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CONCEPT GENERATION AND SKETCHING: CORRELATIONS WITH DESIGN OUTCOME

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ABSTRACT

Design outcome is influenced by many hard-to-measure factors in the design process. This paper examines four of these factors to understand their possible correlation with design success. First, is the quantity of design concepts linked to design outcome? Second, is the timing of concept generation associated with design outcome? In both of these cases, the sketches created by designers were taken as evidence of concept generation. Third, is the type of sketch linked to design outcome? And finally, what is the role of a novice designer's prior experience in design outcome? Statistically significant correlations were found between dimensioned drawings generated at the early stages of design and design outcome, and also between a novice designer's prior fabrication and building experience and design outcome. Ultimately, the goal of this research is to develop paradigms for appropriate graphics- and text-based information tools for design.

INTRODUCTION

There are numerous qualitative factors in the design process that can contribute to a design's success or failure. These factors can be difficult to isolate and are further challenging to quantify. This paper investigates four factors and their potential correlation with design outcome.

The first of these factors is the quantity of design concepts. Does the quantity of ideas generated in the design process lead to a better design outcome? According to Osborn [1], brainstorming a larger number of ideas at the beginning of a process will lead to a better resulting idea at the end of the process. By broadening the initial pool of ideas, "quantity yields quality." This practice has been widely adopted in product design and development in industry. Kelley and Littman [2] hold that generating more ideas through brainstorming leads to more creative design solutions. In this paper, concept generation is observed through the sketches created by designers.

The second factor considered is the timing of concept generation. Designers may form ideas throughout the design cycle. Do concepts generated earlier or later on in the design cycle have a greater effect on design outcome?

Since this work focuses heavily on sketching as a representation of design thought, the third factor relates to the role of sketch type in design outcome. Sketches in this study are divided into two categories: dimensioned drawings, and non-dimensioned drawings.

Finally, what is the value of engineering and non-engineering experience on design outcome? It would be expected that more engineering experience would correlate with better design outcome. However, novice designers by definition lack this experience. What skills and abilities do less experienced designers bring to bear that would aid them in designing successfully?

These questions are significant in the context of design theory and process both in the classroom and in engineering design practice. By better understanding design factors that may affect design outcome, approaches and tools may eventually be developed to facilitate better design.

RELATED WORK

The capture and analysis of design activity is an ongoing research problem within the design community. Much effort has been placed on the protocol analysis of design activity in which designers themselves explain their activities either as they work or after the work is complete [3-8]. Work has also been done in the post-facto analysis of textual information generated by designers [9-11], understanding how they handle information, how to make sense of that information, and how to retrieve that information for reuse.

Other work has focused not only analyzing design activity itself but in linking design activity with design outcome. Both Mabogunje and Leifer [12] and Dong, et al [13] have investigated the association between textual design documentation and team design performance. Dong, et al in particular have found correlations between textual design information coherence of design teams and design outcome. This paper builds on that work and adopts a similar correlation approach for linking concept-related characteristics of design documentation with design performance.

Much work has been done connecting design activity with the act of sketching. Ullman, et al. [14] demonstrate the importance of sketching as a way for designers to represent their design thinking. Goel [15] argues that sketching is critical to capturing the ambiguity inherent in design activity. Suwa and Tversky [16] suggest that designers are able to understand different aspects of a design only through sketching them. The link between designing and visually representing artifacts through sketches and prototypes has been discussed in depth by McKim [17] and Schon [18]. One of the most common activities that takes place during the early stages of design is sketching and prototyping the artifact to be designed. McKim maintains that the ability to think visually is a necessary skill for developing innovative solutions. It has been suggested that the reinterpretation, or perhaps iteration, of a sketch is evidence of the occurrence of new conceptual design knowledge [19]. Observations of industrial practice suggest that design success is further a product of realizing an idea through drawing and prototyping [20].

METHODS

Test bed

The test bed for these experiments was a project-based design course at Caltech comprised of twenty-four students, all upper-level engineering majors. At the beginning of the intensive 10-week course, students were presented with an open-ended, ill defined design challenge: design and build an electro-mechanical robot device for a variation of "capture the flag." Each student designed a device on paper and then fabricated a fully functional prototype in the mechanical engineering machine shop. A final prototype of such a device in shown in Figure 1. At the end of the quarter, the student teams competed against each in a double elimination contest held before the entire campus. A single winner emerged. Students competed in teams of two, but design work and hardware fabrication were performed individually.

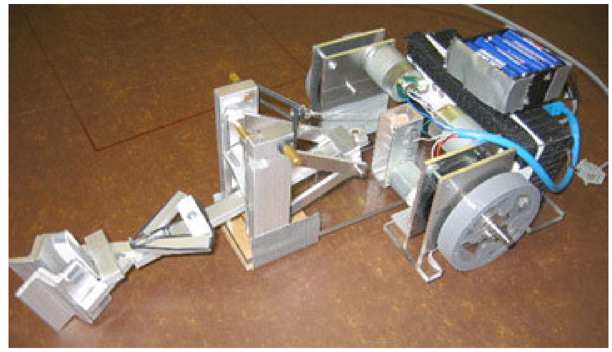

Figure 1 Electromechanical design project

Design Data

The primary source of design data was the paper-based design logbooks kept by students throughout the 10-week term. The resulting information in the logs took a wide range of forms including prose descriptions of their work, detailed process plans for fabrication, a few equations and sketches of many types and levels of detail.

Each individual drawing in each notebook was counted and indexed by date and by type. As with any informal information, there is ambiguity as to what constitutes an individual drawing, and the goal was to be consistent between logbooks. In most cases, however, distinct objects were obvious because of white space separation and/or annotation of the sketch.

It should be noted that this research did not normalize for a student's drawing ability or previous drawing experience. It is certainly possible that the number of sketches produced by a designer was higher or lower simply because of the designer's facility in sketching. It might be possible for a prolific and fluent sketcher to produce many sketches but develop a poor design. Likewise, a sketching-shy designer might still be able to create a good design.

Furthermore, sketch quality was not considered in this analysis. Notions of good and bad sketching are not only difficult to judge, but irrelevant to the questions being investigated. The focus is entirely on sketch quantity.

Although in most cases it was clear what mechanical component a particular drawing was intended to represent (for example, a wheel or gear), no effort was made to keep track of the meaning of each sketch. A record was kept of what will be termed *dimensioned* drawings. Dimensioned drawings differed from other sketches in that they include numeric labels for parameters such as length, width and diameter. Such drawings may be interpreted as a step towards making a design more concrete by understanding how parts will fit together spatially or how a part should be manufactured. It is believed that the presence of these dimensioned drawings indicate the act of making a design more concrete, literally to prepare a design for fabrication or at least understand more definitively a design's spatial constraints. In other words, it is suggested that dimensioned drawings differ from non-dimensioned drawings because they are evidence of advanced realization and three-dimensional prototyping.

The second source of design data was morphology charts. Morphology charts describe alternative embodiments to fulfill a device's functions [21]. The quantity of embodiment alternatives is equated with the number of device concepts. During the first third of the term, each student developed a chart of the desired functions of their device, along with possible approaches to achieving those functions. For example, if the desired function was to "block an opponent," ways to achieve that goal might be to "drive into the opponent," "push the opponent," and so forth. Note that morphology charts only illustrate aspects of a design, but do not directly refer to whole, distinct design concepts.

Finally, to understand the role of experience in design outcome, students completed questionnaires detailing past experience in engineering and design. They were asked to rate themselves on a scale of 1 to 5 on skills that they had likely acquired in school, such as engineering analysis, fabrication and intuition. Non-engineering experience received outside the engineering classroom including sketching, model building or arts-and-crafts projects was also noted.

Design Outcome Evaluation

Two indicators of design outcome were employed in these experiments. The first was the final grade in points for each student. The maximum number of points possible was 100, and was based on overall performance over the 10-week period.

The second indicator was each team's performance in the contest. This performance was based on the total number of wins and losses. It should be noted that contest performance was decoupled from the final grade itself. There are several reasons for those, including the fact that the primary goal of the class is to teach design and design process, not robot competition skills. In addition, the contest produces in a ranking of contestants, which would inherently impose a grading curve. Because of this decoupling of grade and contest performance, it was possible for a team to perform poorly in the contest but earn a good grade, and likewise do well in the contest but earn a poor grade. paper here.

RESULTS & DISCUSSION

Quantity, Timing, and Type of Sketching

The overall quantity of sketching over time is plotted in Figure 1. The lower section of each column represents the average number of dimensioned drawings by time, and the entire column height shows the average number of total drawings for all students.

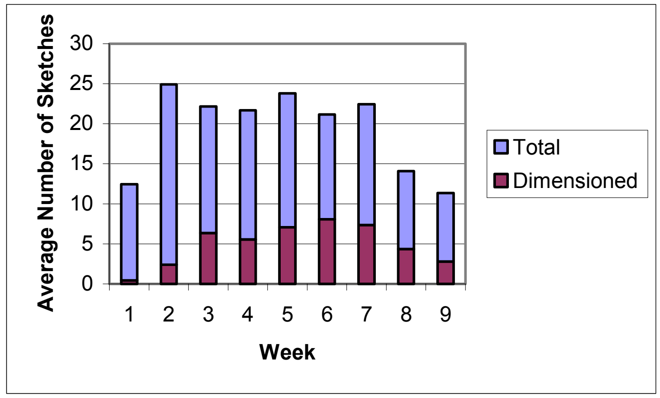

Figure 2 Average weekly total and dimensioned sketches

There are two notable trends in this graph. The first is that there is a proportionately greater number of total drawings during the first part of the term as compared to the remainder of the term. This is in contrast to the lack of dimensioned drawings at the very beginning of the term compared to the remainder of the period. Taken together, these trends indicate abstract conceptual design activity early in the design cycle and more prototyping in the later stages of the design cycle.

The Spearman Ranking Correlation [22] for nonparametric populations was employed to test for correlations between design data and design outcome. The Spearman correlation coefficient R_s is computed in Equation 1:

$$R_s = 1 - \frac{6 \cdot \sum_{i=1}^{N} d_i^2}{N^3 - N} \quad (1)$$

where N is the number of individuals and $d_i = X_i - Y_i$. X and Y are the ordinal rank of the variables being correlated, in this case design data and design outcome. R_s has a value between –1 and 1. If $-1 < R_s < 0$, there is a negative correlation between the two data sets. If $0 > R_s > 1$, there is a positive correlation. For a population N = 24, if the correlation coefficient R_s is not only positively correlated, but exceeds 0.343, it is considered statistically significant for a significance level, or a probability of error, of $\alpha = 0.05$.

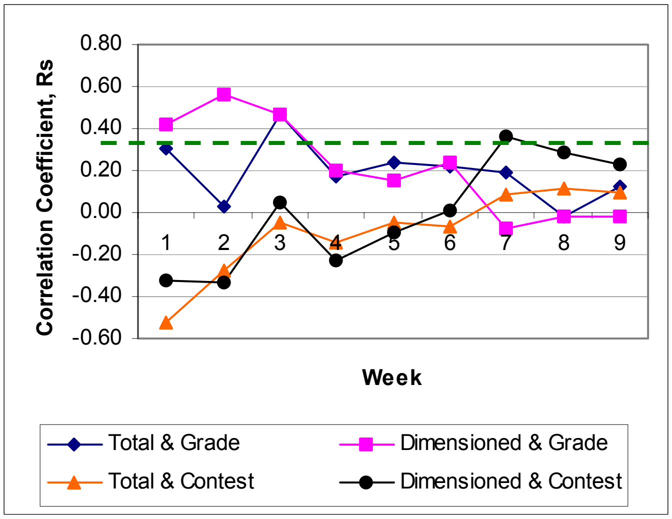

Figure 3 Average weekly sketch output, total and dimensioned, correlated with grades and contest results

Figure 3 plots coefficients R_s for the average total sketches and dimensioned drawings per week correlated with final grades and contest performance over the course of the term. The threshold value for statistical significance is indicated by the dotted line. The graph shows that dimensioned drawings and final grades are positively correlated in a statistically significant way during the first three weeks of the design cycle. The total number of drawings is also positively correlated with during the third week. Furthermore, the quantity of dimensioned drawings correlates significantly with contest performance in week 7. This result is notable because it suggests that the creation of more concrete dimensioned drawings early on in the design cycle does indeed have a positive effect on design outcome.

Interestingly, the correlations with grades tend to decrease over time, while the correlations with contest performance tend to increase steadily over time. This suggests that grades are affected by design effort early in the design cycle, while contest performance is affected by "last minute" efforts.

	CORRELATION COEFFICIENT R_S	
	GRADE	CONTEST
Morphology alternatives	0.16	-0.17

Table 1 Correlation with morphology alternatives

Table 1 shows the results of Spearman Ranking Correlation between the quantity of morphological alternatives with both final grades and contest performance. The number of alternatives reported ranged from 10 to 105 alternatives, with an average of approximately 28 alternatives. Here, N = 20 because of some data unavailability, so for a significance level $\alpha = 0.05$, R_s must be greater than 0.377. The number of morphology alternatives do not correlate positively with either grade or contest performance. This may be explained by the fact that morphology charts are not complete design concepts but rather distinct aspects of design concepts.

	CORRELATION COEFFICIENT, R_S	
	Grade	Contest
ENGINEERING SKILLS		
Engineering analysis skills	-0.03	0.21
Engineering fabrication skills	**0.42**	-0.32
Engineering intuition	0.20	-0.51
EXTRACURRICULAR EXPERIENCE		
Drawing or sketching	0.20	-0.12
Model building/arts & crafts	0.31	-0.16
Taking apart things/tinkering	0.16	-0.21
Construction, machining	0.11	-0.09

Table 2 Correlation of experience with grades and contest results

Finally, the role of experience of a novice designer is examined. The first three categories of experience in Table 2 focus on engineering-related skills including the ability to solve engineering problems analytically, the ability to fabricate and build in the machine shop and the innate grasp of engineering problems. The second set of categories considers extracurricular experience that might affect design outcome. Examples include a background in drawing or sketching, model building and arts & crafts, tinkering and construction. For N =24, R_s must be greater than 0.343 for a significance level of $\alpha = 0.05$. The table above shows that there is a statistically significant correlation between engineering fabrication skills and grade (in bold), but not contest performance. At first glance, this seems like a non-intuitive result. A student who fabricates a good device should do well grade-wise as well as in the contest. However, there are important elements in a contest that have nothing to do with fabrication skill, such as a participant's ability to drive his or her device with radio-controlled joysticks. Furthermore, there is positive, but not significant, correlation between experience designing and building models/arts & crafts and grade.

CONCLUSIONS

Concept Generation and Sketching

Several questions were posed at the beginning of this paper. The first three of these were: Does the quantity of concept generation correlate with design outcome? Is the timing of concept generation associated with design outcome? And is the type of sketch linked to design outcome? This work suggests a relationship among these three questions. Concept quantity, as measured through sketches, is significantly correlated to design outcome, as measured by design grades, under two conditions. First, only sketch volume generated in the first quarter of the design cycle correlates significantly. Second, the sketches must include dimensions.

This suggests that prototyping earlier in the design cycle rather than later leads to better design grades, perhaps because starting fabrication earlier leaves more time for iteration and refinement of a design.

Interestingly, total sketching volume, including both dimensioned and non-dimensioned drawings, did not correlate with graded design outcome, which suggests that it is possible to produce copious drawings during the design process and still have an unsuccessful graded design. Likewise, it is possible for a designer to sketch very little and achieve a better design grade, as long as dimensioned drawings (and probably prototyping) are started at the very beginning of the design process.

Design Experience

The final question this paper poses is: what is the role of a novice designer's prior experience, both in engineering and outside of it, on design outcome? The only prior experience that correlated significantly with design outcome was engineering building experience. This result makes some sense because the course itself is heavily focused on the production of a working electro-mechanical prototype. As with any self-reported data, there is also room for inaccuracy due to under- or over-reporting of design experience and with ambiguity of the categories of experience.

Design Outcome

None of the quantities tested correlate significantly with contest results. This is interesting result because in several aspects, the contest simulates the conditions of real world design. While students were provided with as realistic a testing environment as possible throughout the term, the actual contest included technical issues that could not be replicated beforehand, such as electrical interference, as well as non-technical issues such as the stress and pressure experienced by contestants competing in front of a crowd. However, unlike the real world, a contest is an artificial construct. In real-world design, there is rarely a definite notion of winning or losing. What this result suggests is that "good" design activity may lead to a "good" design outcome in a closed environment, such as a class, but that it may not account for design performance in a real world situation, such as a contest, the open road or a competitive marketplace.

In summary, this paper seeks to answer the question about concept generation: Does quantity breed quality? The answer is yes, under certain circumstances. It depends on how quality is measured, and also on timing and the way ideas are expressed. In particular, the number of ideas generated at the early, conceptual stage of design, correlates significantly with design grades, but not with design contest performance. The impact of these findings could apply to design process in the classroom, and could be extended to design practice in industry. Generating many concepts is important, but these concepts must be generated early on, and they must be concretized.

FUTURE WORK

The greater impact of this work will be derived from the development of relevant design tools to facilitate design information handling. This work focuses primarily on sketching and does not delve into the importance of text in logbooks. However, there exists a related body of research in textual design information analysis [5, 9, 10] as well as work in electronic sketch capture [23]. Furthermore, this work focuses on largely individual design efforts, but in real-world design situations, products are often the end result of collaborative team effort. There is relevant research in the area of electronic design notebooks [24-26], particularly for design team collaboration. Future work may focus on integrating aspects of all of these research areas to produce cohesive design team tools for improved design outcome.

These studies were based on sketches found in paper-based design notebooks. Work in developing computational tools to facilitate, or even promote, concept generation may provide at least the same level of usability and critical affordances as existing notebooks. This includes features such as portability, ease of sketching, and seamless integration with text tools. Some of these attributes have been noted in the other research in design notebooks noted above and in [14]. In addition, these tools need to allow ease of annotation of design sketches with rough dimensions and notes. More formal methods for visualization, such as CAD systems, are appropriate for representing later stage designs, but at the conceptual stage, the goal is to encourage agile, unimpeded concept generation.

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