Exploring Designing Styles Using a Problem-Solution Division

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This paper presents a measurement-based exploration of designing styles within the context of different design disciplines and tasks based on the design cognition of small design teams. Twelve final-year industrial design and twelve mechanical engineering design students were recruited to form teams of two. Each team undertook two conceptual product design tasks with different classes of requirements. Protocols of conversations and observations of design activities were then examined using an ontologically-based coding scheme. A problem-solution index was proposed to classify design sessions into problem-focused and solution-focused designing styles. Results suggest that industrial design student teams have a designing style that is more focused on the design problem than mechanical engineering student teams. The same design team may change its relative focusing on problem or solution in response to different classes of design requirements.

Introduction

Design cognition is often modeled as a search process across two notional design "spaces" of problem and solution. However, there is not a consensus on how a designer's cognitive processes progress during the designing process. The problem-solving view of design claims that the designing process commences with an exploration within the problem space. Goel and Pirolli [1], for example, considered that designers would engage in an initial problem structuring phase before moving into solution development. An alternative school of thought argues that design thinking is primarily abductive or solution-focused

[2]. Designers would jump into the solution space in the very beginning of the designing process, before the problem is formulated. In particular, designers need to employ conjectures of (partial) solutions to analyze the ill-structured or wicked design problems, i.e., "analysis through synthesis" [3], [4]. Differing from these two phase-based views, Schön [5], [6] modeled problem setting ("seeing") and problem solving ("moving") of design as a reflective conversation: designing progresses in cycles of "seeing-moving-seeing" rather than two distinct phases of problem analysis and solution development. This interactive view is echoed with a co-evolutionary model of designing [7], [8].

In addition to the debates about generic design paradigms, the tendency to focus on problem or solution is subject to the designers' experience level. Restrepo and Christiaans [9] and Kruger and Cross's [10] studies found that more experienced industrial designers usually follow a problem-focused strategy, which tends to produce better results. Lloyd and Scott [11], to the contrary, argued that more experienced engineering designers tended to focus more on solutions (higher percentage of generative mode actions) than those with less experience. These conflicting findings imply that designers' problem or solution focusing may be specific to design disciplines. No direct evidence can be found regarding this issue in the current literature.

In order to explore and compare designers' focus on either problem or solution spaces between different disciplines and/or circumstances, we need a new measurement independent of particular assumptions about how problem or solution focus is organized in the design cognitive process. The proposed measurement is developed within an ontological framework, directly capturing the meta-level structures of design cognition, i.e., the designing style of a design session, in terms of problem-focused and solution-focused design issues. This new measurement is then applied to a protocol study comparing industrial and engineering design students' design cognition behind two product conceptual design tasks.

Ontologically-based Protocol Analysis

The empirical basis for the measurement of problem- and solution-focused designing styles comes from protocol analyses of design sessions that are coded using design issues based on the Function-Behavior-Structure (FBS) coding scheme. A general design ontology, namely, the FBS ontology [12], [13], models designing in terms of three basic classes of ontological variables: function, behavior and structure. It creates a useful ground for interpretation of design cognition across different design domains. A domain-independent coding scheme, based this ontology, has been developed with six design issues: function (F), expected behavior (Be), behavior from structure (Bs), structure (S), requirement (R) and design description (D), Figure 1.

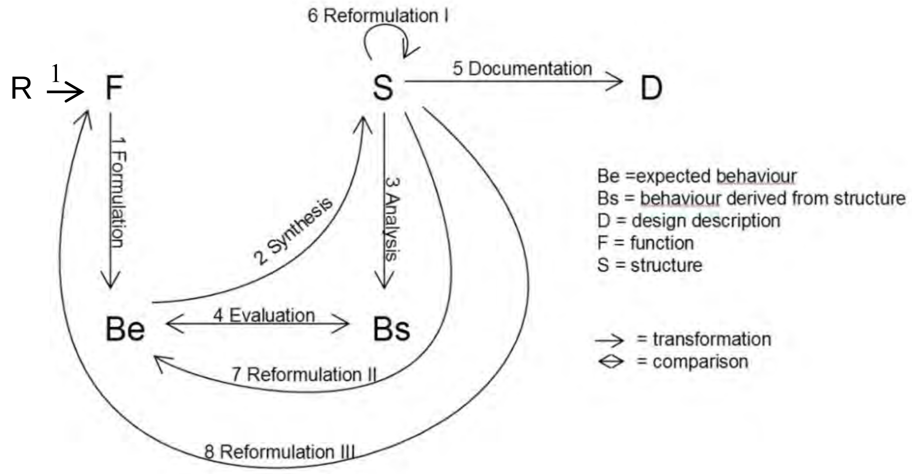

Fig. 1 The FBS ontology [13]

In the FBS ontology, problem formulation mainly involves reasoning about requirement, function and expected behavior, while reasoning about structure and behavior from structure are related to artifacts as a solution to the formulated problem [12], [14]. The ontologically-based design issues can be categorized into problem-focused and solution-focused design issues as shown in Table 1. The FBS-based coding scheme does not code the design description issues with this view of problem and solution spaces. Description issues are therefore excluded in the exploration of problem- and solution-focused designing styles.

Table 1 Mapping FBS design issues onto problem and solution spaces

Problem/solution space	Design issue
Problem space = Problem-focused design issues	Requirement (R) Function (F) Expected Behavior (Be)
Solution space = Solution-focused design issues	Behavior from Structure (Bs) Structure (S)

Problem-Solution index for the whole design session

The designing styles, or the meta-level structure over the cognitive processes behind design activities, can be explored at various levels of granularity. It may refer to an overall characteristic of the entire design session, or a “signature” of a dynamic process that describes the time-based changes of the designers' cognitive focus.

The simplest form is to use a single-value measurement to summarize the designing style of an entire design session. The problem-solution (P-S) index is proposed as a ratio measurement, computing the ratio of the total occurrences of the design issues concerned with the problem space to the sum of those related to the solution space, Equation (1).

$$\text{P-S index} = \frac{\sum(\text{Problem}-\text{related issues})}{\sum(\text{Solution}-\text{related issues})} = \frac{\sum(R,F,Be)}{\sum(Bs,S)} \quad (1)$$

The P-S index value quantifies the relative focusing on problem or solution. We define a design session with a P-S index larger than 1 as one with a problem-focused designing style, and a session with a P-S index value less than or equal to 1 as one with a solution-focused style.

Sequential Problem-Solution index across design session

Designing is a dynamic process. A single value for the P-S index for the entire session will collapse any time-based changes. A fractioning technique is incorporated in this study to tap into the designing styles within a design session [15], [16]. A preliminary exploration of the dynamic nature of designing styles can be undertaken in two halves of the design protocols. The finer subdivision of the design session eventually leads to a sequential P-S index delineating the trajectory of cognitive progression during the design session.

Here the entire design session is divided into 10 consecutive non-overlapping sections each with an equal number of design issues. The P-S index for each section is calculated. A sequence of temporally ordered P-S indexes is read as a "signature" of dynamic designing style.

A Comparative Study Applying the Problem- and Solution-focused Measurements

The proposed measurements for problem- and solution-focused designing styles are then applied to a protocol study comparing final-year undergraduate industrial design (ID) and mechanical engineering design (ME) students' design cognition in various classes of conceptual design requirements [17]. The design experiment used 3×2 mixed-model factorial design. The design discipline is a between-subjects factor. The type of design tasks is a within-subjects factor. Each design team undertook two conceptual design tasks in this study. Four main hypotheses related to students' problem- and solution-focused designing styles are proposed to be tested in this research:

1. All design sessions demonstrate a common pattern of designing behavior, independent of the variables of discipline and type of task;
2. There are significant inter-disciplinary differences between the designing styles of ID and ME teams;
3. A design team's designing style will be different when designing for different classes of design requirements; and
4. There are two mutually exclusive hypotheses about the designing style of mixed teams consisting of both ID and ME participants:
    - 4a. Mixed teams will exhibit a designing style that is the average of ID and ME teams' designing styles; or
    - 4b. Mixed teams will exhibit a designing style that is different from either ID or ME teams' designing styles.

Participants

Twenty-four final-year undergraduate design students (12 ID & 12 ME) from the National University of Singapore participated voluntarily in this research. All participants had finished the taught courses and were involving in their final-year projects at the time of the experiment. All of them had at least three years of design exercises/projects experience and some had intern experience in design firms. According to the pre-test questionnaire and follow-up interviews, they all claimed to have above-average design expertise among their classmates. Five ID students were award winners of international/regional design competitions.

The unit of experiment was a two-person design team. Literature has identified that, to deal with the increasing complexity of contemporary context, product design had shifted from predominantly individual activity towards predominantly team-oriented activity [18]. Two participants, either from the same discipline or different ones, were paired to work collaboratively in two conceptual design exercises. The factor of design discipline therefore has 3 states: ID, ME and Mixed teams.

Experiment tasks

Two conceptual design tasks were used based on Keinonen's taxonomy of product development concepts and visionary concepts [19]. The first task, Task CM, was to design a coffee maker for the existing market. It simulated a typical initial stage of a normal new product development (NPD) process. Designers were expected to consider practical factors related to a NPD project, e.g., market and user analysis, supporting technology and resources.

The second task was to design a next-generation personal entertainment system/device for the year 2025 (Task PES). It was a visionary task beyond the normal NPD time frame and with open-ended requirements. In terms of the three-pronged nature of a design problem that consists of determined, undetermined and underdetermined elements [20], Task PES faced a very limited amount of determined/unalterable factors. Designers were expected to use design concepts as a tangible means to explore future scenarios.

Ontologically-based protocol segmentation and coding

The participants' conceptual design activities (including conversations and gestures) were audio and video recorded, and then segmented and coded using the FBS ontologically-based protocol coding scheme [15]. Each segment in a FBS-coded protocol was strictly assigned only one of the six design issues. There are no overlapped or multi-coded segments. If an utterance was identified to contain more than one design issue, it was further segmented. Those utterances that did not fit in any of six the FBS categories were marked as "other" (O). These non-design issues were discarded in the following analysis.

The FBS-based protocol segmentation and coding process involves subjective judgments. It used the Delphi method to minimize coder bias and improve the coding reliability [14], [21]. Each set of design protocols was separately segmented and coded twice. An arbitration process was then undertaken to resolve previous coding disagreements and improve the quality of final coding.

After arbitration, the re-categorization of the design issues into the problem-related issue and solution-related issue was automatically assigned based on the mapping shown in Table 1. Some coding examples are presented in Table 2.

Table 2 Coding examples

#	**Segmented Protocol**	**Design issue***	**P-S space****
1	We need to consider that this product expects to be launched in 3 years	R	P_S
2	In terms of material, what do you think is the future trend	F	P_S
3	This should be used like reading a book	Be	P_S
4	So the smell can come out from here	Bs	S_S
5	Here is a dispenser …	S	S_S
6	(draw a dispenser)	D	N/A
7	Should we plan out storyboard first or should we draw first?	O	N/A

* The symbols for FBS design issues are the same with Fig. 1

** P_S: problem-related issue; S_S: solution-related issue; N/A: not applicable

Results

As a consequence of the FBS-based segmentation and coding, the observation of design activities were converted into a sequence of design issues, and then problem- and solution-focused issues, which become the foundational data for the subsequent analyses of ID and ME students' designing styles.

Reliability of the FBS-based protocol coding

The use of the Delphi method results in three sets of FBS-coded protocols, i.e., two separate rounds of coding and an arbitrated coding. The agreement between the arbitrated and the second coding (M = 89.1%, SD = 1.7%) is significantly higher than with the first coding (M= 80.6%, SD = 3.7%) The improvement of reliability reflects the "process gain" enabled by the Delphi method. As the disagreements in the first two rounds of coding have been resolved in the arbitration process, the following analyses are performed on the arbitrated protocols, which are considered to be the most reliable dataset.

Descriptive statistics

Each design session's occurrences of design issues were normalized by dividing them with the total number of design issues in that session. The normalized design issue distributions are shown in Table 3 and Figure 2.

Table 3 Normalized distribution of design issues (%)

Groups \ Design issues		Requirement (R)	Function (F)	Expected Behavior (Be)	Behavior from Structure (Bs)	Structure (S)	Description (D)
ID CM	Mean	0.9	23.6	15.6	20.7	20.3	19.0
	SD	0.4	2.8	4.2	3.8	1.7	6.7
ID PES	Mean	1.5	28.0	23.1	15.7	13.2	18.7
	SD	0.6	3.9	2.9	2.4	3.3	4.4
Mix CM	Mean	0.9	17.9	12.7	27.4	21.5	19.6
	SD	0.4	7.9	1.0	6.6	3.0	2.3
Mix PES	Mean	1.5	17.3	14.4	27.2	18.0	21.6
	SD	0.5	2.9	3.6	8.4	4.5	5.2
ME CM	Mean	1.8	11.4	13.5	28.0	28.3	16.9
	SD	0.4	6.0	3.7	3.2	8.2	5.4
ME PES	Mean	1.1	12.1	15.6	31.2	19.8	20.1
	SD	0.4	2.9	6.2	7.2	2.9	7.0

ID sessions had the highest percentages of function issues and then followed by the Mixed sessions and ME sessions. ID sessions also had higher percentages of expected behavior issues than these other two groups. ME sessions had the highest percentages of the solution-related issues and ID sessions had the lowest ones.

For inter-task comparisons, Task PES tended to have more function and expected behavior issues than Task CM, whereas the percentage of structure issues in Task CM was higher than that in Task PES.

Problem-Solution indexes charactering the whole sessions

The values of P-S index for each design session are shown in Table 4. The problem-focused sessions are highlighted by bold fonts. The results are also plotted in Figure 3, against a line at the value of 1.00 for the P-S index signifying the boundary between problem-focused and solution-focused designing styles.

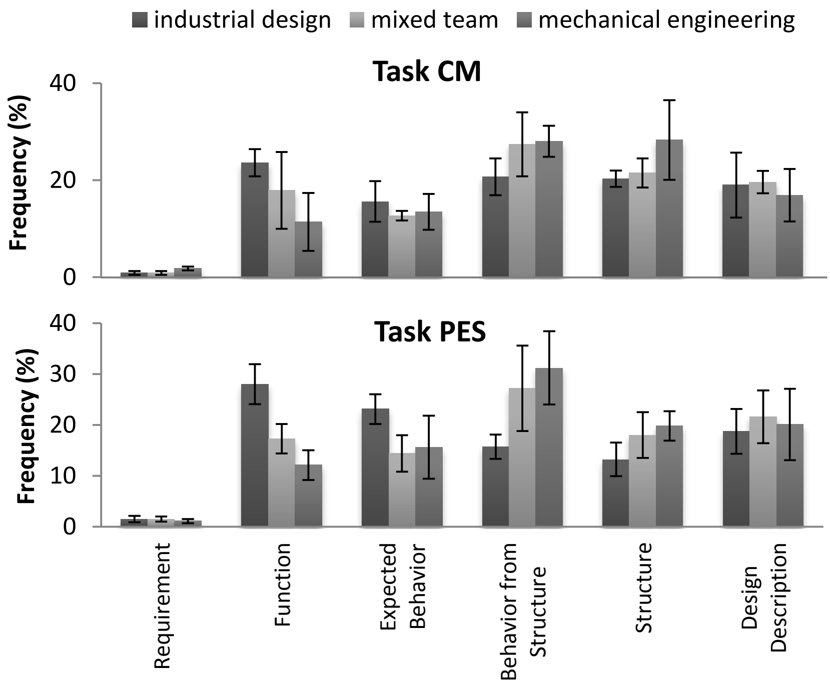

Fig. 2 Frequency distributions of the design issues (%)

Table 4 Values of P-S index

Groups	Value of P-S index for each team				Mean	Std. Dev
	1	2	3	4		
ID CM	0.90	**1.01**	**1.13**	0.88	0.98	0.11
ID PES	**2.04**	**2.32**	**1.74**	**1.40**	1.88	0.39
Mix CM	0.95	0.36	0.89	0.53	0.68	0.28
Mix PES	0.48	0.76	0.77	**1.01**	0.76	0.22
ME CM	0.28	0.34	0.55	0.80	0.49	0.23
ME PES	0.56	0.75	0.46	0.54	0.58	0.12

ID PES sessions had significant higher P-S index values than other sessions, demonstrating a strong tendency of focusing on problem-related issues. The P-S index value of ID CM sessions are around the threshold of problem-solution division. The designing styles of the rest sessions were solution-focused, as indicated by the relatively low P-S index values.

The aggregated P-S index values are presented in Figure 4, against the boundary of the index value equal to 1. This indicates that ID teams generally focused more on the design problem than did the mixed and ME teams.

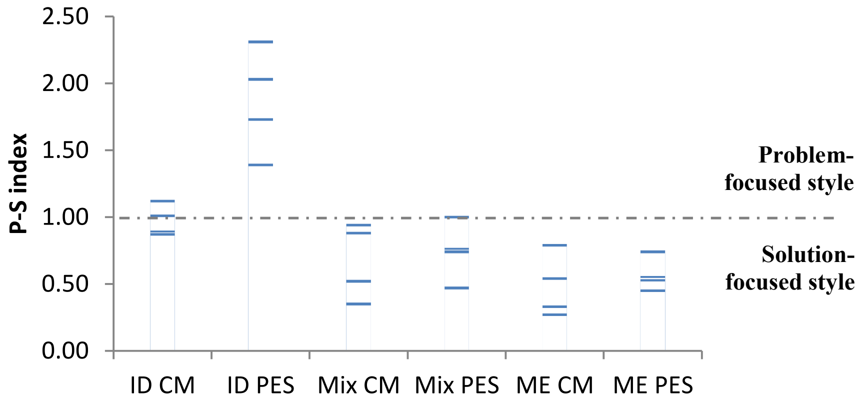

Fig. 3 Values of P-S index and designing styles

The designing styles of ID sessions were significantly different between the two tasks, from near equal focus on both problem and solution for the CM task to a highly problem-focused designing style for the PES task. The mixed and ME teams did not show this behavior.

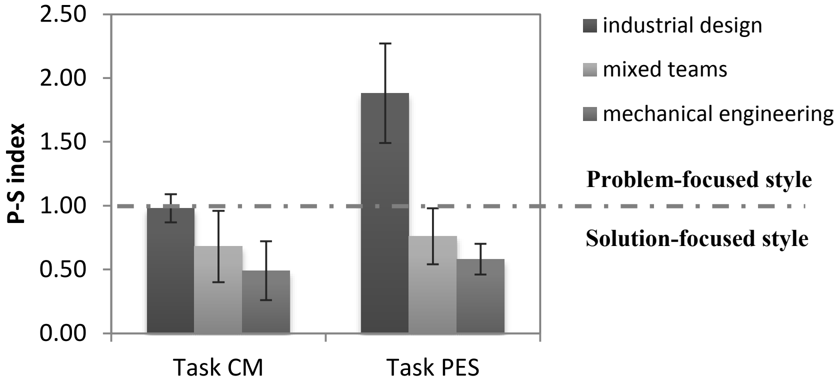

Fig. 4 Aggregated P-S index values

Problem-Solution indexes in fractioned design protocols

The division of the entire session's design protocol into two halves provides a preliminary understanding into the development of design cognition within a design session, Figure 5. Mann-Whitney U tests and Wilcoxon Signed Ranks test were then applied to produce inter-session and within-session comparisons.

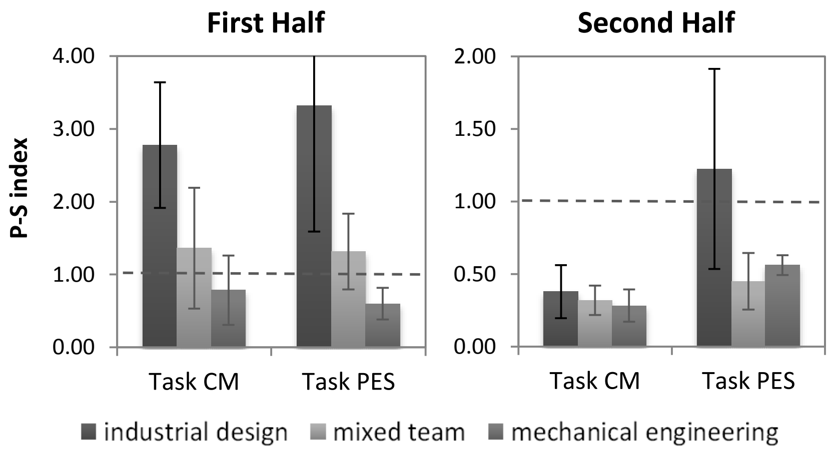

Fig. 5 P-S indexes in two halves of a design session

Inter-session comparisons

The inter-session comparisons of P-S indexes between different disciplinary teams and between different tasks are summarized in Table 5. In the first half of the design sessions' protocols, each disciplinary design team showed a similar designing style between the two tasks. When progressing to the second half of the design session, ID and ME teams significantly focused more on problem in the Task PES than they did in the Task CM. The P-S indexes of the mixed teams' sessions were not significantly different between the two tasks.

Table 5 Inter-session comparisons of P-S indexes in the fractioned protocols

Group	First half of design session	Second half of design session
ID teams	ID CM ≈ ID PES	ID CM < ID PES
Mixed teams	Mix CM ≈ Mix PES	Mix CM ≈ Mix PES
ME teams	ME CM ≈ ME PES	ME CM < ME PES
Task CM	ID CM > Mix CM ≈ ME CM	ID CM ≈ Mix CM ≈ ME PES
Task PES	ID PES > Mix PES > ME PES	ID PES > Mix PES ≈ ME PES

≈ not significantly different
> significantly larger than
< significantly smaller than

Figure 5 and Table 5 also indicate that, in the second half of Task CM sessions' protocols, there were no significant differences between ID, mixed and ME teams' P-S index values. For the remaining halves, the ID sessions had a much higher P-S index than the other two groups. The mixed teams' P-S index was also significantly higher than ME teams in the first half of Task PES sessions.

Within-session comparisons

Comparing the first and second halves of design sessions' P-S indexes indicates that all design sessions' cognitive focus in the first half was more on the problem than in the second, with the exception of the ME PES sessions, Table 6.

Table 6 Comparing P-S indexes between the first and second halves of design sessions' protocols

Task / Discipline	Task CM		Task PES	
	Z Statistics	*p*- value (1-tailed)	Z Statistics	*p*- value (1-tailed)
ID teams	-1.826	0.034*	-1.826	0.034*
Mixed teams	-1.826	0.034*	-1.826	0.034*
ME teams	-1.826*	0.034*	-0.365	0.358

* $p<0.05$

Sequential Problem-Solution division and indexes

After subdividing the entire design session into 10 non-overlapping sections, most groups' sequential P-S division was found to have a significant negative correlation to the fractioned protocol sections, Table 7. As the percentage of problem-related issues and P-S index are two representations of the same set of measurements, their correlation coefficients with time and the *p*-values were the same. The decreasing focusing on problem, measured in sequential P-S indexes, was consistent with the P-S indexes in two halves of design session, Table 6. ME PES sessions' decreasing trend was not statistically significant.

The mean sequential percentage of problem-related issues can be plotted against their fractioned sections along with the boundary of the P-S division of 50%, Figure 6. The corresponding P-S indexes are presented in Figure 7. These two figures can be read as "signatures" of design dynamics over a design session.

Table 7 Correlation between sequential problem issues and fractioned sections

Group	**Spearman's**	**Sig** (2-tailed)	**Slope (Problem-issue %)**	**Slope (P-S index)**
ID CM	-0.914	0.000*	-0.090	-1.586
ID PES	-0.732	0.000*	-0.050	-0.641
Mix CM	-0.724	0.000*	-0.056	-0.425
Mix PES	-0.629	0.000*	-0.048	-0.254
ME CM	-0.518	0.001*	-0.043	-0.124
ME PES	-0.218	0.176	-0.015	-0.092

* $p<0.005$

Preliminary Test of Hypotheses

This section presents a qualitative test in response to the four main hypotheses about whether designers' tendency to focus on problem or solution is affected by design teams' disciplinary backgrounds and the nature of design requirements.

General trend from more problem-focused to more solution-focused

Hypothesis 1 is that there are similarities between design sessions in terms of the designing style, which are independent of specific design disciplines and tasks. Figures 6 and 7 demonstrate that, despite fluctuations, designers' cognitive focus on design problems decreased along with the progression of designing. All session's linear estimation lines for their sequential P-S division and P-S indexes were negative, Table 7.

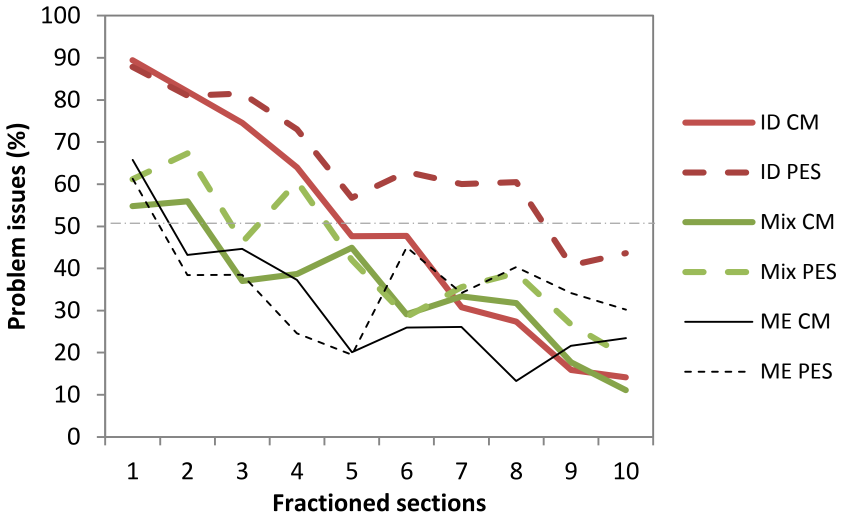

Fig. 6 Sequential distributions of problem-related issues (%)

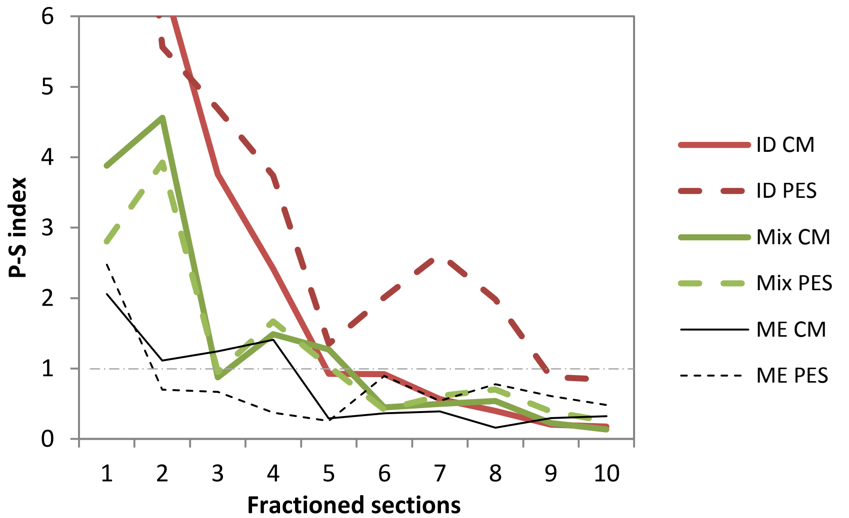

Fig. 7 Sequential P-S indexes along the fractioned 10 sections of session.

This supports the argument that there is a regularity in design cognition transcending specific parameters of designing [15]. However, the decreasing focus on problem is a relatively weak pattern. Some sessions only demonstrate a small tendency to move more towards a solution-focus, as their correlation with the fractioned sections was not significant, Tables 5 and 7.

Inter-disciplinary differences

Hypothesis 2 is that teams with different disciplinary backgrounds result in different designing styles. According to Restrepo and Christiaans [9], Kruger and Cross [10] and Lloyd and Scott's [11] findings, ID teams may focus more on problem-related issues and ME teams tend to be more solution-focused. The evidentiary support for this hypothesis is demonstrated by both the single-value P-S indexes and sequential P-S division.

In both tasks, as shown in Figure 4, ID teams have the highest overall P-S indexes and ME teams present the lowest values. Figures 6 and 7 show that the curves of the ID sessions are generally above the curves of the ME sessions.

In general, ID teams' designing style focuses more on the design problem, and ME teams have a more solution-focused style. However, the identified inter-disciplinary differences do not have the same significance between the two tasks. Figures 5 and 6 show that ID teams demonstrate two distinct designing styles between the two tasks. The problem-focused designing style dominated in the ID PES session, and they gradually shifted from the problem-focused designing style to a solution-focused one during the Task CM sessions. ME teams, to the contrary, show a strong solution-focused designing style for both tasks. They give problem-related issues an equal emphasis to solution-related ones in the beginning of the design sessions, Figures 6 and 7. This result implies that ID teams may lend themselves more to a designing style change in response to the change of design tasks, whereas ME teams adopt one designing style to cope with different classes of requirements.

Inter-task differences

The test of Hypothesis 2 has already involved Hypothesis 3, i.e., the designing style of one team may change in accordance to the requirement changes. Table 4 and Figure 4 indicate that ID and ME teams both show a higher P-S index in Task PES than Task CM. Figure 5 and Table 5 further show that the inter-task differences occurred in the later stages of design sessions; for each disciplinary team, there was no significant difference of P-S indexes in the first half of the design session.

The best-fit line of Task PES's sequential P-S division is also found to have a smaller slope value than that of Task CM, Table 7. The decrease of problem focus progresses at a slower rate in Task PES. The graphs of sequential P-S division, Figures 6 and 7, show that Task CM and Task PES of ID and ME teams each start with a similar focus on the problem, but their designing styles differ as the design session progresses. In the latter part of the design sessions, designing for Task PES, the focus on problem is relatively larger than that of Task CM.

A qualitative assessment of video recording and transcripts [17] indicates that the formulation of design problem is revisited periodically in the latter episodes of Task PES session. The ill-defined, open-ended design task may require more effort on problem reframing. The same behavior is rarely observed in the relatively well-defined Task CM.

Averaging ID and ME styles in the mixed teams

Hypotheses 4a and 4b are mutually exclusive, i.e., whether or not Mixed teams will exhibit a designing style that is the average of ID and ME teams' designing styles. Table 3, Table 4 and Figure 4 show that in most measurements of Mixed teams, the design issues, P-S index value and best-fit line slope of sequential P-S division, the behavior of Mixed teams is always between that of ID and ME teams.

Figures 6 and 7 show finer-grained results about the time-based change of cognitive focus in the P-S division. These two figures show that in the beginning of the design session (i.e., the first two fractioned sections), Mixed teams resemble the ID teams' designing style, deploying their primary focuses on the design problem. With the progress of designing, Mixed teams exhibit a designing style similar to ME teams, as evidenced in the interwoven curves of Mixed and ME teams in the latter 5 fractioned sections. This suggests that ID and ME students may make a stronger contribution in the problem formulation and solution development respectively.

Another finding about Mixed teams is the relative stability of their designing style. The paired-sample Wilcoxon Signed Rank test indicates that Mixed teams' P-S indexes are not significantly different between the two tasks. Visual presentations of sequential P-S division in Figures 6 and 7 also demonstrate a similar trajectory between Task CM and Task PES.

Conclusion

This paper presents a novel measurement of designing styles through reinterpreting the FBS design issues [15], [16] through the dichotomy of problem and solution spaces. Compared to a set of design issues, the single-value P-S division can facilitate an efficient comparison between groups, in particular in the cases involving more than two groups. The translation of the design issues into cognitive focuses on problem and solution, another commonly used terminology in design research, also provides a connection between the FBS-based protocol studies with non-FBS-coded design research.

This new P-S division measurement is then applied to a set of results from an experiment, which examines the effect of design discipline and the type of task on the style of designing. It is found that ID teams tend to have problem-focused designing styles and ME teams have a very solution-focused style. A small design team's designing style may shift while designing with different classes of requirements. The same group of designers tends to focus more on design problem when they deal with open-ended design requirements.

These results also imply that, simply grouping people from different disciplines may result in a designing style mixing the characteristics of those disciplines. An efficient multidisciplinary design team may require team building efforts to make it happen.

Due to the explorative nature of this study, these findings are tentative and limited by the small sample size in this experiment. Future studies with a larger sample size are needed to generalize these findings and provide more insights in the relevant areas.

In addition, ontological design processes are a consequence of the FBS-based protocol segmentation and coding, defined as transitional processes between pairs of design issues [15], [16]. Categorizing ontological design processes into problem-focused and solution-focused design processes may provide a new perspective to examine designing styles.

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