THE EFFECT OF EMPLOYING DIFFERENT DESIGN METHODS ON THE DESIGN COGNITION OF SMALL DESIGN TEAMS

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ABSTRACT

This paper presents the results of comparing the design cognition of 10 design teams, each composed of two students, when employing different design methods while they design assistive technology devices. The design cognition of the teams of designers is obtained from protocol analyses of two sets of design sessions. In one set, the designers use brainstorming, and in the other, morphological analysis as the ideation technique. The protocols are segmented and coded using the Function-Behaviour-Structure coding scheme. This produces the sequence of the design issues for each protocol. These are then analysed for rate of design issue production and the rates for the two sets compared. The results from using the Function-Behaviour-Structure coding scheme can be compared even when the designers are working with different designs. The preliminary results reported in this paper show that there are statistically significant differences in the design cognition of the designers when utilizing these two design methods. Some of these results are in line with expectations from the design methodologies being used. In addition, we report some unexpected results that need to be further investigated with more specific empirical studies.

1. INTRODUCTION

The Ninth Design Thinking Research Symposium set the following generic brief:

> "11% of the world's 6.9 billion people are over 60. By the year 2050 that figure will have doubled to 22%. If we are to support a growing number of older people we need to produce products, spaces, and services that allow them to stay healthy and well in and around their own home. You are asked to design a domestic product, living environment, or service for older people that surpasses conventional expectations."

Within that brief two existing briefs for the design of assistive devices were used to study the effects of employing different design methods on the design cognition of small teams. The experiment described in this paper was used to test hypotheses about the effects of using two different design methods while designing. The two design methods were brainstorming and morphological analysis.

Brainstorming is an unstructured, freeform concept generation technique targeted at stimulating the rapid production of ideas [1]. Aside from a few rules geared towards suspending one's

judgment of the feasibility of concepts presented until after the exercise is completed, there is little other structured guidance. In brainstorming, groups of participants are encouraged to engage in rapid idea generation, by presenting all ideas (including those that may be infeasible) and by building off teammates' ideas [2]. Different structures and communication techniques have been suggested for brainstorming sessions but the essence of all is to generate as many ideas as possible in a short period of time. The ideas are then to be classified and used as alternative solutions. It is claimed that the chances of potentially useful ideas showing up in a larger collection are higher than in a small collection of ideas. Brainstorming techniques rely on this claim to raise the quantity, as well as the quality of the ideas generated by randomly exploring the solution space [1].
Morphological analysis, on the other hand, provides a much more structured framework for concept ideation. Morphological analysis is centred on the idea of decomposing a larger problem into a list of needed features or functions [3], known as sub-problems. Once the problem is decomposed, potential solutions for each sub-problem are ideated. These solutions are then organized in a morphological matrix [4] 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. As opposed to brainstorming, morphological analysis is centred on ideation by first abstracting the core of a product's functionality.

Given the differences between the two techniques, the following four commonly held hypotheses, derived from the structure of the respective methods, regarding their impact on design behaviour were put forward and evidentiary support for them was sought:

1. As morphological analysis is focused in promoting concept generation through functional abstraction, designers will discuss design issues related to a product's expected behaviour more frequently than they would using brainstorming.
2. Similarly, designers using morphological analysis would spend less time relatively in a design session discussing issues related to the structure of a product than those designers using brainstorming.;
3. As morphological analysis asks a designer to evaluate compatability and feasibility amongst the functional concepts, we expect a higher frequency of an analysis design process than those using brainstorming.
4. Because morphological analysis has a prescriptive means of capturing concept ideation in a matrix, we expect its users to display more of a description design process than those using brainstorming.

The remainder of the paper outlines the experiment design, which uses the protocol analysis method and presents and discusses the results in terms of the four hypotheses along with some unexpected results.

2. EXPERIMENT DESIGN

2.1 The Participants

The experiment described in this paper is a within-subject study with students from the senior capstone design sequence in the mechanical engineering (ME) department of a large mid-Atlantic land grant university. This two-semester sequence features teams of students working on large-scale design problems that culminate with a functional product. In class the design projects range from national design competitions (e.g., Formula SAE, ASEE Model Design) to faculty-sponsored projects (e.g., design of a small scale wind turbine, design of a robotic humanoid hand).

In the first semester of the sequence, students attend a lecture series related to all aspects of the product realization process. Relevant to the study described here, students attended lectures related to ideation techniques: specifically, brainstorming [2], morphological analysis [4], and TRIZ [5]. Following each lecture, 10 pairs of students attended an out-of-class design session to participate in the experiment. For each session, each group solved a speculative design brief using the ideation technique covered in the previous week's class. In this paper, the authors present the results from comparing students' use of two ideation techniques: brainstorming and morphological analysis.

2.2 The Briefs

Each group was assigned two different design briefs, one for each ideation technique. In the first experimental session, students were asked to use brainstorming to design a device that could assist the elderly tenants of the building with the force needed to adjust the window sliders without relying on electric power. The brief explained how changes in the humidity during the summer months cause the windows of a 65-years-old nursing building to 'stick', thus requiring a significant amount of force to raise and lower the windowpanes. It also included a brief introduction on the structure of double-hung windows and links to online resources.
The second session's design task challenged the students to use morphological analysis to design a device to help stroke patients, who are unable to perform bilateral tasks, with opening doors in a rehabilitation hospital (adapted from [6]). The brief included a short description about limitations of stroke patients and their difficulties in opening doors by turning the knob and pushing/pulling the door at the same time. The teams were asked to design a system that allows a stroke person to unlock and open a door at the same time with only one hand.

2.3 The Experiment

The experiment covers two ideation techniques: brainstorming and morphological analysis. For the design sessions, each team had the use of a computer with access to the Internet and a whiteboard with colour markers that they could use for sketching or writing notes. The teams were allowed to continue until they came to a conclusion on a satisfactory design. Sessions typically lasted between 45 and 75 minutes. Since the interest is in the design cognition of the teams of designers, the absolute length of a protocol plays no significant role. All of the design sessions were recorded on video to facilitate protocol analysis. Figure 1 shows screenshots from two of the recordings showing the setting of the experiments.

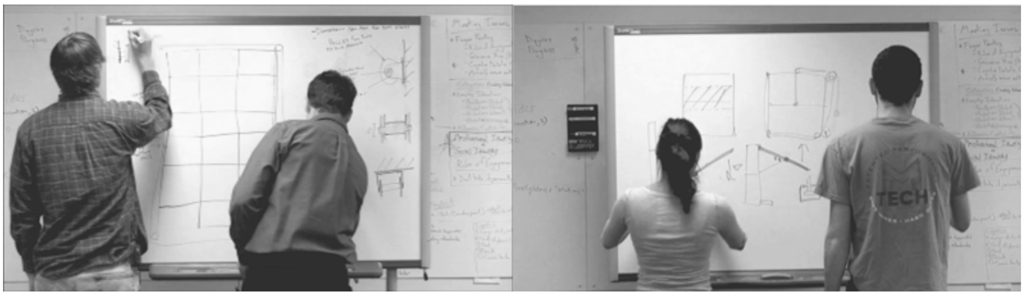

Figure 1. Two screenshots from two of the recorded design sessions.

3. ANALYSIS METHOD

The participants were asked to verbalise their thoughts while they designed; this verbalisation occurs naturally when participants are in teams. The sessions were audio and video recorded. The verbalisations by the participants were transcribed and then non-verbal behaviours such as writing and drawing were added to the text. Segmenting and coding of the protocols [7-9] was carried out by two separate coders and then arbitrated using the Delphi method [10]. The coders' agreement with the arbitrated version ranged from 83.3 to 97.1 percent with a mean agreement of 91.7 percent across the 20 protocols, which is considered a statistically reliable agreement percentage. The Function-Behaviour-Structure (FBS) design issues coding scheme [11], [12] was utilized to segment and code the 20 design protocols. An example from one of the protocols of the segmentation and coding of an excerpt from the utterances is given in Table 1. The design issues become the base data that represents the cognitive design activity in each session.

Table 1. An excerpt from the coded brainstorming protocol B-5.

#	Subject	Utterance	Code
193	A	Because we don't necessarily need to open the window for the person we just need to assist it.	F
194	A	So, if we take half the load […], they might have an easier time opening it. So ..	Be
195	A	We could do something like that,	S
196	A	where it just takes a lot of the load off.	Bs
197	B	I think it's just some sort of a, um… you got a…. like a damper system	S
198	B	I think is how they work, because you've just got like hydraulic fluid in there.	S
199	B	Because they are more for resisting.	Bs

3.1 Function-Behaviour-Structure coding scheme

The Function-Behaviour-Structure design issues coding scheme and its supporting ontology were used for coding the protocols. The FBS ontology of design uses the concept of design issue as the basic unit of its ontology and defines six foundational non-overlapping design issues [9]. The ontological variables that map on to design issues are: function, behavior, and structure plus a design description, Figure 2. Outside the direct control of the designer is the set of requirements, labeled R, provided by the client. The function (F) of a designed object is defined as its teleology; the behavior (B) of that object is either derived (Bs) or expected (Be) from the structure, where structure (S) represents the components of an object and their relationships. Therefore, any design utterance or activity fits into one of these six categories, namely, functions (F), expected behaviours (Be), structure behaviours (Bs), structures (S), Descriptions (D), and requirement (R) [13]. The aim of design activity is to transform a set of function issues into a set of structures and finally document them as a set of descriptions. However, there is no direct route from functions to structure. Instead, the designer goes through a series of transitional processes between different issues to reach a final design. The transition from one design issue to another is a design process. Figure 2 shows the relationships of the six design issues and resulting eight design processes.

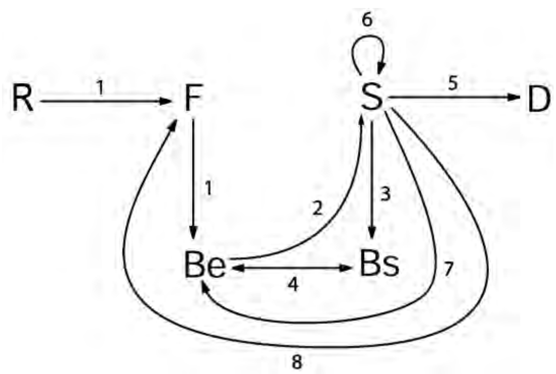

Figure 2. Design issues, labelled with symbols, and the resulting design processes, numbered 1 through 8, defined by the FBS ontology of design.

In Figure 2, formulation (R→F, F→Be), labelled 1, is the design process of producing a set of expected behaviours from the requirement and function issues. The design process synthesis (Be→S), labelled 2, is the design process of generating structure issues from the expected behaviours. The analysis process (S→Bs), labelled 3, occurs when a set of behaviours are deduced from the structure issues. The evaluation process (Bs→Be, Be→Bs), labelled 4, of the ideated structures is produced when comparing the expected and structure behaviours. The documentation process (S→D), labelled 5, can be of the structure or the externalization of any other design issue. In addition to these processes, the FBS ontology of design has three types of reformulations. These processes are aimed at capturing the actively changing state of the design and accounts for changes in structure, behaviour or function issues. The processes are respectively called reformulation-1

(S→S), labelled 6, reformulation-2 (S→Be), labelled 7, and reformulation-3 (S→F), labelled 8, in Figure 2.

Based on the FBS coding scheme, two types of transition processes can be generated from any coded protocol: semantic and syntactic design processes. In the semantic approach, the semantic connection between coded segments of the protocol generates a link between them and depending on which design issue is at each end of the link a particular design process is produced. This kind of linking generates a semantic linkograph. For example if segment number 100 with code S is semantically linked to segment number 120 with code Bs, then the design process analysis (S→Bs) is produced between them. Despite its strong conceptual foundations, employing a semantic approach in protocol analysis depends on the generation of the semantic links between segments that needs a considerable amount of time and resources.

The syntactic approach is based on a weaker model of design activity and relies on the sequential order of the design issues to generate the links between and to produce the design process, which is called the syntactic design process. Here each segment is linked to its immediately preceding segment. We employ the syntactic approach in this paper to produce the syntactic design processes by the participants in each protocol.

3.2 Measuring Design Issues and Design Processes

Measures of design issues and design processes provide the foundation for the understanding of the design cognition of the participants. The occurrences of design issues and design processes are initially measured through the descriptive statistics of means and standard deviations. Any differences are indications of effects of educational interventions.

The cumulative occurrences of design issues and design processes provide other measures. To calculate the cumulative occurrence of each design issue, the generation of that issue throughout the coded protocol is counted in an additive manner. In other words, if segment number, n, is coded as x, then c, the cumulative occurrence of x at segment n, will be $c \quad \sum_{i=1}^{n} x_i$ where x_i equals 1 if segment i is coded as x and 0 if segment i is not coded as x. Plotting the results of this equation on a graph with segment numbers, n, as horizontal axis and the cumulative occurrence values, c, as the vertical axis will illustrate the cumulative occurrence of the design issues. An example of the cumulative occurrence of design issues for the brainstorming protocol of team B-3 is shown in Figure 3. Juxtaposing the graph lines for all of the design issues provides a qualitative representation of how the design issues are occurring while the participants are designing.

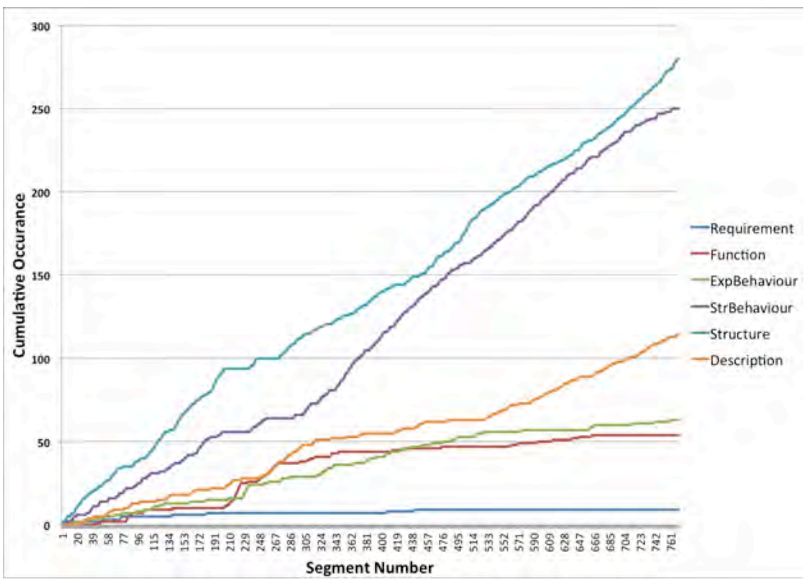

Figure 3. Cumulative occurrence of design issues for brainstorming design session of team B-3.

The cumulative occurrence is an indicator for the amount of cognitive effort that that design team has put into each issue up to that point.
Each design issue's cumulative occurrence graph is modelled by a linear regression. To assure that the linear regression is the best fit for modelling the results, we calculated the coefficient of determination, the R-square values, for each protocol. The average R-square value is 0.909 for brainstorming sessions (SD = 0.148) and 0.856 for morphological analysis sessions (SD = 0.236). This shows that a linear regression could be a proper representation for cumulative occurrence of the design issues. Table 2 shows the results for the exemplary design protocol B-3.

Table 2. Linear regressions of design issue occurrences and their R-squares for the brainstorming design protocol of team B-3.

	Requirement	Function	Exp Behaviour	Str Behaviour	Structure	Description
Linear Regression (Slope)	0.008	0.080	0.091	0.344	0.337	0.140
Linear Regression R-Square	0.785	0.870	0.966	0.986	0.995	0.984

Measuring the linear regressions for the occurrence of the design issues also enables summarising and comparing different protocols. Such cross-case comparisons are usually not possible due the different lengths of their design protocols. However, summarising the occurrence of the issues with a single value (i.e. the slope of the regression line) along with the general applicability of the FBS coding scheme enable comparisons across different protocols regardless of their length. After measuring the best-fit regression line, the slope is used as a single-value indicator for the rate of occurrence of each design issue. The means of slopes is used to summarise the performance of brainstorming and morphological analysis groups. A paired t-test is used to assess any significant differences in the occurrence of design issues between the two groups. The results of these analyses are presented in the next section.

4. RESULTS

4.1 Design Issues

Table 3 shows the means and standard deviations for distributions of design issues in the brainstorming and morphological analysis groups. Each result is the aggregation of the results of the 10 teams that form each group.

Table 3. The means and standard deviations for distributions of design issues in the brainstorming and morphological analysis groups.

	Requirement	Function	Exp Behaviour	Str Behaviour	Structure	Description
	Brainstorming					
Mean %	1.30	4.40	7.21	27.71	40.01	19.38
Standard Deviation	0.004	0.015	0.020	0.028	0.048	0.037
	Morphological Analysis					
Mean %	0.66	6.65	11.80	22.98	37.40	20.51
Standard Deviation	0.003	0.018	0.026	0.034	0.040	0.053

LINKOgrapher [14], an open-source design protocol analysis tool, was used to calculate the statistical descriptors and the cumulative occurrence of design issues in each team. For each design team, the linear regression line was calculated and the slope of the regression line was taken as an indicator for the generation of design issues by each team. The performance of the teams in each group is summarized by calculating the mean slope for each group. Figure 4 shows the mean slopes of cumulative occurrence of design issues in each group. Table 4 presents the numerical values of the average slopes and their standard deviations for the cumulative occurrences of design issues for the brainstorming and morphological analysis groups.

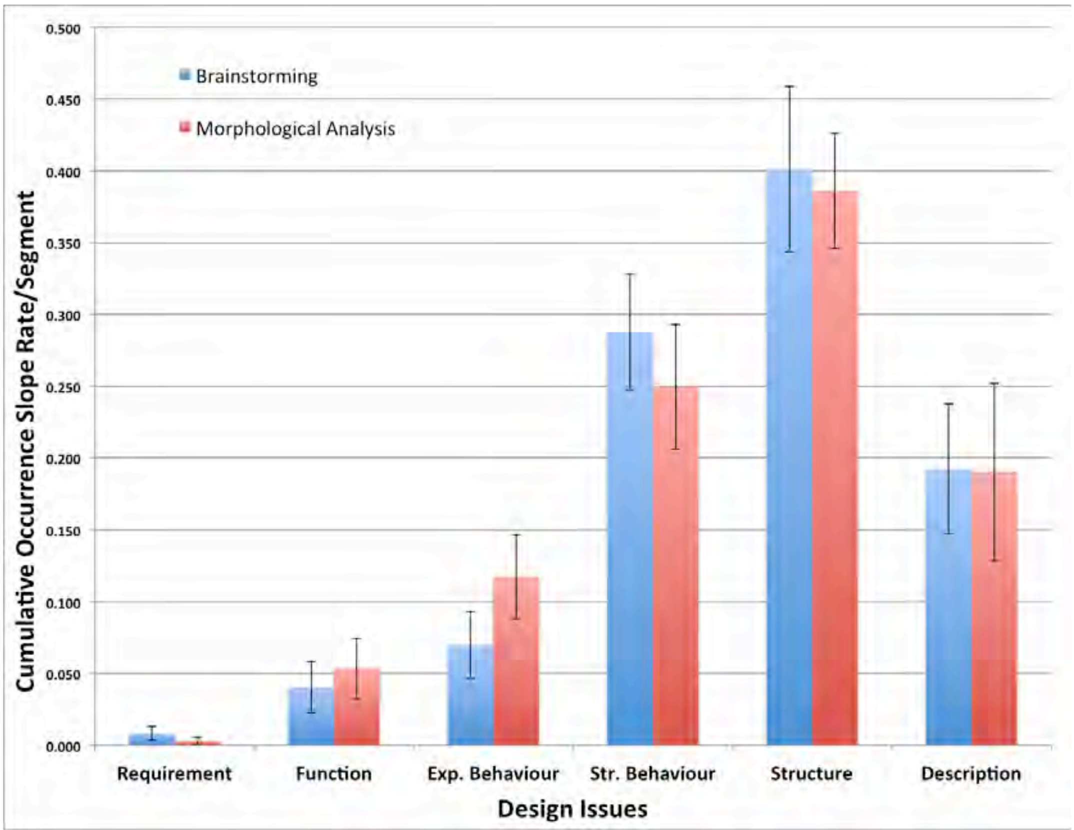

Figure 4. The means and standard deviations for the slopes of cumulative occurrence of design issues for the brainstorming and morphological analysis groups.

Table 4. The average slope and standard deviations for cumulative occurrence of design issues in the brainstorming and morphological analysis groups.

	Requirement	Function	Exp Behaviour	Str Behaviour	Structure	Description
	Brainstorming					
Average Slope	0.008	0.040	0.070	0.288	0.401	0.192
Standard Deviation	0.005	0.018	0.023	0.040	0.057	0.046
	Morphological Analysis					
Average Slope	0.003	0.053	0.117	0.250	0.386	0.190
Standard Deviation	0.002	0.021	0.029	0.043	0.040	0.062

4.2 Syntactic Design Processes

A syntactic model of design processes was produced for each design session following the FBS coding scheme. The cumulative generation of design processes by each team was calculated. Figure 5 shows the slopes of the regression lines for the generation of those syntactic design processes that map onto the FBS ontology.

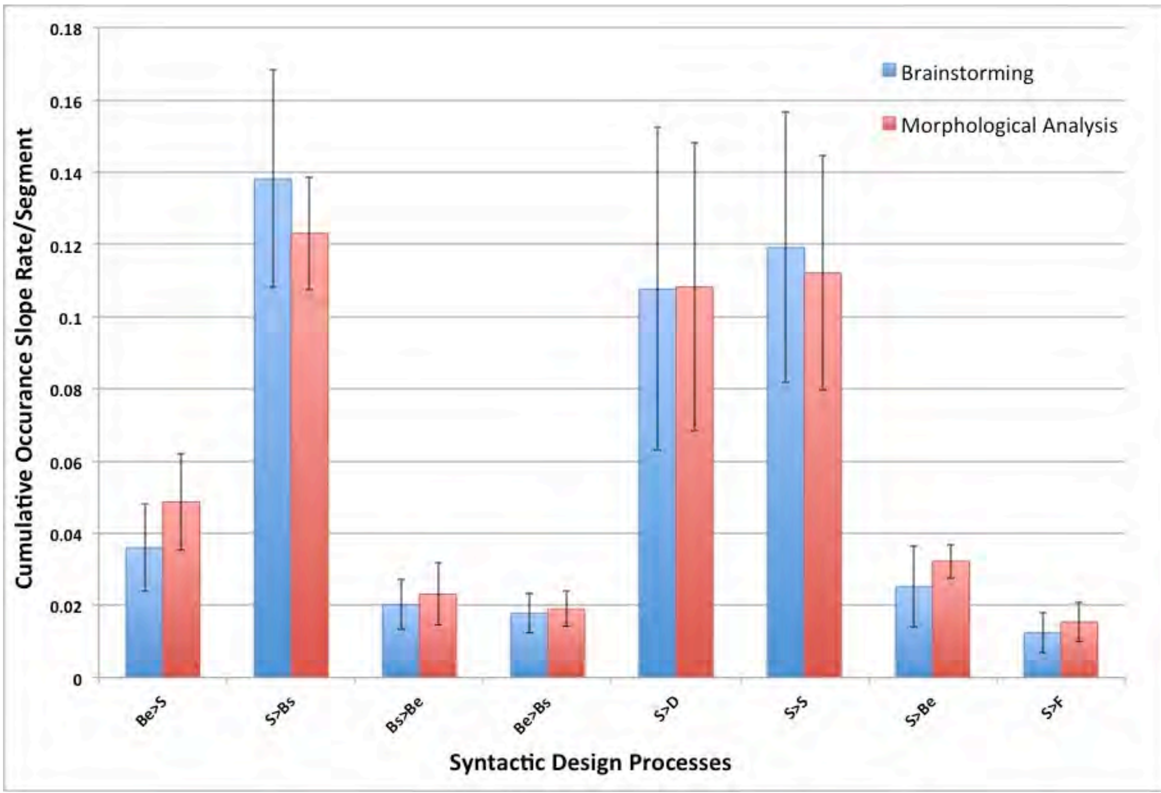

Figure 5. The average slopes of the regression lines for the cumulative occurrence of syntactic design processes in the brainstorming sessions and the morphological sessions.

5. DISCUSSION

Four hypotheses were presented in the Introduction for which evidentiary support is sought through this experiment. The four hypotheses were:

1. Designers using morphological analysis would discuss issues related to expected behaviour more frequently than those using brainstorming;
2. Designers using morphological analysis would discuss structure design issues less frequently than those using brainstorming brainstorming;
3. Designers employing morphological analysis would conduct the analysis design process more than those using brainstorming; and
4. Designers employing morphological analysis will conduct the description design process more than those using brainstorming.

After generating the statistical models for the cumulative occurrence of the design issues and processes in each group, the hypotheses could be tested using paired t-test between the results from the brainstorming sessions and the morphological analysis sessions. The following sections discuss each hypothesis based on the results of these tests.

5.1 Higher Structure Design Issues in Brainstorming

Hypothesis 1 is that brainstorming produces more structure design issues than morphological analysis. Running a paired t-test ($t(18) = 0.859$) between the slopes of the regression lines for occurrence of structure issues in brainstorming group ($M = 0.401$, $SD = 0.057$) and the morphological analysis group ($M = 0.386$, $SD = 0.040$) shows no significant difference in the generation of structure design issues ($p = 0.2$). Therefore, hypothesis 1 is not supported by the data from this experiment. The basis of this hypothesis was that designers using morphological analysis would expend less of their cognitive effort on discussing a product's embodiment and structure due to the focus on functional abstraction. This does not appear to be case.

5.2 Lower Expected Behaviour Issues in Brainstorming

Hypothesis 2 is that brainstorming has less expected behavior design issues than morphological analysis. In the Mechanical Engineering senior design course, morphological analysis is presented in the context of the systematic design methodology proposed by Pahl and Beitz [15]. Specifically, students are taught to decompose a design problem by a product's various functionalities; i.e., the actions, or "expected behaviours," that the product must perform in order to satisfy the design requirements. To complete this part of this mental exercise, designers must frequently revisit the overall purpose of the design. Thus, as the discussion of a product's function and expected behaviour drives the problem decomposition in morphological analysis, it is hypothesized that the occurrences of expected behaviour issues are significantly (t (18) = 3.895, p = 0.0005) lower for student designers using the brainstorming technique (M = 0.070, SD = 0.023) compared to the same student designers using the morphological analysis technique (M = 0.117, SD = 0.029). Hence, hypothesis 2 is supported by the data from this experiment.

5.3 Lower Analysis Processes in Brainstorming

Hypothesis 3 is that designers involved in brainstorming conduct less analysis design processes than when performing morphological analysis. Running a t-test ($t(18) = 2.854$) on the results from two sets of design protocols shows that the rate of occurrence of structure behaviour issues in brainstorming group (M = 0.288, SD = 0.040) is significantly (p = 0.005) higher than in morphological analysis group (M = 0.250, SD = 0.043). The initial expectation is the opposite given that brainstorming focuses on the production of ideas rather than analysing them. To confirm these results, we use the syntactical model of design processes and produce the cumulative occurrence charts in the same way, Figure 5. By definition, the structure behaviour issues are a result of analysing the structure issues. In other words, higher occurrence of structural behaviour issues should be accompanied by higher occurrence of analysis in the process level. As mentioned earlier, the syntactic model of design processes is a weak model. However, it is useful as a quick and easy way of looking at the occurrence of design processes during the design sessions.

A paired t-test (df = 18) was conducted on the results from brainstorming versus the results from morphological analysis. The test highlighted a statistically significant ($p<0.5$) difference in the average slopes of the syntactic analysis process ($S \rightarrow Bs$) with the average slope across brainstorming sessions (M = 0.138, SD = 0.030) being higher than the average slope of morphological analysis sessions (M = 0.123, SD = 0.016). This is in line with our findings about the occurrence of the structural behaviour issues, but contrary to our expectations as stated in Hypothesis 3.

One possible explanation for this may be that the protocols capture a length of the design session past the brainstorming period. Brainstorming is considered to be an unstructured, free-form ideation technique. Thus, during the concept ideation stage, ideas are presented without an analysis of the product behaviour. However, as the design process progresses past the ideation stage and potential solutions are evaluated, the designer must perform a significant amount of analysis to select amongst the numerous potential solutions. Thus one might expect a high rate for discussion of structure behaviour issues after using this technique.

5.4 Lower Description Processes in Brainstorming

Hypothesis 4 is that less description design processes ($S \rightarrow D$) occur during the brainstorming sessions comparing to the morphological analysis sessions. The data from these protocol studies did not support this hypothesis. This result suggests that, although brainstorming lacks the prescribed instruction to document ideas as in morphological analysis, the frequency of a designer's description of concepts is not significantly reduced.

6. CONCLUSION

This paper has taken the generic brief of the Ninth Design Thinking Research Symposium (DTRS9) and has utilized two briefs for designing assistive technology devices to study the effects on students' design cognition of utilizing different design methods while designing. Four different hypotheses based on the literature about brainstorming and morphological analysis design methods [1, 2, 3, 4], were tested. Twenty design protocols were recorded from teams of two designers who used different design methodologies to ideate solutions of their given briefs. The hypotheses were tested using a cumulative approach to the occurrence of FBS design issues across the coded protocols, which enabled the comparison of protocols independent of their lengths.
The hypotheses that brainstorming produces more structure design issues than morphological analysis was not supported ($t(18) = 0.859$, $p = 0.2$) by the data from this study. The hypotheses that brainstorming has less expected behaviour design issues than morphological analysis was supported by the data from this study ($t(18) = 3.895$, $p = 0.0005$).
The hypotheses that brainstorming has less analysis design process than morphological analysis was rejected. The results of this study confirm the opposite of the hypothesis 3 ($t(18) = 2.854$, $p = 0.005$), which means there are more analysis processes occurring across the brainstorming sessions. A possible explanation for this could be the need to analyse more ideas in the later phases of brainstorming design process since more ideas are generated in the early stages of brainstorming. However, further experiments are needed to track the causes of this difference between brainstorming and morphological analysis sessions.
The fourth hypothesis, that brainstorming has less description design process than morphological analysis, was not supported, which suggests that designers' documentation practice is not impacted by prescriptive rules of ideation techniques related to visual organization of ideas.
A novel analytical technique for protocol analysis was applied in this study: the use of cumulative issue and process graphs, exemplified in Figure 3. This produced the unexpected result that structure design issues are generated at a near linear rate across the design session and was independent of the two methods used. Such a result requires further investigation. If it is observed to occur more generally then this result has particular significance for education, which will be elucidated after further study.

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