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CREATIVE DESIGN COGNITION DIFFERENCES BETWEEN HIGH SCHOOL STUDENTS WITH AND WITHOUT DESIGN EDUCATION

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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 dyads engaged in a design task captured both their design approach and their concurrent design conversation. Using the verbal protocol methodology, videos were coded using the Function-Behaviour-Structure ontology. 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. 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. Some discussions of design creativity have focused on the evaluation of the design product (Runco & Pritzker, 1999; Torrance, 1966). Others suggest exploring creativity during the design process (Rosenman & Gero, 1993; Suwa, Gero, & Purcell, 1999). 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. This study aims to explore the relationship between design education and the demonstration of creative design cognition by high school students.

The research described in this paper is an extension of a previously reported study (Wells et al., 2016) that 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

2.1. Measuring creativity of design product

Scholars from psychology, social science, architecture, engineering and industrial design have offered various definitions of creativity. According to psychologists Runco and Prizker, (1999), creativity is characterised as aesthetic appeal, novelty, quality, unexpectedness, uncommonness, peer-recognition, influence, intelligence, learning and popularity. 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.

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.

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 utility, 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 (Boden, 1990; Bruner, 1962; Gero, 1996; Maher, Brady & Fisher, 2013).

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.

Designing can be analysed through the way cognitive effort shifts between the consideration of problems and solutions (Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996). 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 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.

From a cognitive perspective, Bruner (1962) defined creativity as an act that results in "effective surprise" (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 is introduced into the design". 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 (Grace & Maher, 2015; Grace, Maher, Fisher, & Brady, 2015; Maher, Brady & Fisher, 2013; Maher & Fisher, 2012). In the coding process this is accomplished by identifying the number of 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.

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; Kan & Gero, 2017)), is conducted through application of coding schemes used to categorise unique variables within the data. The strength of such 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).

4. Augmenting the FBS Coding Scheme

Gero's Function-Behaviour-Structure (FBS) ontology (Gero, 1990; Gero & Kannengiesser, 2004) has been applied in many cognitive studies (Gero & Tang, 1999; Kan & Gero, 2005) because it is potentially capable of capturing most of the meaningful design processes (Lammi, 2011; Song, 2014) 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 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.

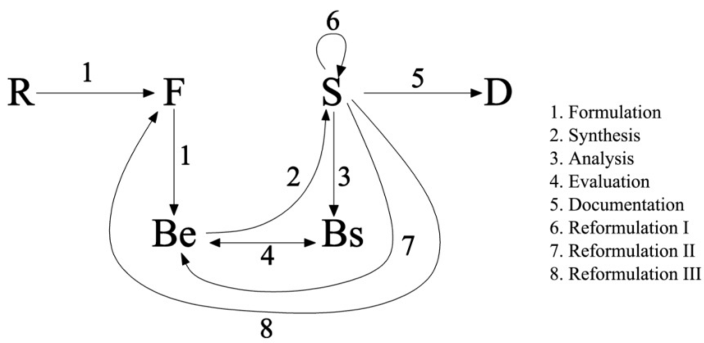

Figure 1. The FBS ontology of variables and processes (Gero & Kannengiesser, 2004)

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 and 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.

5. Experiment Design

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

5.1. Participants

Participants were drawn from a convenience sample of high school students in their senior (12th) year at mid-Atlantic high schools of similar population size offering the same Project Lead the Way – PLTW (PLTW, 2017) pre-engineering course sequence. Purposeful selection was used in assigning students to experiment and control groups (those with and without formal pre-engineering course experience respectively). Prior PLTW course experience for the experiment group ranged from one to two full years. 60% of the dyads were mixed-gender and within both experiment and control groups the gender distribution was approximately the same: 65% male and 35% female.

5.2. Procedures

Dyads were used because that configuration naturally promotes authentic verbal exchanges during collaborative development of acceptable engineering design solutions (Kan & Gero, 2009; Kan & Gero, 2017; Purzer, Baker, Roberts, & Krause, 2008). The design task presented to each dyad was that of designing a solution to assist wheel-chair bound individuals with accessing objects located on shelves in an overhead cabinet, with 45 minutes allowed to produce a design solution. Full details can be found in Wells, et al. (2016). The source data was captured using two video cameras arranged at different vantage points during each design task session. Both students in a dyad wore a high-sensitivity Lavalier wireless microphone. Each recording afforded 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 dyad 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 is treated as a code and 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 a given transcript, coders would meet to arbitrate a final coding. Coding reliability is measured against the final arbitrated version so the standard inter-coder reliability as measured but 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. The publicly available software LINKODER (www.linkoder.com) was used to analyse the data and to generate descriptive statistics and probability analyses of the design sessions.

6. Results for New and Surprising

Results from the original research suggest that students' design cognition is not significantly affected by the design education provided (PLTW) in terms of design issues distributions, as shown in Table 1 (Wells et al., 2016), where the students who had 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 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	3.48	1.45	5.34	34.40	44.42	10.91
	SD	2.01	0.65	2.14	4.74	5.18	5.42
Non-ENG	Average	4.32	2.03	6.88	33.46	44.07	9.25
	SD	2.93	0.97	2.42	6.43	6.31	3.80
	p	0.48	0.12	0.17	0.73	0.89	0.53

Recent research on creative design cognition has developed an augmented FBS coding scheme. 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). Here New means new to the design session and Surprising means unexpected within the context of the design being proposed.

Table 2 shows the results of New and Surprising code distributions between the ENG and Non-ENG student cohorts. Two rounds of coding and arbitration were conducted. Agreement between the two rounds of coding is averaged 94.8%, which suggests the coding results are reliable. Results show that high school students with design education generated significantly more New design issues (average 13.67%, standard deviation 4.04%) during the design process than students with no design education (average10.10 %, standard deviation 4.19%). Similarly, high school students with design education generated significantly more Surprising design issues (average 1.72%, standard deviation 0.73%).) than students with no design education (average 0.98%, standard deviation 0.71%). From paired t-test analysis, there are significant differences in both New and Surprising between students with and without engineering training. There are significantly more New structure behaviour (Bs) design issues and more Surprising structure (S) design issues for the ENG than the Non-ENG students.

Table 2. New and Surprising code distributions of ENG and Non-ENG cohorts and results of testing for differences.

		Overall		**Bs**		**S**	
		New (%)	Surprising (%)	New (%)	Surprising (%)	New (%)	Surprising (%)
ENG	Average	13.67	1.72	3.32	0.12	8.14	1.14
	SD	4.04	0.73	1.19	0.17	3.27	0.53
Non-ENG	Average	10.10	0.98	1.57	0.10	6.84	0.67
	SD	4.19	0.71	0.32	0.15	4.70	0.58
	p (Eng-Non-Eng)	0.027*	0.001*	0.001*	0.744	0.397	0.037*

*$p < 0.05$

Dividing design sessions into halves can reveal distinctions between the design cognition at the early and late stages of a session. Table 3 shows the distributions of New and Surprising codes for the two groups for the first and second halves of their design sessions.

Table 3. 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	19.39	2.72
		SD	5.89	1.49
	Non-ENG	Average	13.30	1.47
		SD	4.96	0.93
Second Half	ENG	Average	8.21	1.03
		SD	3.36	0.83
	Non-ENG	Average	6.84	0.48
		SD	4.40	0.70

Results of paired t-tests, Table 4, 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 for the first halves between the ENG and Non-ENG groups.

Table 4. 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

*$p < 0.05$

7. Analysis of Results

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 segments show differences between those high school students who had received the PLTW engineering design education and those who had not.

This implies the measures of New and Surprising design segments are orthogonal to 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). That most of the New ideas are generated in the first half of design sessions reflects a logical expectation of students 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. However, central to this research is that in the first half of the design sessions there are significantly more (p=0.01) New ideas produced by those students who received engineering teaching than those students who had no engineering teaching.

8. Discussion and Conclusion

As previously suggested in results from the original 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 again analysed using two augmented FBS 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. Furthermore, a greater degree of creative design thinking was found to be expressed at the beginning of these design sessions, and which tended to decrease steadily as dyads progressed through a design session. 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. Specifically, the research implications are that teaching engineering design to novice high school designers supports their construction of a repertoire of cognitive relationships leading to the development of creative design cognition and a capacity for design thinking. With respect to the teaching of high school engineering design, these results show promise for informing the design of instruction and improving critical pedagogical practices. 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).

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