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DOES DESIGNING HAVE A COMMON COGNITIVE BEHAVIOR INDEPENDENT OF DOMAIN AND TASK: A META-ANALYSIS OF DESIGN PROTOCOLS

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ABSTRACT

This paper presents the results of a meta-analysis of three sets of previous, independent protocol studies of student designers from different disciplines carrying out different design challenges. This analysis is used to confirm or deny three hypotheses about commonalities of cognitive behavior that are independent of domain and task. The previous protocol studies cover the domains of mechanical engineering and computer science. The design challenges cover three different mechanical design challenges and three different software design challenges. The meta-analysis tested the following three hypotheses describing cognitive behavior:

1. Quantitative cognitive measures describing “structure” of the artifact would be statistically the same amongst the three groups; and
2. Quantitative cognitive measures describing “structure behavior” of the artifact would be statistically the same amongst the three groups; and
3. Quantitative cognitive measures describing “expected behavior” of the artifact would be statistically the same amongst the three groups.

The meta-analysis used quantitative measures of the cumulative occurrence of the six design issues in the FBS ontology in these existing protocols as the foundation for the determination of commonality in testing the three hypotheses. Based on the evidence from these sets of protocols studies hypothesis 1 is fully supported, hypothesis 2 is partially supported and hypothesis 3 is not supported.

Keywords: Design cognition, design methods, design practice, design protocols

1 INTRODUCTION

Designing is taught and practiced in many disciplines that include traditional design domains such as engineering and architecture and newly established domains such as software design, interface design, interaction design, games design, user experience design and service design. Each of these disciplines presents itself as teaching and practicing design in a unique manner. The traditional design disciplines of engineering and architecture describe themselves very differently. Architecture uses the three concepts first enunciated in writing by Vitruvius [1] as “firmness, commodity and delight”. Engineering defines design as “… the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs” [2]. In Architecture there is a concern with “delight” which is not found directly in engineering, whereas in Engineering there is a concern with “optimality” which is not found directly in Architecture. This appears to imply that these two disciplines have, at least, some fundamentally different goals.

There have been claims that designing is an art, or that designing is a science, or that designing is problem-solving. The research reported in this paper is founded on the claim that designing can be considered within human intellectual activities as distinguishing itself from other human activities by its own characteristics: that designing is designing. There is increasing interest in studying the physiological behavior [3] and neurophysiological behavior [4] of designers to complement and associate with cognitive studies. For such physiological studies to have significance in increasing our understanding of design in general it has to be assumed that there is some common cognitive designer behavior that is independent of domain and task, otherwise such studies will always only have local applicability. There have been very few studies comparing cognitive design behavior across disciplines to determine whether this assumption is correct. One method of representing cognitive design behavior determined from protocol studies of designers while designing is through coding those protocols using an ontological coding scheme that is separate from the domain or setting. The results from these studies could then be compared and hypotheses about common cognitive behavior tested [5, 6, 7, 8].

This paper presents the results of a meta-analysis of three sets of existing protocols that cover two different domains with three different settings that cover three different tasks. The protocols come from existing studies of mechanical engineering students and software design students. These protocols had previously been coded using the Function-Behavior-Structure coding scheme [9] and were coded using different sets of coders. The meta-analysis tested three hypotheses describing cognitive behavior:

1. Quantitative cognitive measures describing "structure" of the artifact would be statistically the same amongst the three groups; and
2. Quantitative cognitive measures describing "structure behavior" of the artifact would be statistically the same amongst the three groups; and
3. Quantitative cognitive measures describing "expected behavior" of the artifact would be statistically the same amongst the three groups.

The paper is structured as follows. Section 2 describes the three sets of design protocols in terms of the experimental settings and the FBS coding scheme. Section 3 presents the meta-analysis including the measures used for quantifying the cognitive behavior of designers. Section 4 presents the results of applying the meta-analysis to the three datasets. These results are used to test the three hypotheses. Section 5 discusses the results and draws conclusions for future studies and potential implications.

2 PROTOCOLS STUDIED

Three sets of design protocols were used representing three different sets of experimental design sessions:

Set 1: Mechanical engineering students at different stages in design education (ME-EDN)

The overall purpose of this study [10] was to research the potential effects of design education on the design cognition of mechanical engineering (ME) students. Protocol analysis was used to analyse and compare the experimental design sessions of two student groups: a control group enrolled in a curriculum with a theoretical engineering science focus, and an experimental group enrolled in a curriculum with a design focus. To explore the effects of the two curricula on design cognition, the research team conducted a longitudinal study that followed students from their sophomore to senior years. Participants were solicited during their sophomore year and agreed to participate in the 3-year study. Student pairs participated in four experimental sessions (beginning of the sophomore year and end of the sophomore, junior, and senior years), resulting in four primary datasets consisting of 42 sessions in total. For the purposes of this paper, we will use only two of these datasets representing 18 individual design sessions from the ME students (labelled ME-EDN) as representative datasets. In the four sessions, student teams were asked to solve a speculative design task focused in realizing an assistive technology. Specifically, students were asked to (i) design a device to help disabled users open a stuck double-hung window without relying on electric power, (ii) design a device to help stroke patients who are unable to perform bilateral tasks with opening doors, (iii) design a device to add to an existing hand/arm-powered wheelchair that will allow paraplegic wheelchair users to traverse a standard roadside curb unassisted, and (iv) design a device to assist patients with getting out of a bath tub.

Set 2: Mechanical engineering students being taught different concept-generation methods (ME-CGM)

The overall aim of this study [11] was to investigate the effects of different concept-generation methods on the design cognition of mechanical engineering students. Specifically, the research investigated three methods: brainstorming, morphological analysis, and TRIZ. Participants were solicited from the ME senior capstone design sequence (and were different to those who were participants in Set 1). Following a lecture related to each of the ideation techniques student pairs attended a design session and solved a speculative design brief using the ideation technique covered in that week's class. Three experimental sessions were conducted resulting in three primary datasets (labelled CGM) consisting of 31 sessions in total. Students in this set were challenged with assistive technology design tasks (i)-(iii) described in Set 1.

Set 3: Software engineering students (SE)

The overall purpose of this study [12] was to explore how interruptions during designing affect the design cognition of software engineering students. In three experiments, 14 pairs of students completed different software design tasks of comparable complexity and scope. Each task involved designing an algorithm, such as finding all duplicate and unique (non-duplicate) elements between two input lists; extracting type elements from a list, and developing tabular statistics from unformatted input data. The first experiment captured designers' activities without interruptions, which served as a baseline for comparison with the other two experiments that explicitly incorporated two interruptive tasks. Conducting the experiments resulted in three datasets (labelled SE) consisting of 41 sessions in total.

All three sets of design protocols were represented uniformly based on the FBS coding scheme [9], i.e. in terms of six ontological design issues: R, F, Be, Bs, S, and D.

Requirements (R): includes all requirements and constraints that are explicitly provided to the designer.

Function (F): includes teleological representations that can cover any expression related to potential purposes or intentions of the design.

Expected Behavior (Be): includes attributes of the design used as assessment criteria or target values for potential design solutions. They may include technical, economic, ergonomic and other characteristics.

Behavior derived from structure (Bs) (or, shorthand, "structure behavior"): includes attributes of the design that are measured, calculated or derived from observation of a specific design solution.

Structure (S): includes the components of a design and their relationships. They can appear either as a set of general concept solutions or as detailed solutions.

Description (D): includes any form of external representation produced by a designer, at any stage of the design process.

The FBS design issues form a principled coding scheme for segmenting and coding transcripts of the experiment videos (i.e., design conversations and gestures, etc.) into a sequence of design issues denoted by semantic symbols, i.e., the FBS codes. The Delphi method [13] was applied to increase the reliability of protocol segmentation and coding. It consists of two separate coding processes undertaken by two independent coders, and an arbitration session to resolve the coding disagreements identified in the previous coding results. Typical inter-coder reliability obtained by this method is in the range 85–95%. The arbitrated result, namely, a sequence of design issues, becomes the foundational data for subsequent analyses that characterise the design cognition of the participants.

To illustrate the coding of design protocols in terms of FBS design issues, an excerpt from a coded, arbitrated design protocol from Set 2 is shown in Table 1.

Table 1. Excerpt from a coded design protocol

Segment number	Utterance	FBS design issue
44	[looks at brief] yeah, "raising and lowering windows".	R
45	how with even normal windows to close them ?	Be
46	you have to like push harder than you would to like open it,	Be
47	to get a good seal on it.	Be
48	But I don't think we have to worry about that: we can just displace vertically up or down.	Be
49	what kind of a machine would do that?	S
50	[writes: "Ideas/concepts"]	D
51	So we are thinking like a pulley system.	S
52	[writes: "pulley system"]	D

3 META-ANALYSIS OF EXISTING RESULTS

The meta-analysis of the existing results follows recent studies applying quantitative measures to the cumulative occurrence of the six design issues [14, 15]. Cumulative occurrence of a design issue across a design session models the cumulative cognitive effort across that design session. We calculate the cumulative occurrence of a design issue across all segments in a design protocol as follows: the cumulative occurrence (c) of design issue (x) at segment (n) is $c = \sum_{i=1}^{n} x_i$ 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 the segments (n) on the horizontal axis and the cumulative occurrence (c) on the vertical axis yields a visual representation of the cumulative cognitive effort represented by the occurrence of the design issues in a protocol, Figure 1. This analysis is performed for each of the six design issues.

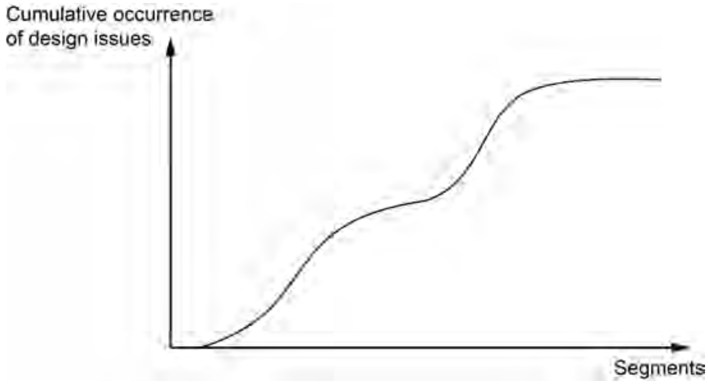

Figure 1. Exemplary graph representing the cumulative occurrence of design issues

In this paper we use two quantitative measures that characterize the graphs of cumulative cognitive effort produced in this way:

- *R-square (RSQ):* is the variance of the graph from a first-order polynomial fitting curve. If RSQ ≥ 0.95, the graph is linear. Linear graphs indicate that the rate at which the design issues are generated is constant and that the cognitive effort is uniformly distributed across the design session for that issue.
- *Slope:* is calculated for all graphs that are found linear. Its numeric value quantifies the rate at which the design issues are generated and the rate at which cognitive effort is expended.

4 TESTING THE HYPOTHESES

Comparing the quantitative measures across the aggregated datasets from the three set of protocols allows testing the three commonality hypotheses formulated at the beginning of this paper. We start the comparison with determining whether there is linearity in the cumulative occurrence graphs within each dataset for expected behavior issues, structure behavior issues, and structure issues. Linearity is identified when the mean RSQ value for a design issue across all design protocols in a dataset is at least 0.950 and when at least 90% of the individual RSQ values for the design issue in the dataset are linear. The results are shown in Tables 2, 3 and 4.

Table 2. Structure issues: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
ME-EDN	0.989 (0.011)	100	Yes
ME-CGM	0.988 (0.017)	97	Yes
SE	0.991 (0.008)	100	Yes

Table 3. Structure behavior issues: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
ME-EDN	0.986 (0.008)	100	Yes

ME-CGM	0.987 (0.012)	97	Yes
SE	0.977 (0.015)	93	Yes

Table 4. Expected behavior issues: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
ME-EDN	0.908 (0.114)	39	No
ME-CGM	0.946 (0.033)	55	No
SE	0.967 (0.026)	78	No

The next step is to calculate mean slopes for all linear graphs within a dataset, Table 5. We can use t-tests to determine whether differences in slopes across the datasets are statistically significant. The t-test results are shown in Table 6, in terms of the t-values and p-values for each t-test. If the p-value associated with the test statistic t is lower than 0.05, the difference between slopes is statistically significant. There are no t-test results shown for expected behavior issues involving ME-EDN as there were too few linear graphs within that dataset.

Table 5. Mean slopes

Dataset	Structure (Stdev)	Structure Behavior (Stdev)	Expected Behavior (Stdev)
ME-EDN	0.393 (0.073)	0.317 (0.046)	0.115 (0.038)
ME-CGM	0.364 (0.070)	0.275 (0.044)	0.131 (0.060)
SE	0.356 (0.083)	0.232 (0.063)	0.179 (0.047)

Table 6. T-tests comparing mean slopes

Datasets compared	Structure		Structure Behavior		Expected Behavior	
	t-value	p-value	t-value	p-value	t-value	p-value
ME-EDN / ME-CGM	1.360	0.183	3.146	0.003	---	---
ME-EDN / SE	1.727	0.093	5.721	0.000	---	---
ME-CGM / SE	0.446	0.657	3.308	0.002	2.872	0.008

5 DISCUSSION AND CONCLUSIONS

The results derived from the meta-analysis to the three datasets were used to test the three hypotheses stated at the beginning of this paper. The results are in the form of statistically significant similarities of linearities and slopes of the design issue being tested. Linearity is a binary measure, so the cognitive behavior in a design issue is either linear or not linear, based on a set of linearity requirements. Slope is a numerical value and the slopes of the datasets are tested for statistical significance. If both the linearities and the slopes are similar for a particular design issue then the claim is made that there is a commonality across the three datasets for that design issue and a hypothesis based on that claim is fully supported. If the linearities are similar, but the slopes are dissimilar for a particular design issue, then the claim is made that there is a partial commonality across the three datasets for that design issue and a hypothesis based on that claim is partially supported. If the linearities are not similar for a particular design issue then the hypothesis for that design issue is negated.

Hypothesis 1 (quantitative cognitive measures describing "structure" are statistically the same amongst the three groups) is fully supported in that linearity was found in the cumulative occurrence graphs for structure issues in all three datasets and in that there are no statistically significant differences between the mean slopes of the linear graphs. This implies that the cognitive effort expended on structure is expended uniformly across all the design sessions independent of the domain and task. Further, the rate of expenditure is independent of domain and task.

Hypothesis 2 (quantitative cognitive measures describing "structure behavior" are statistically the same amongst the three groups) is partially supported based on the linearity found in the cumulative occurrence graphs for structure behavior issues in all three datasets. However, there are statistically significant differences between the mean slopes of the linear graphs across all three datasets.

Hypothesis 3 (quantitative cognitive measures describing "expected behavior" are statistically the same amongst the three groups) is not supported. No linearity was found in the cumulative occurrence graphs for expected behavior issues across the three datasets, and the differences between the mean slopes of the linear graphs are statistically significant.

These results, which are based on a larger set of protocols than is generally seen in the literature, imply that there are some commonalities in designing independent of domain and task. Presumably, where these results do not support commonalities the differences are due to domain and/or task.

This paper shows that this method of meta-analysis can be used to test hypotheses about the commonality of design cognition independently of the specific design domain and design task. It adds to the evidence supporting the claim that there are some fundamental cognitive behaviors while designing that are independent of domain and task. Future work can build on the same meta-analysis to cover more datasets from the same or other design domains. This may also allow testing hypotheses related to the design issues of requirements, function and description. The effect of other factors, such as education, experience, type of tool used, design team composition and collocation can be tested using this approach when protocols are available. Various extensions of the meta-analysis are possible with respect to its input and output. For example, instead of design issues one may use design activities as input, coded based on the FBS process framework [9]. The meta-analysis may also use different quantitative measures as output (in addition to linearity and slope) leading to more detailed statements about cognitive design behavior.

Ultimately, the proposed meta-analysis should enhance the empirical basis for the existence of common cognitive behavior in designing, as increasingly claimed by design theorists [16, 17]. The results presented in this paper already indicate that designing can be studied as a separate cognitive activity whose instances share significant similarities even when executed in different settings. This has the potential to have a profound impact on design education if designing has a common core of cognitive behavior.

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