Proceedings of the ASME 2017 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC2017
August 6-9, 2017, Cleveland, Ohio, USA

DETC2017–68239

DESIGN WHODUNIT: THE RELATIONSHIP BETWEEN INDIVIDUAL CHARACTERISTICS AND INTERACTION BEHAVIORS IN DESIGN CONCEPT GENERATION

Neeraj Sonalkar
Stanford University
Palo Alto, CA, USA

Kathryn Jablokow
Penn State University
Malvern, PA, USA

Jonathan Edelman
Royal College of Art
London, UK

Ade Mabogunje
Stanford University
Palo Alto, CA, USA

Larry Leifer
Stanford University
Palo Alto, CA, USA

ABSTRACT

This paper investigates the relationship between interaction behaviors and the cognitive characteristics of participating individuals in engineering design teams engaged in concept generation. Individual characteristics were measured using the Kirton Adaption-Innovation inventory (KAI), which assesses an individual's cognitive preference for structure in seeking and responding to change. Team interactions were measured using the Interaction Dynamics Notation (IDN), which allows interaction behaviors to be quantitatively analyzed. A correlation analysis revealed statistically significant correlations between individual characteristics and specific interaction behaviors and ideation utterances. An interaction sequence analysis of the team data also revealed specific interaction sequences associated with greater probabilities of idea occurrence within the team. These findings serve as a first step towards building a cognitive-behavioral model of engineering design team performance.

Keywords: Design teams, design behavior, design cognition

INTRODUCTION

The ability to innovate in the design of complex products and systems is a key factor in enhancing industry competitiveness, long-term productivity growth, and the generation of wealth [1]. Prior research has identified teams as a key determinant of an organization's ability to innovate [3, 4, 5], including the teams involved in engineering design – an inherently socio-technical activity [2]. Engineers interact with each other and with different artifacts and tools as they exchange information, generate concepts, and develop and test prototypes in order to design complex products and systems. Our understanding of engineers interacting and working in teams is therefore central to our understanding of and our efforts to improve the quality of technical innovation.

Engineers at all levels, from novices to experts in both academia and industry, frequently blame team dysfunction on anecdotal reports of "difficult personalities" or "personality clashes", while praising the way other teams are able to "leverage their diversity" and "gel" to produce outstanding results. Is there hard evidence that personality and other individual characteristics are manifested in team interaction behavior? Previous research on the interactions of engineering design teams has focused primarily on specific behaviors, such as gestures [6], emotional expression [7], question-asking [8], and prototyping [9], and/or on team interactions in specific design-related scenarios, such as concept generation [10] and design reviews [11]. This early research on the interaction behaviors observed in design teams rarely (if ever) addresses the individual characteristics of the participating designers and the influence those characteristics have on the observed behaviors. On the other hand, research on the individual characteristics of designers often makes use of personality and other cognitive assessments, such as the Myers Briggs Type Indicator (MBTI) [12, 13], the Kirton Adaption-Innovation inventory (KAI) [14], the Herman Brain Dominance Indicator (HBDI) [15], or the NEO Five Factors Inventory [16], but does not address how these individual characteristics actually manifest through moment-to-moment behavior to influence design outcomes. If we are to understand the relationship between personality and other individual characteristics and the interaction behaviors of engineering design teams, our research needs to address them simultaneously within our experimental design. To this end, this paper presents a preliminary study of design teams where characteristics of individuals and their moment-to-moment behaviors are analyzed together with respect to the design outcomes (i.e., ideas) that were generated.

RESEARCH OBJECTIVE: A COGNITIVE-BEHAVIORAL MODEL OF DESIGN TEAM PERFORMANCE

The work presented here is part of a larger effort in which we are mapping the individual characteristics of design team members and their interactions to their performance in terms of innovative design to identify the behavioral building blocks of design teams that produce high performance outcomes (i.e., High Performance Design Teams). The identification of such behavioral building blocks will lead to scientific cognitive-behavioral models of design teams that will apply in academic and industry environments, as well as new tools for improving the effectiveness of those teams. Our aim to identify and map the behavioral building blocks of High Performance Design Teams (HPDTs) is composed of two functional objectives (see Fig. 1):

1) Identify the behavioral interaction sequences and individual characteristics that characterize high performance design teams (the HPDT "genome"); and
2) Map these sequences and characteristics to innovative design outcomes.

Fig. 1. Mapping the high performance design team "genome"

The reported study marks one of our first steps toward creating such a scientific model based on detailed observation and analysis of real engineering design teams.

MEASURING INDIVIDUAL CHARACTERISTICS

Among the many frameworks proposed for understanding cognitive diversity [14, 18-20], Kirton's Adaption-Innovation (A-I) theory [16] excels in explaining the complexity of individual characteristics in an accessible way. In addition, the problem solving context in which A-I theory was originally developed makes its application to the study of engineering teams straightforward and effective [21-32]. A-I theory [14] is based on the key assumption that all individuals are creative, where creativity is characterized by four variables: cognitive level, cognitive style, motive, and opportunity. In our work here, cognitive style and cognitive level are of primary interest. *Cognitive level* is defined as an individual's capacity for problem solving and creative behavior, as assessed through measures of both potential capacity (e.g., intelligence, aptitude) and manifest capacity (e.g., knowledge, skills). In contrast, *cognitive style* is defined as one's stable, characteristic cognitive preference for structure in seeking and responding to change, including the solution of problems [14].

Cognitive level is a unipolar construct (measured on a continuum from low to high), while cognitive style is a bipolar construct (measured on a continuum between two different, but equally valued, extremes). Specifically, Kirton's Adaption-Innovation (A-I) cognitive style ranges along a continuous spectrum between highly adaptive and highly innovative preferences [14, 21, 33], with mild and moderate degrees of those preferences in between. In general, individuals who are *more adaptive* prefer more structure (with more of it consensually agreed), while *more innovative* people prefer less structure (with less concern about consensus). Research shows that these characteristics produce distinctive patterns of behavior (working alone or with others), although an individual can and does behave in ways that are not preferred, at an extra cognitive cost (i.e., *coping behavior* [14]). When engineers work together, their diverse cognitive characteristics will influence their collaboration in both positive and negative ways. Kirton uses the term *cognitive gap* to describe differences in cognitive level and/or cognitive style that can appear between two individuals, an individual and a group, two groups, and/or between an individual/group and the problem at hand [14, 34].

Kirton's Adaption-Innovation Inventory (KAI)

In the context of engineering design teams, cognitive level is typically assessed through readily available information, such as degrees earned, years' experience in relevant areas, known skill sets, etc. Assessment of cognitive style is best accomplished via KAI® (the Kirton Adaption-Innovation inventory) [14, 35], which has been rigorously validated and is currently being used in a variety of contexts, including engineering, education, business, and the U.S. military [14]. For large general populations and across cultures, the distribution of KAI total scores forms a normal curve within the theoretical range of (32–160), with an observed mean of 95 (SD =17) and an observed range of (43–149); lower scores correspond to more adaptive cognitive styles, while higher scores correspond to more innovative styles. Through multiple validation studies, Kirton also identified three sub-scores that correspond to three sub-factors of cognitive style: Sufficiency of Originality, Efficiency, and Rule/Group Conformity. These sub-factors are also normally distributed within the following theoretical ranges: SO (13–65), E (7–35), and R/G (12–60) [16].

The Sufficiency of Originality (SO) sub-factor highlights differences between individuals in their preferred ways of generating and offering ideas. The more adaptive tend to generate more highly detailed ideas that remain more closely connected to the original constraints of a problem, while more innovative individuals tend to generate ideas that challenge the problem definition and constraints [14-16]. The Efficiency (E) sub-factor reflects an individual's preferred methods for managing and organizing ideas and for solving problems. The more adaptive prefer to define problems and their solutions carefully, paying closer attention to details and organization, while the more innovative often loosen and/or reframe the definition of a problem before they begin to resolve it [14, 16]. Finally, the Rule/Group Conformity (R/G) sub-factor reflects differences in the ways individuals manage the personal and impersonal structures in which their problem solving occurs. The more adaptive generally see standards, rules, traditions, and instructions as enabling and useful, while the more innovative are more likely to see them as limiting and irritating. When it comes to personal structures (e.g., teams, partnerships), the more adaptive tend to devote more attention to group cohesion, while the more innovative are more likely to "stir up" a group's internal dynamics [14, 16].

MEASURING TEAM INTERACTION BEHAVIOR

Team interaction can be defined as reciprocal action between the members of a team. For a design team, it is the sequences of verbal and non-verbal actions and responses between individuals as they go about understanding problems, generating solutions, and developing prototypes. In order to measure such team interaction behavior, we chose the Interaction Dynamics Notation (IDN), a visual representation system that was specifically designed to capture these reciprocal actions between individuals in a design team [36, 37]. The Interaction Dynamics Notation is based on force dynamics theory from the field of cognitive semiotics [38], which highlights the forces exerted through language. IDN captures these forces through symbols based on principles of improvisational behavior [39] (see Fig. 2).

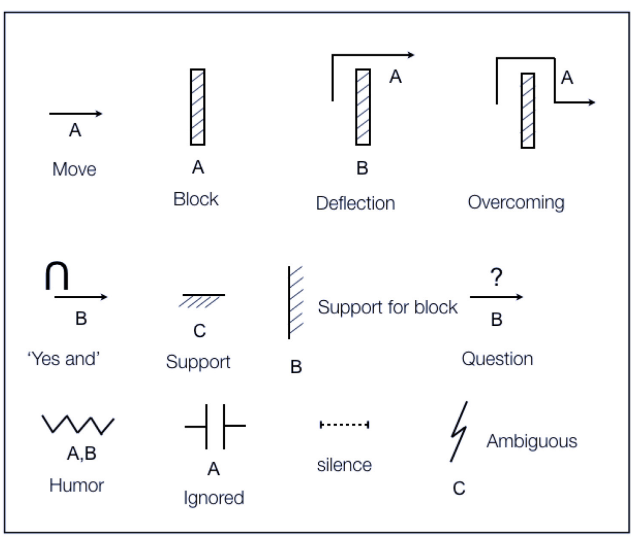


Fig. 2. Interaction Dynamics Notation (IDN) symbol set.

Each IDN symbol is assigned to an action, both verbal and non-verbal, that is conducted by a participant and responded to by her team members. This assignment is based not on what the action *is*, but rather on the *response* the action receives. For example, an action will be assigned the symbol *block* because others in the team responded to that action by indicating they were blocked, not because the action "is" (was intended as) a block. Thus, IDN captures the reciprocity of interaction and models *team* interaction rather than a sequence of individual contributions. Figure 3 shows an example of a team interaction segment visualized and coded using IDN.

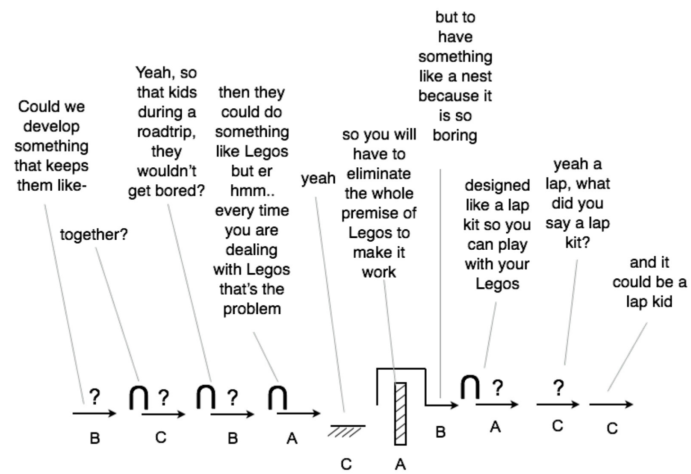


Fig. 3. Team interaction represented using IDN: A, B, C are individuals in the team.

ADVANCING THE SCIENCE OF DESIGN TEAMS

The development of the Interaction Dynamics Notation gives us access to moment-to-moment analysis of design team interactions through a formal representation. Earlier research on team interactions used text-based discursive methods such as Conversation Analysis to describe interaction behaviors in design teams [40]. IDN advances the measurement of team interaction to a formal representation that can be further analyzed quantitatively. This could be likened to the advancement in the field of chemistry from describing a chemical reaction in natural language to representing it formally through chemical equations. The combination of IDN for team interaction measurement and a cognitive diversity measure such as KAI now gives us an opportunity to create a cognitive-behavioral model of team performance that could be integrative as well as generative in terms of influencing design practice and opening new directions for design research.

Research Questions for Model Creation

The key research questions underlying our development of a cognitive-behavioral model of team performance are:

1. What is the relationship between individual characteristics and interaction behaviors in design teams?
2. How could this relationship be represented in a descriptive model?

We investigate these research questions by applying KAI and IDN to a team concept generation dataset created by Edelman [9]. The objective is to present our proposed methodology of model creation, as well as some preliminary findings about the relationship between individual characteristics and interaction behaviors in design teams. Since each of the IDN symbols pertains to a distinct interaction behavior, we probe the link between the KAI scores and these distinct interaction behaviors. We hypothesize that individual cognitive styles measured through KAI could have a significant correlation with multiple interaction behaviors, indicating that these behaviors have a dependence on the cognitive styles of the participants. We then identify interaction sequences associated with concept generation in these teams, and investigate whether the cognitive styles of the individuals in a team are associated with distinct interaction sequences for concept generation. Both correlation analysis and interaction sequence analysis shed light on the relationship between individual characteristics and interaction behaviors in teams in the context of design concept generation.

DATASET

The dataset we are utilizing to develop a preliminary model consists of 14 non-hierarchical teams of three individuals each. The teams consisted of individuals from engineering design and product design backgrounds who were undergraduate students, graduate students, design instructors, or industry practitioners. Eight of the teams were mixed gender teams, four were all-make teams, and two were an all-female team. The ages of the team members ranged from 20 to 54 years old. The teams engaged in a concept design task, in which they were given an engineering drawing of a fictitious device called the 'material analyzer' and asked to develop it further. At five minutes into the activity, the teams were given another prototype of the device to help stimulate their concept development. Different teams were given different prototypes – some were given a foam model, some were given a cardboard model, some were given a concept sketch, and others were given a working cardboard prototype. The teams each worked for a total of 30 minutes and delivered a solution concept for an "improved" material analyzer. Their design activity was video recorded and transcribed.

This study was originally designed by Edelman [9] to investigate the influence of media models on concept generation behavior. We are utilizing this particular dataset for studying the relationship between individual characteristics and team interaction behaviors for the following reasons:

1. It is a dataset of design teams engaged in a concept development activity typical of engineering design practice;
2. The participants in the teams composed for this study were familiar with each other and were from mechanical engineering design or product design backgrounds. The teams could thus be considered as proxies for engineering design teams working in industry setting;
3. The data are in video format, which can be used to create IDN representations of team interactions; and
4. The individuals participating in the study completed the KAI when the study was conducted by Edelman.

In this paper, we present a preliminary analysis of four of the 14 teams in the dataset. There of these four teams were mixed gender and one was a all-male team. These four teams were selected because they were homogeneous in terms of their cognitive styles as measured by KAI – i.e., the individual KAI total scores for each team were very similar (within 20 points; see Table 1). Homogeneous teams are generally more comfortable working together, and the team members are more likely to revert to their natural preferred behavior [14]. As a result, their team interactions can be considered as exemplars of the interaction behaviors you would expect to see for that particular style [14]. Thus, the four homogeneous teams enabled a team-to-team comparison that is close to a person-to-person comparison for their specific cognitive styles.

ANALYSIS METHODS

Data analysis consisted of six steps, beginning with coding of the videos previously collected by Edelman [9]:

1. Coding team videos with IDN:

The video data of each team were coded by at least two IDN analysts, who were all trained with standardized IDN coding flowcharts to ensure data reliability. Furthermore, inter-rater reliability of IDN coding was evaluated using the weighted Levenshtein's distance, which is used to compare sequential data, such as two strings of symbols [41]. The mean weighted Levenshtein's ratio for IDN coding of the four teams was 0.72, which was in the moderate agreement range. Any disagreement in coding was resolved through consensus coding sessions, which involved all analysts watching the video together, debating the disagreement, and coming to a consensus about the assignment of IDN symbols.

2. Segmenting the design activity into interaction segments:

Once the four team videos were converted into IDN codes, the codes were aligned with the transcripts of the appropriate team interaction and broken down into interaction segments. Interaction segments are sequences of interpersonal interactions organized around a continuous coherent topic. An interaction segment consists of a chain of responses, each dependent on the preceding responses in the sequence. When an expression no longer directly refers to a preceding response and introduces a new topical direction, it signifies the end of one interaction segment and the beginning of another.

Once the IDN representations were broken into interaction segments, the total number of segments per team was counted and used as an indicator of topical spread in the team interaction. Furthermore, the links between different interaction segments were analyzed using the principle of links between speaker turns proposed by Goldschmidt [42]. The links between two interaction segments were identified based on whether the two segments were connected topically (e.g., if both segments referred to a touch screen as a solution feature). This analysis gave us the following measures for each of the teams: the total number of interaction segments; the ratio of linked to unlinked segments; and the level of depth of links, which indicated the maximum number of linked segments (e.g., 2, 3, 4, etc.).

3. Identifying ideation utterances in the interaction data:

The third step was the identification of ideation utterances in the dataset as a measure of team design concept generation outcomes. We utilized the ideation utterance identification scheme developed by Edelman [9], which counted any verbally expressed change to the original material analyzer concept as "an idea". Further, a sub-category of "unique ideas" was identified, such that multiple verbal expressions relating to one major change could be considered as contributing one unique idea. A category of "sub-ideas" was also created to account for the different feature-related ideas belonging to each of the unique ideas developed by the team. For example, one team had five verbal idea utterances (total ideas = 5) that led to the development of one unique idea regarding a sensor. This interaction consisted of two sub-ideas, one relating to the placement of the sensor and the other to its tilt mechanism.

4. Cognitive style (KAI) assessment:

The KAI was administered to the teams at the time of the study; the KAI scores of the four teams featured in our analysis are given in Table 1. From these results, we see that even this small sample of subjects had considerable cognitive style diversity, with a KAI total score range of 44 points and internal team cognitive gaps up to 16 points. The sub-scores (SO, E, and R/G) are all in line with their respective KAI total scores, indicating that the teams' behaviors and interactions related to idea generation, methodology, and conformity to rules and group norms should also exhibit a range of diverse responses.

Table 1: Cognitive style (KAI) scores for Teams 2, 7, 9, and 10

		Individuals				***Team***	
	Person	KAI Total	SO	E	R/G	Max. Internal Gap	Mean KAI score
Team 2	A	94	49	24	21	13	93
	B	86	43	14	29		
	C	99	42	21	36		
Team 7	A	112	50	21	41	11	110
	B	103	49	17	37		
	C	114	48	23	43		
Team 9	A	109	50	18	41	12	102
	B	100	47	21	32		
	C	97	46	20	31		
Team 10	A	123	56	23	44	16	133
	B	139	55	29	55		
	C	137	59	22	56		

The mean KAI score of a team serves as one measure of a team's cognitive climate – i.e., the general cognitive "flavor" of the team's approaches, behaviors, and outcomes [14, 21, 24, 32-34]. Research shows that the just noticeable difference for cognitive climate between teams is 5 points between the team KAI means [14]. The cognitive style gaps between the KAI means of the homogeneous teams of Table 1 are all greater than 5 points, indicating that the cognitive climates of these teams should be readily distinguishable under normal operation (given sufficient time for observation). For example, we can expect Team 2 (the most adaptive team) to be the most structured of the four teams, while Team 10 is the least structured – with Teams 7 and 9 falling between the two. Research shows that style-related differences can be observed in both the processes and the outcomes of homogeneous teams, including the number and type of ideas generated and ways of making decisions [14].

5. Correlation analysis:

The KAI scores, IDN symbols, idea measures, and interaction segment measures were analyzed using Minitab® to identify any statistically significant correlations between them. We applied the Holm-Bonferroni correction in our correlation analysis to account for probability of Type 1 (false positive) errors due to multiple comparisons [17, 45].

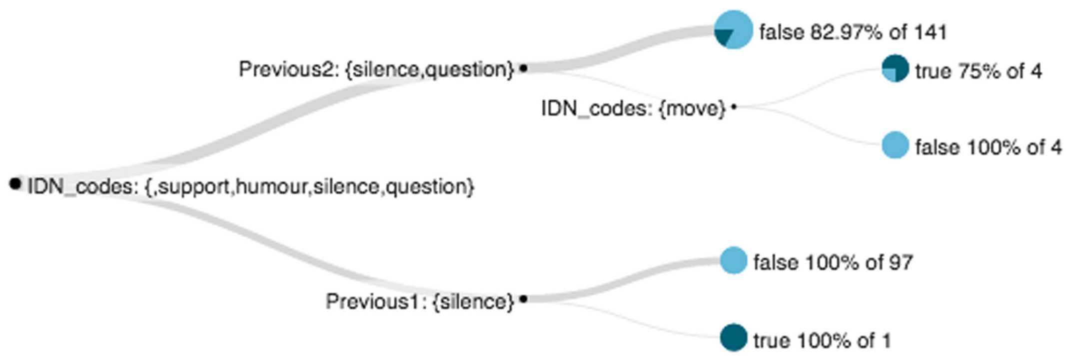
6. Sequence analysis:

A sequence analysis of the IDN data was conducted to reveal team-level interaction sequences associated with ideation utterances in each of the four teams, each with its own distinct cognitive climate. This enabled us to investigate if the team members' cognitive styles are associated with distinct interaction sequences for concept generation. The IDN data were analyzed using a decision tree method called the Classification and Regression Trees (CART) algorithm [43]. Decision trees are used in data mining to create predictive models of how a target (dependent) variable could be arrived at through a combination of its input (independent) variables. Classification and Regression Trees are a category of decision trees that follow an algorithm developed by Breiman et al. [43] to recursively partition the observed combination of independent variables in order to reach the value of the target dependent variable. We used the CART algorithm implemented in the Datameer® software [44] to reveal possible interaction sequences of consecutive IDN responses that predict the occurrence of an idea or a unique idea for each of four teams. The link level depth was selected as "4", which implies a maximum of three decision nodes leading to the target variable of an idea or unique idea occurrence.

KEY FINDINGS

Correlation Analysis

Finding 1: KAI scores did not correlate with IDN response behaviors. Testing each of the distinct interaction behaviors described in the IDN against KAI scores, we did not find any statistically significant relationship between individual KAI scores and IDN response behaviors after applying the Holm-Bonferroni correction [17, 45] for multiple comparisons. In



other words, there was no significant connection revealed between the cognitive style of an individual team member and the likelihood of their association with a particular interaction behavior as defined by IDN.

Fig. 4. CART diagram for Team 10 with *unique idea* as target.

Finding 2: KAI total score and Sufficiency of Originality sub-score were positively correlated with occurrence of unique ideas. In Table 2, the statistically significant and moderately strong positive correlations between the number of unique ideas and the KAI total score and SO sub-score indicates that the more innovative team members were more likely to offer a larger number of unique ideas in the team ideation sessions. This result aligns with A-I theory, which suggests that more innovative individuals prefer to proliferate novel options with little filtering to determine whether those options are feasible, while the more adaptive prefer to offer a manageable number of novel options, which they "pre-screen" more carefully for feasibility within the current system. It is important to note that this does not mean that more innovative individuals will always offer more ideas than their more adaptive counterparts will; cognitive level is another key factor in determining how many ideas an individual will generate. A highly adaptive person with a higher cognitive capacity or more experience may offer more solutions than a highly innovative person who knows less about the problem or is less motivated to solve it.

Table 2: Correlations between KAI and ideation utterances

Ideas (individual) / KAI Score	*KAI Total*	*SO*	*E*	*R/G*
Total ideas	0.327	0.46	0.022	0.295
Unique ideas	0.702*	0.794**	0.317	0.631
Sub ideas	0.228	0.364	-0.03	0.2

*$p < 0.05$, **$p < 0.01$

Finding 3: Mean KAI score at the team level was positively correlated with the ratio of linked to unlinked interaction segments. In Table 3, the statistically significant and strong positive correlation between the ratio of linked/unlinked topical segments and the mean KAI of the team is striking. This indicates that the more innovative a team's cognitive climate (i.e., the higher the KAI mean of the team), the more likely they were to exhibit more linked topical segments in their team interactions. In face-to-face observation, this would likely appear as team members circling back more frequently to revisit a topic that had been discussed earlier, with a higher degree of "interwoven-ness" among those topics. This result aligns with A-I theory, which suggests that the more innovative are more likely to form tangential connections across domains, while their more adaptive counterparts are more likely to create deep connections within those domains [14].

Table 3: Correlations between KAI and interaction segment parameters

Interaction segment parameters	*Mean KAI*
Total segments	-0.407
Linked/unlinked	0.987*
Depth Level	0.518

*$p < 0.05$, **$p < 0.01$

IDN Sequence Analysis

The IDN sequence analysis of team interactions led to Classification and Regression Tree (CART) diagrams for each of the four teams. One CART diagram per team was created using *unique ideas* as the target variable, and another diagram was created using (*total*) *ideas* as the target variable. See Fig. 4 for an example CART diagram for Team 10. The CART analysis was conducted for each of the four teams separately because we did not want to generalize across the individual characteristics, which differed from team to team. This also enabled us to compare interaction patterns across homogeneous innovative and homogeneous adaptive teams from a cognitive style (KAI) perspective.

In Fig. 4, the end state of "true" indicates the probability of occurrence of *unique ideas*, and the state of "false" indicates the probability of non-occurrence of *unique ideas*. The independent variables here are the sequence of IDN responses, starting with the IDN code that corresponds to the same speaker turn as the unique idea, the previous IDN response (called Previous1), and the IDN response before that (called Previous2). The tree consists of three nodes, with each bifurcating into two paths. The top path is the one in which the node condition does not occur, and the bottom path is the one in which the node condition does occur. As shown in Fig. 4, the path for achieving 75% probability of occurrence of a *unique idea* is as follows:

1. The top path for the base node (IDN_code *not* among *support*, *humor*, *silence*, or *question*) +
2. The bottom path for the second node (Previous2 is either *silence* or *question*) +
3. The top path for the third node (IDN_code is not *move*).

Table 4 shows the team interaction sequences measured with IDN and the corresponding probabilities of occurrence of *unique ideas* for Team 10. The three columns in the table (Previous2, Previous1 and IDN code) represent a sequence of consecutive responses from left to right. The table indicates that there are specific interaction sequences that predict the occurrence of unique ideas in Team 10, a homogeneous innovative team. For example, an interaction sequence in which a person responds with silence or a question during interaction, followed by another person responding with any of the IDN categories, followed by another person responding with anything *other* than support, humor, silence, question, or move, is shown to lead to the occurrence of a unique idea with 75% probability. Similarly, an interaction sequence in which silence is followed by support, humor, silence, or question is shown to lead to unique idea occurrence with 100% probability.

Table 4: Interaction sequences associated with unique idea occurrence in Team 10.

Previous2	***Previous1***	***IDN code***	***% Probability of unique idea occurrence***
Silence or question	Any	Anything other than support, humor, silence, question or move	75
Any	silence	Support, humor, silence or question	100

The CART analyses with *unique ideas* as the target variable did not reveal any interaction sequences in Teams 7 and 9 that were associated with unique idea occurrence with a probability greater than 50%. The analysis for Team 2 (the most adaptive team) did reveal one interaction sequence associated with a 66% probability of unique idea occurrence, as shown in Table 5. This indicates that in Team 2, a homogeneous adaptive team, *yesand* plays an important role in the occurrence of unique ideas. A sequence in which *yesand* is followed by *move*, which in turn is followed by another *yesand* response, is shown to lead to unique idea occurrence with 66.67% probability.

Table 5: Interaction sequences associated with unique idea occurrence in Team 2

Previous2	***Previous1***	***IDN code***	***% Probability of unique idea occurrence***
yesand	move	yesand	66.67%

A CART analysis with *(total) ideas* as the target variable for the four teams revealed an interaction sequence that predicted 89.5% probability of idea occurrence for Team 10 (see Table 6). The rest of the teams had interaction sequences with less than 50% probability of idea occurrence. These findings indicate that interaction sequences with *yesand* behavior are implicated in the occurrence of (total) ideas, though only in Team 10.

Table 6: Interaction sequences associated with (total) idea occurrence in Team 10

Previous2	***Previous1***	***IDN code***	***% Probability of idea occurrence***
Yesand or question	Any	Yesand	89.47

DISCUSSION

The research questions guiding our study were as follows: (1) what is the relationship between individual characteristics and interaction behaviors in design teams; and (2) how could this relationship be represented in a descriptive model? Our preliminary analyses did point to the existence of a relationship between the individual cognitive characteristics of participants in a team and the team's interaction behavior. While the findings did not reveal statistically significant correlations between KAI and IDN interaction behaviors, the analysis did show that the presence of individuals on the more innovative end of the KAI spectrum (i.e., those who inherently tend to generate ideas that challenge the problem definition and constraints) is correlated with a greater occurrence of unique ideas in the team. The correlation between KAI team mean score and the ratio of linked to unlinked segments indicates that teams with a greater proportion of individuals on the innovative end of the KAI spectrum tend to have interactions that have a greater degree of integration or interwoven-ness between topics.

The IDN sequence analysis revealed distinct ways in which individuals in a team interact that have a greater probability of being associated with the occurrence of ideas or unique ideas. When each of the four teams was analyzed for interaction sequences associated with a greater probability of idea or unique idea occurrence, we found that the most homogeneous adaptive team and the most homogeneous innovative team in the dataset exhibited interaction sequences associated with greater than 50% probability of unique idea or idea occurrence. The rest of the teams in the data set (i.e., those in the middle portion of the Adaption-Innovation range) did not reveal any such sequences. This indicates that there could be distinct interaction sequences occurring within particular KAI team configurations that influence the development of design concept outcomes, such as ideas or unique ideas.

These findings show that IDN and KAI are valid tools for uncovering meaningful relationships between individual cognitive characteristics and team interaction behavior. Our findings also serve to validate a new application of Adaption-Innovation theory in a team context (i.e., design teams) using a new combination of tools (KAI and IDN).

Table 7 shows the key parameters investigated in this study at the individual level and team level of analysis, respectively, that were implicated in a potential relationship. These relationships taken together suggest that a model could be developed with KAI cognitive style parameters as inputs and specific IDN team interactions as behavioral pathways influencing the development of design outcomes.

Table 7: Key relationships parameters between cognitive style, interaction behaviors, and design outcomes

Level	***Cognitive style***	***Interaction Behaviors***	***Design Outcomes***
Individual	KAI total score, SO sub-score	-	Unique ideas
Team	Mean KAI score	Linked/unlinked interaction segments	-
Team	Homogeneous-adaptive vs Homogeneous-innovative	Specific interaction sequences	Occurrence of unique ideas

While the dataset we analyzed in this study was too small to generalize results across all design teams, the IDN sequence analysis and the correlation analyses taken together give us a glimpse of the potential for a cognitive-behavioral model of team performance that could be developed further using a similar methodology. These analyses do not, however, indicate what kind of a relationship there could be between individual characteristics, team interaction behavior, and design outcomes. For example, how much are team interaction behaviors influenced by the cognitive styles of the participants? Are these cognitive parameters causal or merely correlational to interaction behaviors and the resultant design outcomes? Do they play a mediating or a moderating role? These questions will require further studies that are specifically designed to address the nature of the relationship beyond the evidence of presence of a relationship.

The existence of a relationship between individual characteristics and team interaction behaviors indicates that the behavior that is effective in developing certain design outcomes could be effective only in the *context* of certain cognitive styles. This raises additional questions, such as these: Could we develop design methods that are cognizant of cognitive styles of participants? Could we develop modular design methods with process modules that could be adapted to different individual characteristics of the participants? The answers to these questions will have profound implications for both design practice and design education. While we currently promote a process-centric view of engineering design innovation in both design practice and education, the research we have embarked on here could provide the foundation for a human-centric (person and team) practice and teaching of design, where the humans in question include not only the user but also the designer and the design team itself.

LIMITATIONS AND FUTURE WORK

Limitations of this study include the following four issues:

1. *Small number of teams*: We started with a dataset of 14 teams, but selected four teams that were homogeneous in terms of the KAI profiles of their participants. While we found some statistically significant results that indicated relationships between individual characteristics and team interaction, we need a larger dataset to validate and further probe these relationships.
2. *Limited cognitive parameter*s: Not all possible individual cognitive parameters were included in analysis. Individual characteristics were measured in terms of cognitive style only, without considering cognitive level. The individuals participating in the teams had variations in their cognitive levels (e.g., disciplinary backgrounds, areas of expertise, years of experience), as well as their cognitive styles. The variations in cognitive level could account for some of the behavioral variations observed in these teams and the subsequent variations in their design outcomes.
3. *Limited interaction parameters*: Not all interaction parameters were included in the analysis. We included the IDN interaction patterns in this analysis, but did not include time-based patterns of interaction that could also mediate the occurrence of ideas or unique ideas in design teams.
4. *Low ecological validity*: The teams were engaged in a 30-minute task to develop a concept from an initial engineering drawing that was handed to them. This short timeframe and the lack of familiarity with the object being designed could have influenced their team interaction behaviors and interfered with their concept generation.

In this analysis, we focused mainly on revealing the existence of relationships between individual characteristics and interaction behaviors in design concept generation. In future work, we plan to gather data from a greater number of engineering design teams in industry who are addressing complex design problems. This will give us an opportunity to analyze individual characteristics, interaction behaviors, and design outcomes at a greater level of ecological validity, as well conduct further analyses to probe the nature of the relationship between individual characteristics and team interaction behaviors in the context of effective design outcomes. The small number of teams in this preliminary analysis could have suppressed certain relationships that could be revealed when the analysis is conducted with a larger dataset. The design outcomes will also be measured not just in terms of the occurrence of ideas, but also in terms of the quality of the deliverables as related to novelty, usefulness, and elaboration (for example). Such future studies will allow us to overcome the limitations of this study and advance beyond this preliminary analysis towards building a comprehensive cognitive-behavioral model of design team performance.

ACKNOWLEDGMENTS

This research was funded by the National Science Foundation through ESD Grants #1635437 and #1635386.

REFERENCES

[1] Duderstadt, J. J. (2005). Engineering Research and America's Future: Meeting the Challenge of a Global Economy. *National Academy of Engineering*.

[2] Minneman, S. L. (1991). *The Social Construction of a Technical Reality: Empirical Studies of Group Engineering Design Practice*. PhD dissertation, Stanford University.

[3] West, M. A. (2002). Sparkling Fountains or Stagnant Ponds: An Integrative Model of Creativity And Innovation Implementation In Work Groups. *Applied psychology*, *51*(3), 355-387.

[4] West, M. A., Hirst, G., Richter, A., & Shipton, H. (2004). Twelve Steps to Heaven: Successfully Managing Change Through Developing Innovative Teams. *European journal of work and organizational psychology*, *13*(2), 269-299.

[5] West, M. A. (2012). The Essence of High Performance Teams. In *Ready for Change?* (pp. 111-127). Palgrave Macmillan UK.

[6] Tang, J. C. (1991). Findings from Observational Studies of Collaborative Work. *International Journal of Man-machine studies*, *34*(2), 143-160.

[7] Jung, M. (2011). *Engineering Team Performance and Emotion: Affective Interaction Dynamics As Indicators Of Design Team Performance*. PhD Dissertation, Stanford University.

[8] Eris, O. (2002). *Perceiving, Comprehending, And Measuring Design Activity Through the Questions Asked While Designing*. PhD Dissertation, Stanford University.

[9] Edelman, J. (2011). *Understanding Radical Breaks: Media and Behavior in Small Teams Engaged in Redesign Scenarios.* PhD Dissertation, Stanford University.

[10] Cross, N., Christiaans, H., & Dorst, K. (1996). *Analysing Design Activity.* Wiley, London.

[11] Adams, R. and Siddiqui, J. (2015). *Analyzing Design Review Conversations,* Purdue University Press. West Lafayette, IN.

[12] Wilde, D. J. (2008). *Teamology: The Construction and Organization of Effective Teams*. Springer Science & Business Media.

[13] Kress, G., & Schar, M. (2011). Initial Conditions: The Structure and Composition of Effective Design Teams. *In the Proceedings of the 18th International Conference on Engineering Design* (ICED), Lyngby/Copenhagen, Denmark.

[14] Kirton, M. J. (2003). *Adaption-Innovation in the Context of Diversity and Change*. London: Routledge.

[15] Schar, M.F. (2011) *Pivot Thinking and The Differential Sharing of Information Within New Product Development Teams*. PhD Dissertation. Stanford University.

[16] Kichuk, S.L. and Wiesner, W.H. (1997) The Big Five Personality Factors and Team Performance: Implications for Selecting Successful Product Design Teams. *Journal of Engineering and Technology Management*, 14(3), pp.195-221.

[17] Holm S. (1979) A Simple Sequential Rejective Method Procedure. *Scandinavian journal of statistics*, pp. 65-70.

[18] Sternberg, R. J., & Grigorenko, E. L. (1997). Are Cognitive Styles Still in Style? *American psychologist*, 52(7), 700.

[19] Sternberg, R. J., & Grigorenko, E. L. (2001). A Capsule History of Theory and Research On Styles. *Perspectives on thinking, learning, and cognitive styles*, 1-21.

[20] Allinson, C. W., & Hayes, J. (1996). The Cognitive Style Index: A Measure of Intuition- Analysis for Organizational Research. *Journal of Management studies*, 33(1), 119-135.

[21] Buffinton, K. W., Jablokow, K. W., & Martin, K. A. (2002). Project Team Dynamics and Cognitive Style. *Engineering Management Journal*, 14(3), 25-33.

[22] Neill, C. J., & DeFranco, J. F. (2011). Problem-Solving Style and Its Impact On Engineering Team Effectiveness. *In Proc. 9th Conference on Systems Engineering Research*. Los Angeles, CA.

[23] Jablokow, K. W. (2008). Developing Problem Solving Leadership: A Cognitive Approach. *International Journal of Engineering Education*, 24(5), 936-954.

[24] Vercellone-Smith, P., Jablokow, K., & Friedel, C. (2012). Characterizing Communication Networks in a Web-Based Classroom: Cognitive Styles and Linguistic Behavior of Self-Organizing Groups in Online Discussions. *Computers & Education*, 59(2), 222-235.

[25] Samuel, P., & Jablokow, K. (2011). Toward an Adaption-Innovation Strategy for Engineering Design. In the *Proceedings of the 18th International Conference on Engineering Design (ICED)*, Copenhagen, Denmark.

[26] Jablokow, K. W., Teerlink, W., Yilmaz, S., Daly, S., Silk, E., & Wehr, C. (2015). Ideation Variety in Mechanical Design: Examining the Effects of Cognitive Style and Design Heuristics. *Proc. ASME 2015 International*

Design & Engineering Technical Conferences (IDETC), Boston, MA.

[27] Wright, S., Silk, R., Daly, S., Jablokow, K., & Yilmaz, S. (2015). Exploring the Effects of Problem Framing on Solution Shifts: A Case Study. *Proc. ASEE 2015 Annual Conference on Engineering Education*, Seattle, WA.

[28] Yilmaz, S., Daly, S., Jablokow, K. W., Silk, E., & Rosenberg, M. (2014). Investigating Impacts on the Ideation Flexibility of Engineers. *Poster and Proc. ASEE 2014 Annual Conference on Engineering Education*, Indianapolis, IN.

[29] Yilmaz, S., Berg, M., Daly, S., Jablokow, K. W., Silk, E., & W. Teerlink (2015). Impact of Problem Contexts on the Diversity of Design Solutions: An Exploratory Case Study. *Proceedings and poster presentation ASEE 2015 Annual Conference on Engineering Education*, Seattle, WA.

[30] Silk, E. M., Daly, S. R., Jablokow, K. W., Yilmaz, S., & M. Rosenberg. (2014). Interventions for Ideation: Impact of Framing, Teaming, and Tools on High School Students' Design Fixation. *Proc. of the 2014 Annual Meeting of the American Educational Research Association (AERA)*, Philadelphia, PA.

[31] Silk, E., Daly, S., Jablokow, K. W., Yilmaz, S. & Rosenberg, M. (2014). The Design Problem Framework: Using Adaption-Innovation Theory to Construct Design Problem Statements. *Proc. ASEE 2014 Annual Conference on Engineering Education*, Indianapolis, IN. (Best PIC II Paper Award, 2014).

[32] Jablokow, K., Teerlink, W., Yilmaz, S., Daly, S., & E. Silk. (2015). The Impact of Teaming and Cognitive Style on Student Perceptions of Design Ideation Outcomes. *Proc. ASEE 2015 Annual Conference on Engineering Education*, Seattle, WA.

[33] Jablokow, K. W., & Kirton, M. J. (2009). Problem Solving, Creativity, and the Level-Style Distinction. *In Perspectives on the Nature of Intellectual Styles* (L.-F. Zhang & R. J. Sternberg, Eds.). Springer, New York, NY.

[34] Jablokow, K. W., & Booth, D. E. (2006). The Impact and Management of Cognitive Gap in High Performance Product Development Organizations, *Journal of Engineering and Technology Management*, 23(4), pp. 313–336.

[35] Kirton, M. (1976). Adaptors and Innovators: A Description and Measure. *Journal of applied psychology*, 61(5), 622.

[36] Sonalkar, N., Mabogunje, A., & Leifer, L. (2013). Developing a Visual Representation to Characterize Moment-To-Moment Concept Generation in Design Teams. *International Journal of Design Creativity and Innovation*, 1(2), 93-108.

[37] Sonalkar, N., Mabogunje, A., Pai, G., Krishnan, A., & Roth, B. (2016). Diagnostics for Design Thinking Teams. In Leifer, L., Meinel, C. and Plattner, H. (Eds.). *Design Thinking Research.* Springer International Publishing.

[38] Talmy, L. (1988). Force Dynamics in Language and Cognition. Cognitive science, 12(1), 49-100.

[39] Gerber, E. (2007, April). Improvisation Principles and Techniques for Design. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 1069-1072). ACM.

[40] Matthews, B. 2009. Intersections of Brainstorming Rules and Social Order. *CoDesign* 5 (1): 65–76.

[41] Yujian, L., & Bo, L. (2007). A Normalized Levenshtein Distance Metric. *IEEE transactions on pattern analysis and machine intelligence*, 29(6), 1091-1095.

[42] Goldschmidt, G. (2014). *Linkography: Unfolding The Design Process*. MIT Press, Boston.

[43] Breiman, L., Friedman, J., Stone, C. J., & Olshen, R. A. (1984). *Classification and Regression Trees*. CRC press.

[44] Sravanthi, K., & Reddy, T. S. (2015). Applications of Big Data in Various Fields. *International Journal of Computer Science and Information Technologies*, 6(5).

[45] Gaetano J. (2013) Holm-Bonferroni Sequential Correction: an EXCEL calculator ver. 1.2. Available from:http://www.researchgate.net/profile/Justin_Gaetano2

