were divided into 20 teams of pairs, 10 of which were comprised of students having experienced PLTW Engineering courses and 10 comprised of students who had not. Of the 20 pairs, 60% were mixed-gender and within both experiment and control groups the gender distribution was approximately the same: 65% male and 35% female. Protocol analysis method is based on relatively small sample sizes sufficient for statistical testing. In protocol studies of designers each design session will typically generate between 300 and 1,200 data points, which provide extensive detail of the design process.

5.2. Procedures

Pairs were used because that configuration naturally promotes authentic verbal exchanges during collaborative development of acceptable engineering design solutions (Kan & Gero, 2009; Purzer, Baker, Roberts, & Krause, 2008). The task presented to each team was that of producing a design to assist wheel-chair bound individuals with accessing objects located on shelves in an overhead cabinet and 45 minutes was allowed for generating a design solution. Full details can be found in Wells (2016). Participants' design processes were captured using two video cameras arranged at different vantage points during each design task session. Both students in a team wore a high-sensitivity Lavalier wireless microphone. Each recording produced a time-stamped audio/video record of the entire design session, Figure 2.

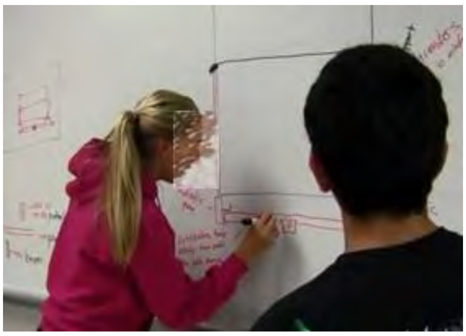

Figure 2. Frame from a video of participants sketching final design solution descriptions.

Audio recordings from each design session were transcribed manually with utterances from each student entered verbatim into alternating rows of an Excel spreadsheet. Included in the transcription were timestamps inserted every three minutes providing reference points throughout the entire video. Transcriptions were segmented based on the FBS ontology where each of the six variables – R, F, Be, Bs, S, and D — represents a design issue. Independent coders simultaneously segmented and coded transcripts, repeatedly dividing an utterance until each individual segment contained a single code reflecting only one of the six possible design issues. Following independent segmentation and coding of each transcript, coders would arbitrate to produce a final coding. Coding reliability is measured against the final arbitrated version so the standard inter-coder reliability as measured by Cohen's kappa is not applicable here. Coding reliability is measured by comparing each coder's coding against the arbitrated code expressed as a percentage agreement. Consistent with prior research (Williams, Gero, Lee, & Paretti, 2011), coder reliability against the final codes ranged from 85% to 95%. The arbitrations resulted in final protocol data sets that were used in the statistical analyses. Final protocols for a 45-minute design session typically resulted in between 200 and 800 individually coded segments. Given there are six codes, this implies that on average each code will likely appear 83 times, thereby providing a sufficiently large data set for later statistical analysis.

6. Results for New and Surprising

Results from the earlier research study (Wells et al., 2016) suggest that students' design cognition is not significantly affected by the pre-engineering design education provided (PLTW) in terms of design issues distributions, as shown in Table 1 (Wells et al., 2016), where the students who had received pre-engineering design teaching are designated by ENG and those who did not are designated by Non-ENG. Paired *t*-tests resulted in *p* values of greater than 0.1 for all measures. This was unexpected and implied the effect of the PLTW pre-engineering design education on a student's design cognition was minimal.

Table 1. Design issue distributions for ENG and Non-ENG cohorts

		R %	**F %**	**Be %**	**Bs %**	**S %**	**D %**
ENG	Average (SD)	3.5 (2.01)	1.5 (0.65)	5.3 (2.14)	34.4 (4.74)	44.4 (5.18)	10.9 (5.42)
Non-ENG	Average (SD)	4.3 (2.93)	2.0 (0.97)	6.9 (2.42)	33.5 (6.43)	44.1 (6.31)	9.3 (3.80)
p (ENG vs Non-ENG)		0.48	0.12	0.17	0.73	0.89	0.53

Transcripts previously segmented and coded using the FBS codes undergo a second pass of coding using two further codes: one for New ideas in segments and the other for Surprising ideas (Gero & Kan, 2016). In this way any of the previous FBS codes can be additionally coded as "New" and "Surprising". No "R" or "D" will be coded as "New" because the consideration of requirement and documentation do not bring in any new variables. "Surprising" means unexpected within the context of the design being proposed. Logic dictates that surprising issues are also new issues, because if not new, there can be no unexpectedness. It refers to a design issue that is not within the common expectation of the coders. In addition, the coding of "Surprising" also depends on the context, an utterance by itself cannot be coded as "Surprising", however within the context of the design situation, it might be "Surprising". Table 2 shows some examples of New and Surprising coding.

Table 2. Examples of New and Surprising coding when designing a device to aid a wheelchair bound person to reach and bring down items from higher level shelves

Utterance	**Coding**	**FBS Code**
We'll just have people reach across	New	Be

so, I guess we'll start with a rod	New	S
Just draw a little half bedded one	New	S
That's a circle. They can have like a wire	New	S
Like a surface of a basketball.	Surprising	S
yes… no… cool… big tweezers…	Surprising	S
like so kind of like on a dog leash	Surprising	S

Within the context of this study, “New” and “Surprising” are both derived from a traditional understanding of “novel” and “surprising” in other creativity studies. However, this protocol study focused on quantitative analysis of “New” and “Surprising” as a means to understand creative design processes. This articulation of the FBS model affords additional coding of the six design issues as “New” and “Surprising” without altering the original FBS coding scheme. Therefore, “New” and “Surprising” segments are structured chronologically, which can be analysed using standard protocol analysis techniques making it possible to identify creative design processes (Gero & Kan, 2016).

New and Surprising code distributions between the ENG and Non-ENG student cohorts are shown in Table 3. Instructions with examples of New and Surprising were provided to the coder. Following two rounds of coding and arbitration, agreement between the two rounds of coding and the final arbitrated version averaged 94.8%, which implies the coding results are reliable. This agreement is high by the standards of protocol coding and is due to the relatively small number of instances of New and Surprising codes. As a consequence, a further round of coding was executed following the arbitration sessions. The agreement between the third coding and the arbitrated results averaged 89.1%. Results show that high school students with engineering design education generated significantly more New design issues (average 13.7%, standard deviation 4.04%) during the design process than students with no engineering design education (average 10.1 %, standard deviation 4.19%). Similarly, high school students with engineering design education generated significantly more Surprising design issues (average 1.7%, standard deviation 0.73%).) than students with no engineering design education (average 1.0%, standard deviation 0.71%). From paired *t*-test analysis, there are significant differences in both New and Surprising between students with and without engineering design education.

Table 3. New and Surprising code distributions of ENG and Non-ENG cohorts and results of testing for differences.

		Overall	
		New (%)	Surprising (%)
ENG	Average (SD)	13.7 (4.04)	1.7 (0.73)
Non-ENG	Average (SD)	10.1 (4.19)	1.0 (0.71)
	p (ENG vs Non-ENG)	0.027*	0.001*

*$p < 0.05$

The results of a correspondence analysis of New and Surprising results of Engineering and Non-Engineering group are shown in Figure 3. Correspondence analysis describes the similarities of the data qualitatively and is used to explore the relationships between categorical variables. It does this by projecting the categories into high-dimensioned space and finding characteristics of that space that reduce the number of dimensions needed to cover the variance of the data in the categories. It then projects that into two dimensions, i.e., it is a form of dimensional reduction. In doing this the resulting dimensions are a consequence of the underlying processes and have no meaning within the context of the categories. Correspondence analysis suggests how similar the variables are at the categorical level, which is an effective method for exploring relationships between variables (Greenacre, 2007).

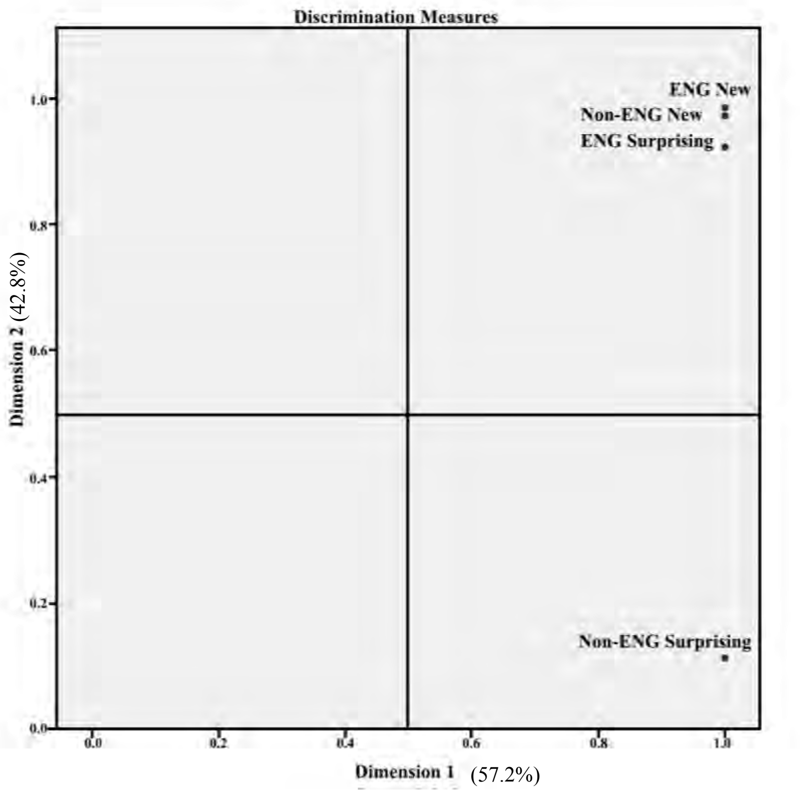

Figure 3. Correspondence analysis of New and Surprising codings of Engineering (ENG) and Non-Engineering (Non-ENG) groups.

From Figure 3 we can see that New design issues both Engineering and Non-Engineering groups sit in the same quadrant, while Surprising design issues for Engineering and Non-Engineering groups sit in different but adjacent quadrants. This suggests that at the categorical level, new issues for both the ENG and Non-ENG groups is similar, while surprising issues for the two groups are different at the categorical level. The differences of "surprising" issues between the two groups may be because engineering design education is potentially beneficial for generating unexpected ideas, not only quantitively, but also qualitatively.

Dividing the duration of design sessions into halves can reveal temporal distinctions between the design cognition at the early and late stages of a session. In this study, the division is based on the number of segments. Although there are potential limitations associated with dividing design sessions this way due to possible differences in design style, for example, individual designers may totally abandon initial ideas and start from the beginning, this situation was not evident in the current study. The distributions of New and Surprising codes for the two groups for the first and second halves of their design sessions are shown in Table 4.

Table 4. New and Surprising code distribution for ENG and Non-ENG groups for first and second halves of design sessions.

			New (%)	**Surprising (%)**
First Half	ENG	Average (SD)	19.4 (5.89)	2.7 (1.49)
	Non-ENG	Average (SD)	13.3 (4.96)	1.5 (0.93)
Second Half	ENG	Average (SD)	8.2 (3.36)	1.0 (0.83)
	Non-ENG	Average (SD)	6.8 (4.40)	0.5 (0.70)

Results of paired *t*-tests, Table 5, indicate there was a significant difference in New instances between first and second halves of the design sessions within each group. There were insufficient Surprising instances in some of the data when design sessions were divided into halves, so it was not possible to carry out significance testing of Surprising instances. However, results revealed that in both first and second halves of the design sessions, there were significant differences ($p<0.05$) in New instances between ENG and Non-ENG groups;

and for the first halves there were significant differences between the ENG and Non-ENG groups.

Table 5. Testing New code distributions between first and second halves of design sessions.

		p (New)
First half vs. Second half	ENG	0.000*
	Non-ENG	0.001*
ENG vs. Non-ENG	First half	0.01*
	Second half	0.301

*$p < 0.05$

The correspondence analysis of New and Surprising coding of Engineering and Non-Engineering group in halves is shown in Figure 4. From the results in this figure, we can see that for New coding, ENG and Non-ENG are different in both first half and second halves of the design session in one dimension only, i.e., they sit in adjacent quadrants. Within the dimensions generated by the correspondence analysis the ENG and Non-ENG halves lay on opposite sides of Dimension 1, implying a categorical difference not evident in the whole sessions in Figure 3. Within the Non- ENG group, the first and second halves are dimensionally close to each other. However, for the ENG group, this result is different. This means that for Non-ENG group, categorically there are fewer differences in terms of producing new ideas in the first and second halves of the design session; for the ENG group the results indicate the opposite. For the Surprising coding, the first and second halves are very similar within the ENG group but for the Non-ENG group they are different. This means for that for the ENG group, Surprising design issues are categorically similar for both the first and second halves of the design session while for the Non-ENG group the opposite holds.

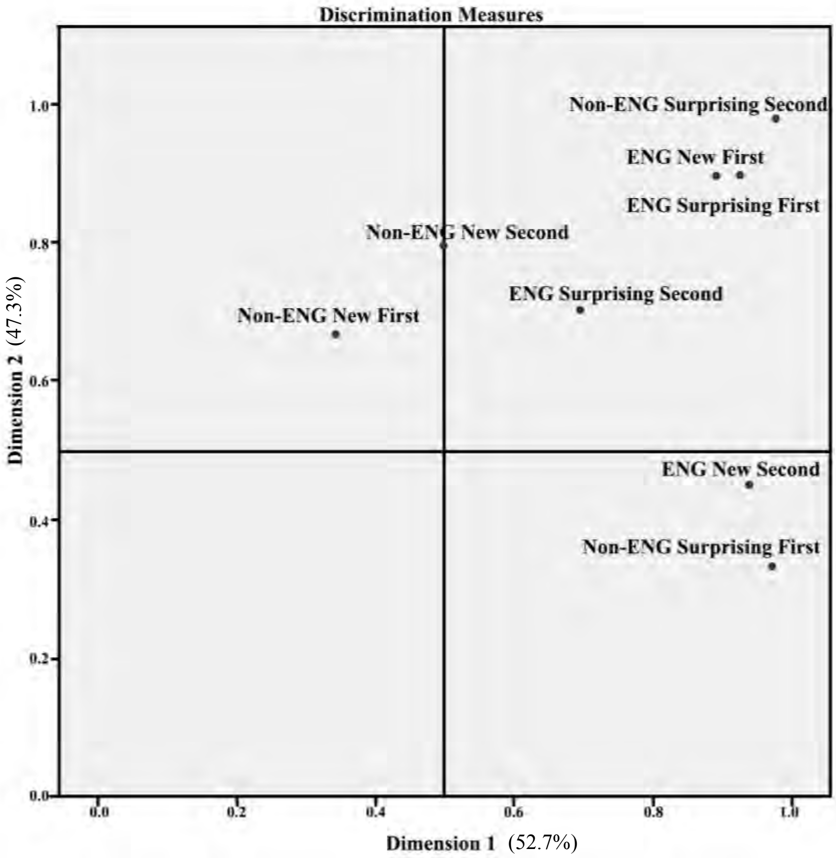

Figure 4. Correspondence analysis of New and Surprising codings of ENG and Non-ENG group in halves

The average New coding distributions in FBS design issues for ENG and Non-ENG group are shown in Figure 5 and Table 6. From the table and figure, we can see that the Engineering group has more New coding in Be, Bs, and S. Paired sample *t*-test indicate that there are significant differences of New coding in Be and Bs between Engineering and Non-Engineering group. This suggests that engineering training potentially assists in producing new ideas related to setting up design goals (Be) and considering ways of achieving design goals (Be), as well as examining existing design (Bs).

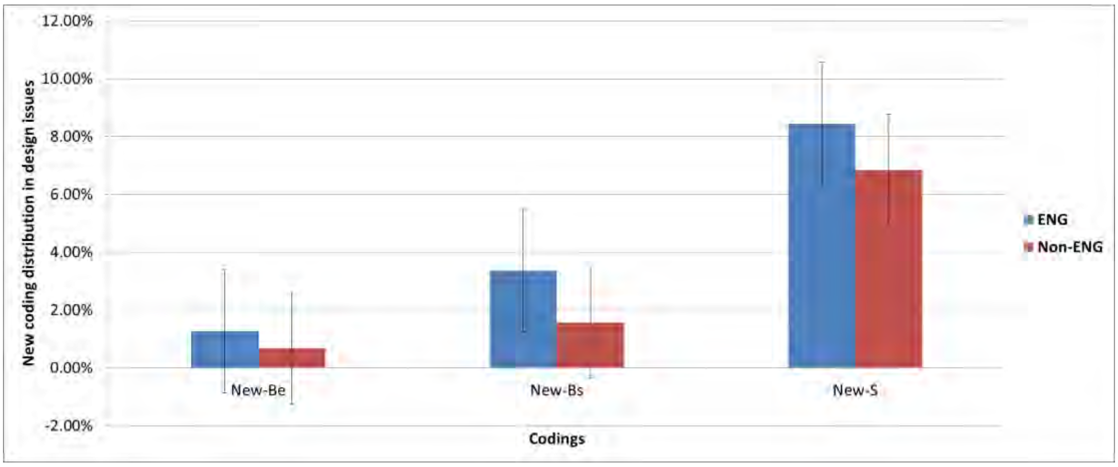

Figure 5. ENG and Non-ENG New coding distributions as a percentage of all FBS design issues

Table 6. Average New FBS design issues as percentage of all design issues

		New-Be (%)	New-Bs (%)	New-S (%)
ENG	Average (SD)	1.3 (0.79)	3.4 (1.20)	8.4 (3.08)
Non-ENG	Average (SD)	0.7 (0.52)	1.6 (0.31)	6.9 (4.61)
p		0.0070*	0.0006*	0.3031

*$p < 0.05$

Figure 6 and Table 7 present the proportion of each New design issue category as a percentage of all New design issues. Since the number of R, F, D instances are too small, we classified the total number of these three codings as "Others". From the figure and table, we can see that in terms of proportion, Engineering and Non-Engineering groups are very similar in Be and others. However, there are many more New coding in Bs in the Engineering group than the Non-Engineering group. This suggests that in all the New codings produced, the Engineering group shows more time spent in examining the existing design and less time working on the actual structure. This potentially indicates from the Engineering training, there are more evaluation criteria for judging design were taught, which results in more examining of the existing design.

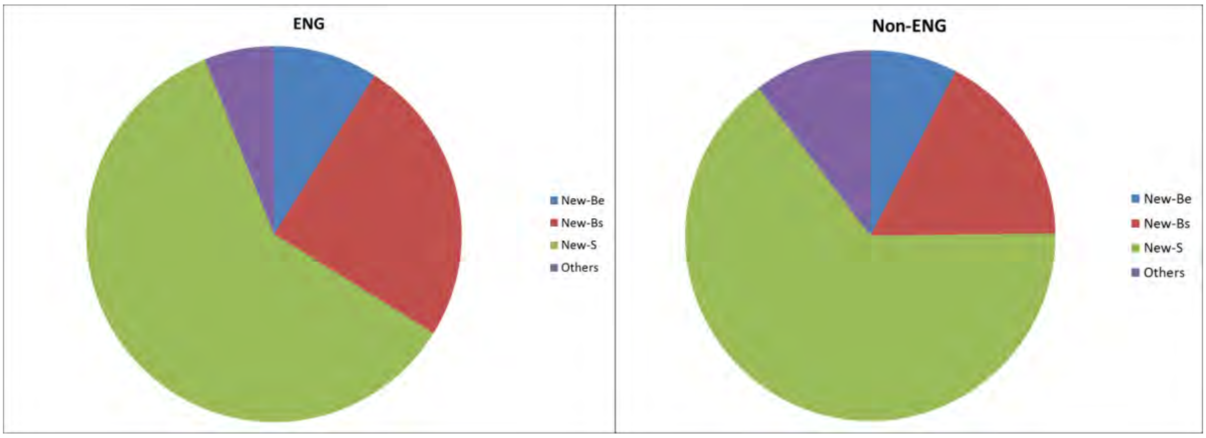

Figure 6. Proportion of ENG and Non-ENG New coding distributions in design issues

Table 7. Average New FBS design issues as a percentage of all New design issues

		New-Be (%)	New-Bs (%)	New-S (%)	Others (%)
ENG	Average (SD)	9.0 (5.03)	24.8 (8.63)	60.1 (9.31)	6.0 (7.08)
Non-ENG	Average (SD)	7.7 (5.52)	17.2 (4.96)	64.9 (11.67)	10.3 (12.45)
p		0.3045	0.0049*	0.3496	0.1672

*$p < 0.05$

The average normalized cumulative occurrences of all New design issues are shown in Figure 7. From the figure we can obtain qualitative results about rates on issue generation. We can observe that during the whole design session New design issue generation occurs at a slightly faster rate in the ENG group than Non-ENG group. At the beginning of the design session New design issues are generated at a faster rate in the ENG group, this trend continues until two-thirds of the way through the session. At the end of the design sessions, the generation of New design issues is slower in the ENG group than Non- ENG group.

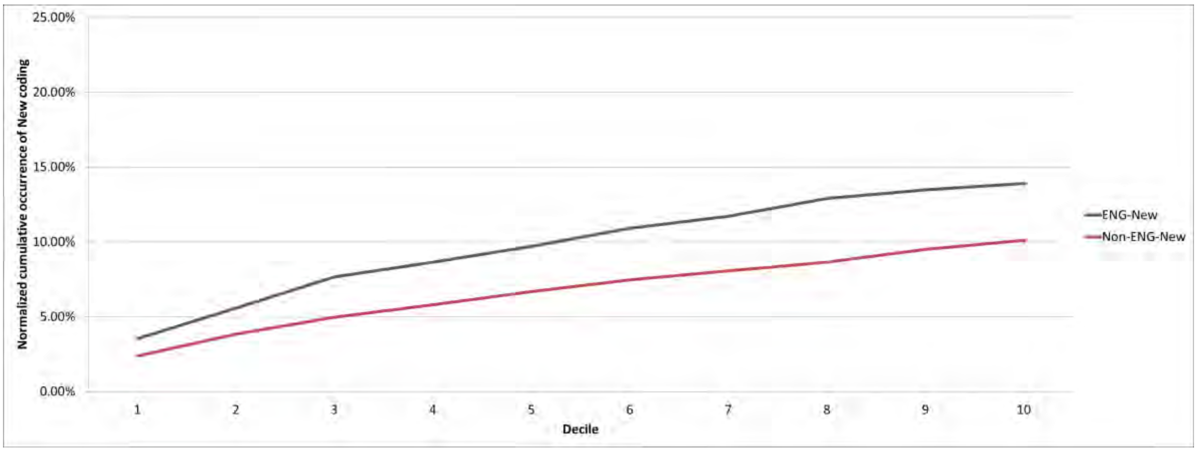

Figure 7. Average normalized cumulative occurrences of New design issues shown in deciles

7. Analysis of Results

The analysis of results presented in the previous section indicates that for FBS design issues there are no significant differences over the whole design session. However, the numbers of New and Surprising design issues show differences between those of the high school students who had received the PLTW engineering design education and those who had not.

This implies that the measures of New and Surprising design issues are separate from the FBS measures. We are therefore able to use these two measures to discriminate in ways that the FBS coding alone does not. In so doing data analysis reveals there are significant differences in both New (p=0.027) and Surprising (p=0.001) design issues between students who received engineering design education and those who did not. For this study, this suggests that engineering teaching has the potential to foster student development of New and Surprising ideas.

Furthermore, for both groups there are more New instances in the first half of the design sessions than the second, and with very low p values (0.000 and 0.001) implying strong significant differences. That most of the New ideas are generated in the first half of design sessions reflects a logical expectation of designers as they progress through a design session where occurrences of New and/or Surprising ideas steadily decrease the closer they come to finalizing their solution and concluding their design description. An important finding of this research is that in the first half of the design sessions there are significantly more New design issues (p=0.01) produced by those students who received engineering teaching than those students who had no engineering teaching.

For New segments there are no categorical differences between ENG and Non-ENG groups across the entire design sessions, while differences are found for Surprising design issues. However, there are dimensions uncovered through correspondence analysis where categorical differences in halves can be found. This suggests that engineering training is important for students to generate surprising/unexpected ideas from various perspectives. From the New design issues distribution analysis, we can infer that there are more New design issues related to Be (p=0.0070) and Bs (p=0.0006) in the ENG group, which means that engineering training potentially assists students with setting up and exploring ways to achieve design goals. Furthermore, the ENG group generated new design issues faster than Non-ENG group.

8. Discussion and Conclusion

As previously suggested from the results in the earlier engineering cognition research (Wells et al., 2016), the teaching of engineering design received by participating high school students did not significantly affect their primary design cognition. Given that a fundamental goal of teaching engineering design is to effect a change in students' engineering behaviour and design thinking, this result was unexpected. However, detected within those results were small differences in the vernacular exhibited by novice designers in both control and experiment groups. To investigate this further, the original data were analysed further using two augmented codes (New and Surprising) as measures of design creativity. Revealed through this analysis were significant differences in creative design cognition while engaged in the design process between students who had received engineering teaching and those who had not. From this research, the following conclusions can be drawn:

Firstly, the augmented FBS coding scheme can be used to distinguish creative design cognition between students with and without design education. The augmented coding scheme contains two additional design cognition codes “New” and “Surprising”, besides the original FBS coding scheme. Results demonstrate that these two new design cognition codes can capture the creative instances during design process.

Secondly, temporal differences in creative design cognition have been identified. “New” and “Surprising” moments are captured and differences are found among participants’ design processes. A greater degree of creative design issue generation was found to be expressed at the beginning of these design sessions, which tended to decrease steadily as pairs progressed through a design session. This suggests that temporal differences in creative design cognition can be revealed by applying this method.

Thirdly, differences in temporal creative design cognition are found between students with and without engineering design education. The generation of new ideas is faster with students having engineering design education. These results suggest that the teaching of engineering design to high school students plays an important role in fostering development of design creativity. Moreover, these results imply there are direct relationships between elements of pre-engineering curricula, educational environments, and instructional strategies that promote the creative capacity requisite to student development of designerly thinking.

Considering results from both the original research and this extension, teaching of engineering design to novice designers at the high school level does appear to foster creative design cognition and their capacity for design thinking, if these results are generalizable. With respect to the teaching of high school engineering design, these results show promise for informing the design of instruction. At the secondary school level, technology and engineering education classrooms and teachers are instrumental in providing the unique learning environments and instruction needed to foster creative student behaviours (Lewis, 2005).

The results of this research are necessarily limited. Firstly, engineering training provided to participants in this study is through specific courses from one particular high school pre-engineering program: PLTW. Differences in the teaching of course content may have different effects on individual learning outcomes. Secondly, this research is focused on creative design processes, and the creativity of design product was not measured. Creative design processes do not necessary lead to creative products. However, it will be meaningful to conduct correlation analysis in a future study, to explore if design education is beneficial for producing creative design outcome. Thirdly, “Surprising” coding is depending on the coders’ common expectation, which may vary between coders with different backgrounds. However, the surprising examples have been discussed between coders with the aim of ensuring a consistency of coding. Fourthly, given the sample size it was not possible to determine if different design styles of individuals may have an effect on the results. For instance, designers who take a systems approach, which produces more levels of hierarchies, are more likely to have “New” design decisions than the ones who take a holistic approach. Also, a designer who carries out numerous generate and test cycles would have a different distribution than someone who commits early. One of the future directions for this work is to connect “New” design instances with system based engineering design, associated with problem decomposition and recomposition (Song et al., 2016). Another direction in the future is to explore the correlations between the creativity of design outcome and “New” and “Surprising” occurrence during the design process.

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