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# Investigating the Influence of Designers' Cognitive Characteristics and Interaction Behaviors in Design Concept Generation

*This paper investigates relationships among the cognitive characteristics, interaction behaviors, and ideation outcomes of 14 engineering design teams engaged in concept generation. Cognitive characteristics were measured using the Kirton Adaption-Innovation Inventory (KAI), which assesses an individual's cognitive preference for structure in generating and working with ideas in problem solving. Team interactions were assessed using the Interaction Dynamics Notation (IDN), which allows interaction behaviors to be quantitatively analyzed, while team outcomes were measured in terms of ideation utterances (ideas and unique ideas). Our analyses revealed that cognitive style (KAI) did not correlate significantly with interaction response behaviors (IDN) or with the quantity of ideas/unique ideas produced. However, the cognitive style diversity of the teams did influence the number of topics they discussed, as well as the interconnectedness of those topics. In addition, several specific interaction responses were associated with the occurrence of ideas/unique ideas, although the sequences associated with those responses varied widely; the more adaptive teams also had greater position specificity in these sequences than the more innovative teams. Our findings highlight the importance of forming cognitively diverse design teams and suggest that specific interaction behaviors should be encouraged or taught as a means to increase the occurrence of ideas and/or unique ideas during team concept generation.* [DOI: 10.1115/1.4043316]

## Introduction

The ability to generate inventive solutions 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 [1,2]. Prior research has identified teams as a key determinant of an organization's inventive capacity, including the teams involved in the inherently sociotechnical activity of engineering design [3–10]. In design, engineers interact with each other and with different artifacts [11], tools [12–14], and techniques [15,16] as they exchange information, generate and select concepts, and develop and test prototypes in order to create 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 problem solving and invention.

Engineers at all levels, from novices to experts in both academia and industry, frequently blame team dysfunction on anecdotal reports of "difficult people" or "personality clashes", while praising the way other teams are able to "leverage their diversity" and "come together" to produce outstanding results. Is there hard evidence that personality and other individual designer characteristics are manifested in team interaction behavior? If so, what is the best way to assess and model those relationships, and can they be used to influence team design outcomes? Previous research on the interactions of engineering design teams has focused primarily on specific behaviors, such as gestures [7], emotional expression [17], question-asking [18], and prototyping [19], and/or on team interactions in specific design-related scenarios, such as concept generation [2,16,20] and design reviews [21]. This early research on the interaction behaviors observed in design teams does not address the individual cognitive characteristics of the participating designers and the influence those characteristics have on the designers' observed behaviors.

On the other hand, research on the individual characteristics of designers, which often makes use of personality measures and/or other individual assessments, such as the Myers Briggs Type Indicator [22,23], the Kirton Adaption-Innovation Inventory (KAI) [24], the Hermann Brain Dominance Instrument [25], or the NEO Five-Factor Inventory [26], has not addressed how these individual characteristics actually manifest through moment-to-moment behavior to influence design outcomes. If we are to understand the relationships 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 study of 14 design teams in which the cognitive characteristics of the designers 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 cognitive characteristics of design team

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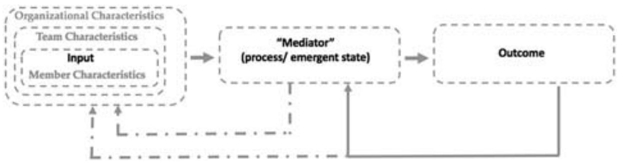



**Fig. 1 IMOI framework [29,30]**

members and their interactions to their performance in terms of creative design to identify the behavioral building blocks of design teams that produce high performance outcomes (i.e., high performance design teams) [27,28]. The identification of such behavioral building blocks will lead to scientific cognitive–behavioral models of design teams that will be applicable in academic and industry environments, as well as new tools for improving the effectiveness of those teams. Underlying this work is the premise that while some general predictions can be made based on the individual cognitive characteristics, dynamic interactions, and design outcomes of a team, these relationships are complex and have not, as yet, been fully investigated. As a result, while we may anticipate some aspects of the relationships among the individual cognitive characteristics, team interactions, and design outcomes observed and assessed here, there will be other aspects of this work that remain exploratory.

In particular, we can investigate the relationships among the individual cognitive characteristics, team interactions, and team outcomes with respect to the input-mediator-outcome-input (IMOI) framework derived from Ref. [29] and developed by Ilgen et al. [30] (see Fig. 1). In our use of this framework, individual cognitive characteristics (e.g., cognitive level, cognitive style) serve as inputs. Team interactions (e.g., interaction behaviors) mediate the influence of these individual cognitive characteristics in the creation of team outcomes, the assessment of which might include actual performance metrics (e.g., ideation utterances) and/or team members' perceptions of their performance (e.g., self-assessed quality). Feedback from the evaluation of team outcomes has the potential to influence some individual cognitive characteristics (e.g., learned experience) and team interactions (e.g., decision-making behaviors), while feedback from the evaluation of team interactions has the potential to influence some member characteristics (e.g., individual motives, learned experience) as well. In the following sections, we describe our approach to each of these framework elements, leading to our specific research questions for this study

## Assessing Individual Cognitive Characteristics

**Kirton's Adaption-Innovation (A-I) Theory.** Among the many frameworks proposed for understanding cognitive diversity [24,31–33], Kirton's Adaption-Innovation (A-I) theory [24] is highly comprehensive, and the problem-solving context in which it was originally developed makes its application to the study of engineering teams straightforward and effective [34–45]. A-I theory [24] is based on the key assumption that all individuals are creative, where creativity and its impact are 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 [24]. Cognitive style can also be assessed via multiple constructs, including Kirton's Adaption-Innovation [24,46], Jackson's Risk-Taking [47], and Eysenck's Introversion-Extraversion [48,49].

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 construct ranges along a continuous spectrum between highly adaptive and highly innovative preferences [24,36,50], 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 (whether working alone or with others), although an individual can and does also behave in ways that are not preferred, albeit at an extra cognitive cost (i.e., coping behavior [24]).

**Assessing Cognitive Level and Style.** In the context of engineering design teams, cognitive level can be assessed through various forms of personal information, such as degrees earned, years of experience in relevant areas, and known skill sets [11,27,28]. In our study, some (but not all) participants provided academic rank, discipline, occupation, and/or age information, all of which also qualify as cognitive level variables. Assessment of A-I cognitive style is best accomplished via KAI [24,46], which has been rigorously validated and is currently being used in a variety of contexts, including engineering, education, business, and the military [11,24,27,28,34–45]. 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.[2]

Through multiple validation studies, Kirton also identified three subscores that correspond to three subfactors of cognitive style: Sufficiency of Originality (SO), Efficiency (E), and Rule/Group Conformity (R/G). The SO subfactor highlights differences between individuals in their preferred ways of generating and offering ideas, while the E subfactor reflects an individual's preferred methods for managing and organizing ideas and for solving problems. Finally, the R/G subfactor reflects differences in the ways individuals manage the personal and impersonal structures in which their problem solving occurs.

**Cognitive Style Diversity in Team Contexts.** When individuals work together, their diverse cognitive characteristics can influence their collaborations 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, or between an individual/group and the problem at hand (e.g., the level of expertise required to solve a problem and the extant expertise within the team) [24,51]. In previous work related to KAI and teams, Kurtzberg [52] studied the creative fluency of homogeneous teams and heterogeneous teams (as categorized by KAI cognitive gaps) and found that heterogeneous teams outperformed homogeneous teams in terms of creative output (i.e., number of ideas). Hammerschmidt [53] studied team success and cognitive style diversity using KAI and found that teams had higher levels of success when tasks were aligned with KAI (e.g., a more adaptive task aligned with a more adaptive subteam). His work also revealed that when subteams had similar KAI scores (i.e., were homogeneous), overall team success increased as a result of enhanced interteam communication, while diverse (i.e., heterogeneous) teams were more likely to fail as a result of unresolved cognitive gaps. Jablokow et al. [45] explored the effects of cognitive gaps on dyad performance and interactions between design team members during concept generation. Their results suggest that as the cognitive gap between team

[2]Note that higher KAI scores do not indicate a "better" cognitive style, since all positions along the A-I continuum have equal value for problem solving when considered overall.

members increases, the more adaptive team member tends to feel that they contributed less to team ideation, while the more innovative team member tends to feel that they contributed more.

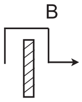
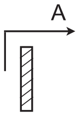
Finally, in our previous preliminary work with a subset of the current dataset [27], the results suggested that the presence of more innovative individuals on a team may be correlated with a greater occurrence of unique ideas in the team. We also found that more innovative teams (by KAI mean) tended to exhibit team interactions with a higher degree of interconnectedness between topics.

## Assessing Team Interaction Behavior

Team interaction can be defined as reciprocal action between the members of a team. For a design team, interactions are the sequences of verbal and nonverbal actions and responses between individuals as they go about understanding problems, generating solutions, and developing prototypes. To capture this reciprocity of interaction in our current study, we needed a method that would facilitate the analysis of moment-to-moment interpersonal responding by capturing not what a designer said or intended to say but rather how his/her speech or action influenced the *subsequent* response in the ongoing interaction. In the past, researchers have used conversation analysis to study design interactions [54–56]; while conversation analysis does offer a way to relate talk turns to each other through descriptive explanation; it does not directly capture the reciprocity of interaction. As a result, we turned to the Interaction Dynamics Notation (IDN), a visual representation system that was specifically designed to capture these reciprocal actions between individuals in a design team [57–59], for our studies of team interaction behavior.

**The Interaction Dynamics Notation (IDN).** The development of IDN is described in detail in Refs. [57,58]. IDN is based on force dynamics theory from the field of cognitive semiotics [60], which highlights the forces exerted through language; IDN captures these forces through symbols based on principles of improvisational behavior [61,62]. See Table 1 for a complete list of IDN symbols, their definitions, and simple examples.

**Table 1 Descriptions of each symbol used in IDN [57]**

| Symbol | Name | Description | Example |
|---|---|---|---|
|  A | Move | A Move indicates that a participant has made an expression that moves the interaction forward in a given direction | A: I need to buy Legos (at) home. Think about how therapeutic it would be. |
|  A | Question | A Question indicates an expression that elicits a Move | A: Where should we start? |
|  C | Yesand | Yesand accepts the content of the previous Move and adds on to it | A: What about … if we made a toy that incorporates girls and boys playing together…<br>C: I think that's a good point to have some sort of educational point in it |
|  B | Support | Support indicates that the speaker understands and/or agrees with the previous Move | C: Safe and entertaining (bending forward to write)<br>B: Safe and entertaining, yes |
|  C | Block | Block indicates an obstruction to the content of the previous Move | B: Maybe have something which looks like a computer, but you can just type your name or do a simple math…<br>C: Er, but I don't know, I mean, considering the age segment we are targeting 3–7 years |
|  C | Block-support | Block-support indicates an acceptance of a Block by another person | A: But that's also, I think that's already done<br>C: Yeah, it's already there<br>B: Ok |
| B  C | Overcoming | Overcoming a Block indicates a speaker was able to overcome the Block and persist on course of the original Move | C: Er, but I don't know, I mean, considering the age segment we are targeting 3–7 years<br>B: So, 7 years they go to school, they would learn A, B, C, right? |
| A  B | Deflection | A speaker can deflect the Block with a Move that presents an alternative direction for the interaction | B: So, when you say we need to divide the age-group, but you cannot have like 3, 4, 5<br>A: No, no of course not, but I mean you might have a few different (concepts) |
|  A,B | Humor | Humor indicates instances of shared laughter in teams | A: I don't know I probably would have swallowed but (all of them laugh) |
|  A | Ignored | Ignored indicates that a person was heard but not responded to by the rest of the team | A: We could build Lego forts and have little people in them<br>B (looks at A, and then turns to C): I was thinking we could do a Lego zoo |
|  | Silence | Silence is a state when none of the participants speak as they are engaged in individual level activities | |
|  X | Ambiguous | Ambiguous is used when it is not clear what a person said | A: Shall we finalize on Lego sandbox?<br>X: (inaudible) |

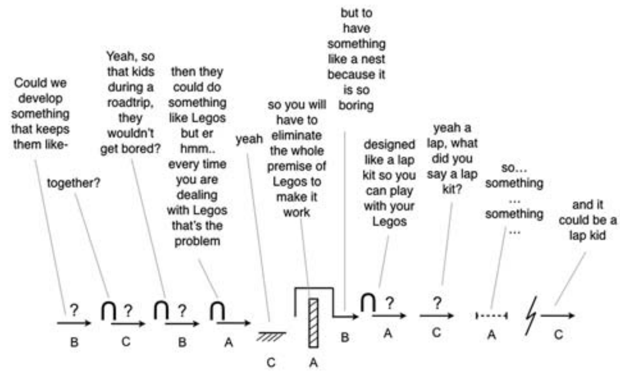



**Fig. 2 Team interaction visualized using IDN—A, B, and C are individuals in the team [63]**

Each IDN symbol is assigned to an action, both verbal and nonverbal, that is conducted by a participant and responded to by her/his 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) to Block them. Thus, IDN captures the reciprocity of interaction and models team interaction rather than a sequence of individual contributions. Figure 2 shows an example of a team's topic segment visualized and coded using IDN.

In previous work, IDN has been used to identify interaction patterns associated with transitions between concept space and knowledge space (as per C-K theory [64]) during concept generation in student design teams [57]. It was also used to detect interpersonal interaction patterns correlated with the novelty and utility of concepts generated by seven design teams [59,63]. Most recently, IDN was used to study the interactions of entrepreneurial teams engaged in design activities and their relationships with the cognitive characteristics and design outcomes of the participants [28].

### Assessing Design Team Outcomes

In general, there are two main types of assessment methods for design concept generation: process-based methods (*how* do designers generate design concepts) and outcome-based methods (*what types* of design concepts do they generate). In this research, we focus on outcome-based methods of assessment, which include those found in Dean et al. [65], Nelson et al. [66], Shah et al. [2,67], and Verhaegen et al. [68], among others. Across these works, the outcomes of design concept generation (both individual and team-based) are often assessed through variations on four metrics that relate to how much the generated concepts expand and explore the design space—i.e., the quantity, quality, novelty, and variety of the design concepts. However, in shifting our attention to the moment-to-moment resolution of team interaction behavior, Sonalkar [57] notes the difficulties inherent in applying such detailed outcome metrics to the simple ideation utterances observed along the temporal path from start to finish of a concept generation activity. If interaction behavior is the matter of interest, then the outcome parameter that comes closest to that behavior is an ideation utterance (as opposed to a full design solution). Therefore, similar to the overall "generativity" of designers discussed in Ref. [69], we chose to assess the number of ideas (simple ideation utterances) observed in our design teams (as defined by Sonalkar [57]), as well as the number of *unique* ideas (defined as "new to the current team discussion"), as suggested by Edelman [19]—both of which were also applied in our previous work [27]. In future work, we will consider the adaptation and application of more detailed outcome metrics, especially to the final design concepts generated by the teams.

### Research Questions

With the IMOI framework of Fig. 1 as a backdrop, we examined the relationships among designers' cognitive characteristics, team interactions, and team outcomes—all to inform the development of our descriptive cognitive–behavioral model of design team performance. In particular, we applied KAI and IDN to a design team concept generation dataset created by Edelman [19]. The three key research questions underlying this development, all in the context of team design concept generation, are as follows:

- *Research Question 1 (RQ1)*: *Does cognitive style influence individual/team interaction behaviors?* Based on the general nature of IDN responses, we hypothesize that cognitive style (KAI) will not correlate significantly with interaction behaviors (IDN) at the individual or team levels. While common misperceptions of cognitive style might lead one to expect more adaptive individuals to introduce more Blocks into a design discussion or more innovative individuals to ask more Questions, A-I theory posits that broad behavioral responses (like those identified using IDN) are equally likely all along the cognitive style spectrum, although the *way* in which these responses are introduced and their *aims* may differ. For example, a more adaptive person might introduce a Block because he/she feels that the current design idea is too loosely defined, while a more innovative person might introduce a Block related to the *same* idea because she/he feels that it is too tightly constrained. Currently, IDN does not take these differing aims into account.
- *Research Question 2 (RQ2)*: *Does cognitive style influence team design outcome parameters?* Based on the independence of cognitive level and cognitive style [24,50], we hypothesize that cognitive style (KAI) will not correlate with the *total number* of ideas/unique ideas produced by the design teams, but that predictable relationships may exist between cognitive style and the *way* in which ideas/unique ideas are offered within a team's design activity. Kirton [24] and others [28,50,70] have demonstrated that while cognitive style influences the preferred *manner* in which an individual generates, filters, and offers ideas to others, the *capacity* to generate ideas is governed by cognitive level and motive, not style.
- *Research Question 3 (RQ3)*: *Do individual/team interaction behaviors influence team design outcome parameters?* Based on previous IDN research related to design outcomes [57], as well as other literature linking improvisation and idea generation [61,62], we hypothesize that IDN will correlate with the number of ideas/unique ideas generated by each team. In particular, we hypothesize that the IDN symbols that correlate with the occurrence of ideas/unique ideas will be those that derive from improvisational principles that have been theoretically associated with idea generation [61,62] (e.g., Yesand, Support, and Block). Early application of IDN to design team interactions also linked Yesand, Humor, Overcoming, Deflection, and Question responses to the occurrence of ideas [57].

### Dataset

The dataset we used here to inform our investigation of a cognitive–behavioral model of team performance consisted of 14 nonhierarchical teams of 3 individuals each (see Table 2). The teams included individual volunteers from engineering design and product design backgrounds, assigned according to common schedule availability. The teams were composed of undergraduate students, graduate students, design instructors, and industry practitioners; most teams were homogeneous by participant type (student versus nonstudent). Eight of the teams were mixed gender teams, four were all-male teams, and two were all-female teams. The ages of the team members ranged from 20 to 54 years old. We presented a preliminary analysis of 4 of the 14 teams in Ref. [27]; in this paper, we extend our analysis to the full dataset.

Table 2 Cognitive style (KAI) scores and gender for teams 1–14

| Team (style homogeneity) | Person (gender) | KAI total | Maximum cognitive gap | Mean KAI |
|---|---|---|---|---|
| Team 1 (MHET[a]) | A (M) | 119 | 11 | 125 |
| | B (M) | 126 | | |
| | C (F) | 130 | | |
| Team 2 (MHET) | A (M) | 94 | 13 | 93 |
| | B (M) | 86 | | |
| | C (M) | 99 | | |
| Team 3 (HET[b]) | A (M) | 104 | 24 | 94 |
| | B (M) | 80 | | |
| | C (F) | 97 | | |
| Team 4 (HET) | A (F) | 108 | 43 | 101 |
| | B (M) | 76 | | |
| | C (M) | 119 | | |
| Team 5 (HET) | A (M) | 105 | 44 | 107 |
| | B (M) | 86 | | |
| | C (M) | 130 | | |
| Team 6 (MHET) | A (F) | 101 | 19 | 96 |
| | B (F) | 103 | | |
| | C (F) | 84 | | |
| Team 7 (MHET) | A (F) | 112 | 11 | 110 |
| | B (M) | 103 | | |
| | C (M) | 114 | | |
| Team 8 (MHET) | A (F) | 118 | 19 | 111 |
| | B (M) | 115 | | |
| | C (M) | 99 | | |
| Team 9 (MHET) | A (M) | 109 | 12 | 102 |
| | B (M) | 100 | | |
| | C (F) | 97 | | |
| Team 10 (MHET) | A (M) | 123 | 16 | 133 |
| | B (M) | 139 | | |
| | C (F) | 137 | | |
| Team 11 (MHET) | A (M) | 114 | 13 | 106 |
| | B (M) | 104 | | |
| | C (M) | 101 | | |
| Team 12 (HET) | A (F) | 109 | 22 | 111 |
| | B (M) | 101 | | |
| | C (F) | 123 | | |
| Team 13 (HET) | A (F) | 109 | 29 | 101 |
| | B (F) | 111 | | |
| | C (F) | 82 | | |
| Team 14 (HET) | A (M) | 93 | 25 | 106 |
| | B (M) | 107 | | |
| | C (M) | 118 | | |

[a]Mildly heterogeneous (11 points < maximum cognitive gap ≤ 20 points).
[b]Heterogeneous (maximum cognitive gap > 20 points).

All data collection occurred in the Center for Design Research at Stanford University, where each team participated separately using a common experimental protocol [19]. The teams engaged in a concept design task, in which each team was given an engineering drawing of a fictitious device called the "material analyzer" (see Fig. 3) and the following design prompt: "The object in front of you allows the identification of the material composition of objects. Redesign it." Note that the participants were *not* prompted about the number of concepts to generate (e.g., "generate as many ideas as possible"). After 5 min, 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 (see Fig. 4). The teams each worked for a total of 30 min and delivered a solution concept for an "improved" material analyzer. Their design activity was video recorded and transcribed.

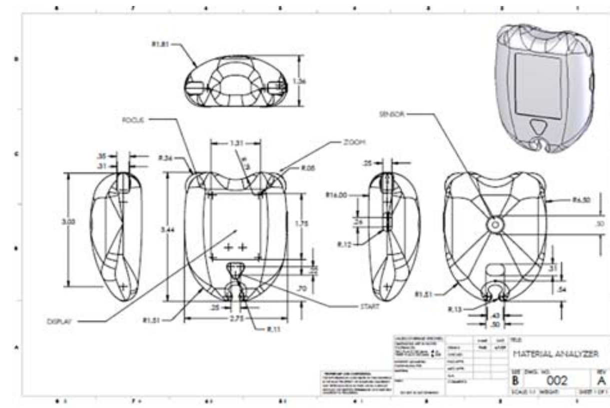



**Fig. 3 Engineering drawing for the material analyzer used in the design brief [19]**

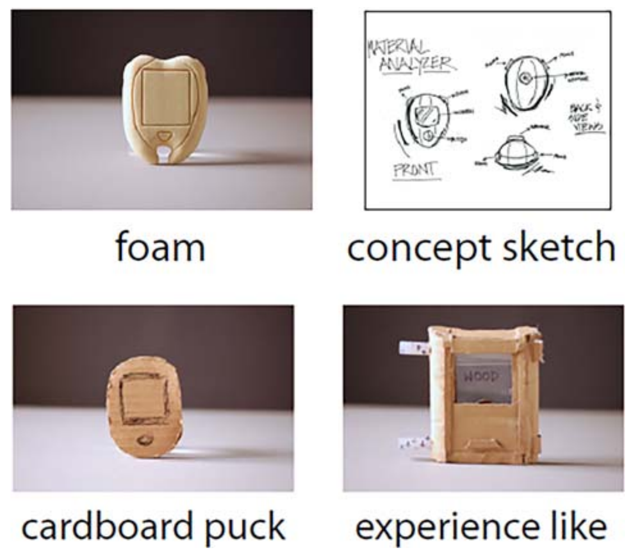



**Fig. 4 Secondary media used to promote concept development in the design task [19]**

This study was originally designed by Edelman [19] to investigate the influence of media models on concept generation behavior. His findings indicate that while these different media models were sometimes used by the teams to "anchor" a solution (i.e., block the development of a new concept by direct reference to the media), this effect was equal across the different media modalities.

## Analysis Methods and Metrics

**Coding Team Videos with IDN.** The video data of each team were coded by at least two IDN analysts, all of whom were 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 [71]. The original mean weighted Levenshtein's ratio for IDN coding of the 14 teams was 0.76, which was in the moderate agreement range. Any disagreements in coding were resolved through consensus coding sessions, in which the analysts watched the relevant video segment together, debated the disagreement, and came to a consensus about the final assignment of IDN symbols.

**Segmenting the Design Activity Into Topic Segments.** Once the team videos were converted into IDN codes, the codes were aligned with the transcripts of the appropriate team interaction and broken down into topic segments. Topic segments are sequences of interpersonal interactions organized around a continuous coherent topic. A topic 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 topic segment and the beginning of another. We checked the reliability of topic segmentation through an inter-rater agreement percentage score. Four raters coded the files, with at least two coders for each file; the average inter-rater agreement was 72% (high: 88%; low: 56%).

Once the IDN representations were broken into topic segments, the total number of segments per team was counted as an indicator of topical spread in the team interaction. Furthermore, the links between different topic segments were analyzed using the principle of links between speaker turns proposed by Goldschmidt [72]. Links between two topic 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). If a topic recurs after being changed once, the original topic segment is said to be *linked* to the topic segment in which the topic recurs. If the topic does not recur, the topic segment is said to be *unlinked* to any other topic segment. The maximum number of linked segments in a team's conversation is the *link depth*. The total number of linked topic segments divided by the total number of unlinked topic segments is the *ratio of linked to unlinked topic segments*.

Table 3 illustrates the concepts of linked and unlinked topic segments. In this example, topic segments 1, 3, and 5 (bold) are linked due to the recurrence of the one-handed operation topic, while topic segments 4 and 6 (italics) are linked due to the recurrence of the ergonomic sensor topic. Topic segments 2 and 7 (plain font) are unlinked. In practical terms, the ratio of linked to unlinked topic segments provides a relative measure of how interconnected a team's discussion is (i.e., how often do they return to the same topics), while the link depth provides a measure of the maximum degree of connectedness exhibited among the topics (i.e., how deeply the team explores a particular topic within their linked segments).

**Identifying Ideation Utterances in the Interaction Data.** The third step of our analysis was the identification of ideation utterances as a measure of team outcomes associated with design concept generation. We utilized the ideation utterance identification scheme developed by Sonalkar [57] and Edelman [19], which counted any verbally expressed change to the original material analyzer concept as "an idea". Furthermore, a subcategory of "unique ideas" was identified, such that multiple verbal expressions relating to one major change could be considered as contributing one unique idea [19]. For example, one team had five verbal idea utterances (total ideas = 5) that led to the development of one unique idea regarding a sensor. The repeatability of this coding process was checked by multiple raters.

Table 4 shows an example series of interactions, with ideation utterances identified and classified as "ideas" and "unique ideas". A unique idea is the *first* utterance of a conceptual change to the original product, while an idea is *any* utterance of a conceptual change to the product. Here, person B is the first to utter an idea related to infrared laser thermometers; C and A build on this notion and develop the concept of a point-and-shoot form and moving the display, respectively.

**Cognitive Style (KAI) Assessment.** Kirton's Adaption-Innovation Inventory (KAI) was administered to the 14 teams at the time of Edelman's original study. By definition [24], the just noticeable difference (i.e., just noticeable cognitive gap) for *individual* KAI scores (JND-I) is 10 points—i.e., differences in KAI total scores of 10 points or less often remain undetected, while larger differences are more noticeable. Specifically, McCarthy's work [73] demonstrated that KAI total score differences of 11–20 points are typically noticed over time and may cause some friction, while differences greater than 20 points are readily detected and often require extra care to manage successfully in collaboration; these larger gaps have also been shown to hinder team performance [51,53]. Based on these factors, teams in our study with maximum cognitive style gaps of 10 points or less were identified as *homogeneous teams*; teams with gaps of 11–20 points were identified as *mildly heterogeneous teams (MHET)*; and teams with gaps greater than 20 points were identified as *heterogeneous teams* (*HET*). Likewise, each team was analyzed in terms of its *cognitive climate* (i.e., the general cognitive "flavor" of the team's approaches, behaviors, and outcomes), as represented by its KAI style mean [24,37,45,50,51].

**Correlation Analysis.** The KAI scores, IDN symbol codes, idea measures, and topic segment measures were analyzed using Minitab to identify any statistically significant correlations between individual cognitive characteristics, interaction behaviors, and team outcomes. In each case, we applied the Holm–Bonferroni correction in our correlation analyses to account for the occurrence of Type I (false positive) errors due to multiple comparisons [74,75].

**Table 3 Examples of linked/unlinked topic segments and resulting metrics**

| Linked topics | Topic segment | Topic | Resulting metrics |
|---|---|---|---|
| 1, 3, 5 (bold)<br>4, 6 (italics) | **1** | **One-handed operation** | Total topic segments = 7<br>Total linked segments = 5<br>Total unlinked segments = 2<br>Ratio of linked to unlinked topic segments = 5/2 = 2.5<br>Link depth = depth of maximum linked topic segment = 3 |
| | 2 | User age groups | |
| | **3** | **One-handed operation with start button** | |
| | *4* | *Ergonomic positioning of sensors* | |
| | **5** | **One-handed operation** | |
| | *6* | *Sensor size and positioning* | |
| | 7 | Production costs | |

**Table 4 Example interaction sequence with ideas and unique ideas identified**

| Speaker | Transcript | Idea/unique idea |
|---|---|---|
| B | So why is it this size? Do you think the machine has to be this big? Like the—the innards? Could it be bigger? Could it be smaller? Could it be like a little, you know umm— | |
| C | Yeah | |
| A | Well, let's assume it can be—it can be as flat as you wanted it | |
| C | And you've got kind of left— | |
| B | *Use uhhh thermometers, the infrared laser thermometers* | Idea/unique idea |
| C | *Ohhh! Now you're talking. Let's, let's do this totally as a point and shoot. And so—* | Idea |
| A | Yeah | |
| B | What do those even look like? I'm trying to picture that | |
| C | Soooo— | |
| A | This one is— | |
| C | Basically— | |
| B | Has like a little— | |
| A | *This is the, the concept is move the display out of the way, you know, from under the hand* | Idea |

**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 14 teams. This enabled us to investigate if the team members' cognitive styles were associated with distinct interaction sequences for concept generation. The IDN data were analyzed using the classification and regression trees (CART) algorithm [76]. 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. [76] 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 [77] to reveal possible interaction sequences of consecutive IDN responses that predict the occurrence of an idea or unique idea for each of the 14 teams. The link depth was selected as "3", which implies a maximum of three decision nodes leading to the target variable of an idea or unique idea occurrence.

## Key Findings: Research Question 1 (RQ1)

**Cognitive Style Assessment.** The KAI scores of all participants are shown in Table 2. Examining these data, we note that our sample contained considerable cognitive style diversity, with a KAI total score range of 63 points and internal team cognitive gaps up to 44 points. Based on the KAI JND for individuals (JND-I), we also see that none of the 14 teams were strictly homogeneous (i.e., with all cognitive gaps $\leq$10 points); however, teams 1 and 7 were within one point of homogeneity, while team 9 was within two points, and teams 2 and 11 were within 3 points. Applying our definitions strictly, 8 of the 14 teams were identified as *mildly heterogeneous* (*MHET*) and 6 as *heterogeneous* (*HET*).

Research shows that the just noticeable difference for cognitive climate between *teams* (JND-T)—i.e., the just noticeable cognitive style gap—is 5 points between the teams' KAI means [24]. The cognitive style gaps between the KAI means of the 14 teams shown in Table 2 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 MHET team) to be the most structured of the 14 teams, while team 10 is the least structured MHET team—with the other teams falling between them.

*Finding 1 (RQ1): A-I cognitive style (at both the individual and team levels) did not correlate with IDN response behaviors.*

As noted previously, A-I cognitive style has been associated with characteristic behaviors in general contexts (e.g., more adaptive individuals specifying solutions in greater detail; more innovative individuals generating ideas that are more paradigm-bending). To explore this relationship even more rigorously within the design team context, we used correlation analysis to first investigate whether **individual** designers with particular cognitive styles were more/less likely to exhibit particular IDN response behaviors during a design activity. We also examined whether **teams** with particular cognitive style means were more/less likely to exhibit particular IDN response behaviors as a group.

Testing each of the distinct interaction behaviors described by IDN against **individual** KAI total and subscores, we found *no statistically significant relationships* between individual KAI scores and specific IDN response behaviors; these results align with and validate those of our previous work with a limited portion of the dataset (i.e., teams 2, 7, 9, and 10) [27]. In other words, there was no significant connection revealed between the cognitive style of an individual team member and the likelihood of their exhibiting a particular IDN response. Likewise, by testing each IDN response behavior (summed across each team) against **team** KAI total score means, we also found *no statistically significant relationships* between team cognitive climate and team-level IDN responses.

While these results may appear counterintuitive based on popular notions of behavior and cognitive style, they are consistent with A-I theory and its underlying assumptions [24]. For example, the popular notion that people who are more structured thinkers (i.e., more adaptive, in Kirton's terms) will resist change more strongly—and might therefore, respond with a Block more often than more innovative people—was not borne out here. Likewise, the popular stereotype of a less structured thinker (i.e., an innovator, in Kirton's term) as a person who is more likely to overcome or deflect Blocks was also not supported by our data. These notions were also refuted from a team perspective—i.e., the more adaptive teams did not Block more than the more innovative teams, and so on. Instead, as A-I theory proposes [24], our analysis suggests that individuals and teams of all cognitive styles are equally likely to respond in all the ways encompassed by IDN (i.e., blocking, overcoming, deflecting, moving, etc.).

## Key Findings: Research Question 2 (RQ2)

*Finding 2a (RQ2): A-I cognitive style (at both the individual and team levels) did not correlate with the occurrence of ideas or unique ideas.*

Our previous study of 4 of the 14 teams in this dataset [27] revealed statistically significant and moderately strong positive correlations between the number of unique ideas and the KAI total score and SO subscores of the participants, suggesting that the more innovative team members were more likely to offer a larger number of unique ideas in the team ideation sessions. In expanding our analysis to include all 14 teams, however, this result was **refuted**, with *no statistically significant correlations* found between **individual** KAI total and subscores and the number of ideas/unique ideas generated by that individual. In addition, *no statistically significant relationships* were found between the mean KAI score of a **team** (cognitive climate) and the number of ideas/unique ideas generated by that team.

In combination, these results suggest that individuals of different cognitive styles and teams with different cognitive climates are equally likely to generate similar numbers of ideas and unique ideas within design tasks. These results align with A-I theory and present an interesting contrast to popular notions about cognitive style and idea generation, which often suggest that people who are (in Kirton's terms) more innovative will naturally generate more ideas than their more adaptive counterparts under *any* conditions. Instead, in drawing a careful distinction between cognitive level (capacity) and cognitive style (preference), A-I theory predicts that, when allowed to generate ideas *in their preferred manner* (as the teams in our study were enabled to do via the lack of formal process instructions), individuals of similar *levels* (of whatever styles) are more likely to generate similar numbers of ideas, rather than cognitive style being the determining factor. Based on the expanded dataset, these latest results should be considered more robust than those from our own previous work [27].

*Finding 2b (RQ2): Maximum cognitive gap of the team was positively correlated with the number of topic segments in team discussion, as well as the depth of linked segments.*

In our preliminary analysis with 4 of the 14 teams, we found that the ratio of linked to unlinked topic segments had a high correlation ($r = 0.987$) with the KAI mean of the team ($p < 0.05$) [27]. There was no significant correlation with the maximum or mean internal cognitive gap of the team or the depth of linked topic segments, however. This suggested a link between more innovative teams (indicated by a higher KAI mean) and the interconnectedness of a team's conversations (indicated by a higher ratio of linked to unlinked topic segments). However, when we completed the same analysis with all 14 teams in the dataset, we observed a very different result. With 14 teams, the correlation between the KAI mean of the team and the ratio of linked to unlinked topic segments was no longer statistically significant at the 95% level, although the relationship did *approach* significance ($r = 0.531$, $p = 0.051$). More notably, however, the correlations between the maximum cognitive

**Table 5 Correlations between topic segment parameters and maximum cognitive gap**

| Topic segment parameters | Maximum cognitive gap |
|---|---|
| Total segments | 0.673[a] |
| Linked segments | 0.622[b] |
| Unlinked segments | 0.65[b] |
| Depth level | 0.68[a] |

[a]$p < 0.01$.
[b]$p < 0.05$.

gap within the team and the numbers of linked topic segments, unlinked topic segments, and total topic segments, as well as the depth of linked segments, were all found to be statistically significant (see Table 5).

The results shown in Table 5 imply that the *cognitive diversity* of the team (as reflected in the maximum cognitive gap) is more relevant than the general cognitive climate (as reflected in the team's KAI mean) when it comes to the manner in which topics are discussed. In particular, the greater the cognitive diversity of the team, the greater the number of topics discussed by the team, as well as the greater the number of both linked and unlinked topics. Interestingly, however, there is no correlation between KAI and the *ratio* of linked to unlinked topics, which implies that teams with high cognitive diversity may see an increase in both linked and unlinked topics in such a way that the ratio does not differ from teams with low cognitive diversity. Greater cognitive diversity is also linked to greater topic linkage depth, which implies that teams with greater cognitive diversity revisit a topic more often than teams with less cognitive diversity. This finding aligns with A-I theory in reflecting the need for teams of greater cognitive diversity to spend more time and energy coming to the consensus needed to solve problems—in this case, to complete the given design challenge.

## Key Findings: Research Question 3 (RQ3)

**IDN Sequence Analysis.** The IDN sequence analysis of team interactions was supported by classification and regression tree (CART) diagrams for each of the 14 teams. One CART diagram per team was created using *ideas* as the target variable, and another diagram was created using *unique ideas* as the target variable. The CART analysis was conducted for each team separately, since the individual cognitive characteristics differed from team to team; our approach enabled us to compare interaction patterns between teams from a cognitive style (KAI) perspective.

Figure 5 shows an example of a CART diagram for team 10 with unique ideas as the target. The end-state of "true" indicates the probability of the occurrence of unique ideas, and the state of "false" indicates the probability of nonoccurrence of unique ideas. The independent variables here are the elements of each sequence of IDN responses, starting with the IDN code that corresponds to the same speaker turn as the unique idea, the previous IDN response (Previous1), and the IDN response before that (Previous2).

The tree in Fig. 5 consists of three nodes, with each node 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. For example, the path for achieving 75% probability of the occurrence of a unique idea for team 10 is: Base Node(top path)[IDN_code $\not\subseteq$ {Support, Humor, Silence, or Question}] → Second Node(bottom path)[Previous2 = {Silence or Question}] → Third Node(top path)[Previous1 ≠ {Move}].

Using the IDN sequence data generated from the classification and regression tree analysis, we first investigated whether the occurrence of certain IDN symbols was correlated with the total number of ideas and/or unique ideas at the team level. In other words, if a team had more Yesand or Question or Support (etc.) IDN responses, would that team also have a greater number of ideas and/or unique ideas originating from the interaction? We then investigated whether certain sequences of IDN symbols had greater than 50% likelihood (i.e., greater than pure chance) of leading to idea or unique idea occurrences. Finally, returning briefly to Research Question 2 and based on the higher preference for structure of more adaptive individuals, we tested whether the more adaptive teams had greater specificity in their high probability interaction sequences than the more innovative teams.

*Finding 3a (RQ3): Several specific interaction behaviors (IDN* ***symbols****) were more strongly associated with the occurrence of ideas and unique ideas.*

Our correlation analyses (which included the application of the Holm-Bonferroni correction) revealed that only Deflection was moderately correlated ($r = 0.75$) with the total number of idea occurrences ($p < 0.05$); no other IDN symbol showed a statistically significant correlation with either total ideas or total unique ideas. Given that we did not see significant correlations at the individual IDN symbol level, except for Deflection, we assessed which IDN symbols were most commonly seen within the interaction sequences leading to ideas/unique ideas with a greater than 50% probability, combined over all 14 teams (see Fig. 6).

As shown in Fig. 6, in sequences associated with *ideas*, Yesand occurred almost twice as often as the rest of the IDN symbols (14% versus 8% average symbol occurrence). In sequences associated with *unique ideas*, Move and Question occurred more often than Yesand. It is notable that Blocks occurred equally (8%) in both idea and unique idea sequences; however, there is a difference in the response to Blocks between these two end-states. In unique idea sequences, Overcoming occurred more commonly than Deflection in response to Blocks, while in idea sequences, Deflection occurred more common than Overcoming. These results, which confirm the findings reported in our earlier work [27], suggest that if specific interaction behaviors can be encouraged (e.g., Deflection, Yesand, Move, and Question), the occurrence of ideas and/or unique ideas during team concept generation might be increased.

*Finding 3b (RQ3): The interaction (IDN)* ***sequences*** *associated with the occurrence of ideas and unique ideas were highly varied across teams, with most sequences tending to be broad rather than specific.*

As shown in Table 6, the interaction sequences that appear in CART diagrams can be *specific* (i.e., each position in the sequence

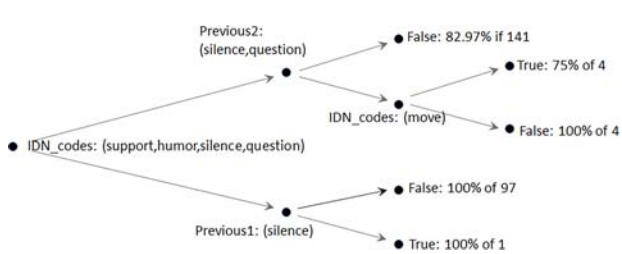



**Fig. 5 Example CART diagram for team 10 with *unique ideas* as the target**

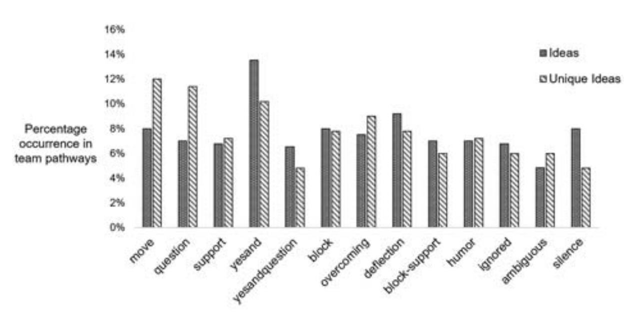



**Fig. 6 The percentage occurrence of IDN symbols in sequences leading to ideas and unique ideas, combined over all 14 teams**

**Table 6 Example of a broad interaction sequence versus a specific interaction sequence**

| IDN code/sequence type | Previous2 | Previous1 | Idea/unique idea occurrence |
|---|---|---|---|
| Broad sequence | In (Support, Question, Yesand, Block, Overcoming, Deflection, Ignored, Silence, Yesand-question, Ambiguous, Block-support) | In (Move, Question, Yesand, Yesand-question, Block, Block-support, Overcoming, Deflection, Ignored, Humor, Silence, Ambiguous) | In (Yesand-question, Deflection) |
| Specific sequence | In (Question) | In (Move) | In (Yesand) |

shows only one interaction response) or *broad* (i.e., each position in the sequence shows multiple possible interaction responses). Similar to our previous work with four teams from this dataset [27], our expanded analysis revealed large variations in the specificity of sequences associated with ideas/unique ideas across the 14 teams. Some teams had sequences that were very specific (e.g., teams 9 and 14), whereas other teams had sequences that were very broad in at least one position (e.g., teams 4, 11, and 12).

We computed the *average specificity* for each team by calculating the average of the maximum number of possible interactions across all of that team's high probability idea/unique idea sequences. With average specificity scores ranging from 1 to 13 (mean: 7.8, median: 8.4), most teams (11 of 14) exhibited broad sequences (average specificity > 4), with only three teams (teams 6, 9, and 14) exhibiting very specific sequences (average specificity ≤ 4). To consider the specificity of each *position* in each sequence in a team, we multiplied the number of possible interactions available at each position in a sequence and added all such scores for all sequences within a team to get a team score. The team *position specificity* values were as follows for teams 1–14, respectively: [416, 129, 52, 81, 67, 7, 104, 97, 1, 176, 12, 312, 180, 8] (mean: 117, median: 89). Here, a score of 1 (e.g., for team 9) implies that *all* sequences for that team contained only one IDN possibility per position. The highest position specificity score occurred for team 1 (i.e., 416), which implies that team 1's sequences contained a much greater number of possibilities for each position than, say, team 3 (position specificity = 52). With only three teams having single-digit position specificity scores, this analysis confirms that teams tended to exhibit broad interaction sequences leading to ideas/unique ideas across sequence positions. Taken together with finding 4, these results suggest that while certain specific interaction responses (e.g., Yesand behavior) may lead to more ideas/unique ideas, the sequencing of these interactions appears to vary significantly.

*Finding 2c (RQ2): The more adaptive teams had greater* ***position specificity*** *in their high probability interaction sequences than the more innovative teams*.

Armed with our specificity analysis results, we return briefly to Research Question 2 to determine whether cognitive style had any impact on the teams' interaction sequences by investigating the relationship between the specificity of their high probability interaction sequences (i.e., average and position specificity scores) and cognitive style (i.e., teams' mean KAI scores and cognitive gaps). We did not find any statistically significant correlations between the teams' *average* specificity scores and their KAI means or cognitive gaps. However, repeating this analysis for the *position* specificity scores resulted in a statistically significant ($p < 0.05$) positive correlation ($r = 0.246$) between position specificity and team KAI mean.

These results, which confirm our previous findings [27], suggest that teams that are generally more adaptive (lower KAI mean) tend to maintain greater specificity across their interaction sequences (lower position specificity scores) than teams that are generally more innovative (higher KAI mean), although the correlation coefficient was not high. This aligns with A-I theory, which predicts that more adaptive individuals/teams tend to be more focused and are less likely to explore pathways of discussion that may fall outside what they perceive to be the "clearly desired outcome" of a problem-solving task.

## Discussion

We summarize our key findings in Table 7, with a brief interpretation of each finding and the research question it addresses. In considering how these results could be used to inform and improve engineering design education and practice, Finding 1 shows that KAI cognitive style did *not* influence IDN interaction behaviors at either the individual or team level. In practical terms, these results may seem counterintuitive to those who propose that more adaptive thinkers (i.e., those who prefer to incrementally refine current systems) are more resistant to new ideas, as might be indicated by a greater tendency to respond using Block behaviors. In fact, more innovative thinkers (i.e., those who prefer to radically restructure current systems) appear just as likely to respond with Blocks as their more adaptive counterparts. Likewise, the common perception of more innovative individuals as highly generative "idea people" might suggest that they would employ Yesand behavior more often than more adaptive individuals, but this too is unsupported by our results. Instead, it appears that people of all cognitive styles are equally likely to accept a teammate's previous idea and add on to it through a Yesand response—although we might anticipate that *what* they "add on" would be different. In summary, Finding 1 may challenge some commonly held generalizations about design concept generation in practice, and these generalizations should be reexamined as we form and mentor design teams.

Next, Finding 2a suggests that a "most desirable" team composition based on KAI cognitive style does ***not*** exist with respect to the *number* of ideas/unique ideas generated by the team. Note that this finding, which supports the principle of cognitive style-cognitive level independence as discussed in Kirton [24], Sternberg and Grigorenko [31,32], Jablokow et al. [70], Goldsmith [78], and Chan [79], relies on all team members being allowed to function according to their cognitive style preferences, as they were here. For example, we did not compel the more adaptive team members to think "outside the box" or the more innovative team members to think "inside the box", both of which represent coping behavior from a cognitive style perspective. Note, too, that our findings relate only to the *number* of ideas/unique ideas but not to the *type* of ideas generated. The literature suggests that the cognitive style composition of a team may, in fact, be an important factor when a particular *type* of idea (e.g., incremental versus radical) is desired—but this was not a focus of our investigation. Future studies might expand the assessment of team performance to include both the quantity of ideas/unique ideas *and* the cognitive characteristics of those ideas. For further discussion of the influence of group composition on the types of ideas generated, see Refs. [24,50,51,53,79].

In Finding 2b, we see that greater cognitive style diversity in a team resulted in more discussion topics and a greater tendency to return to a previous topic. This finding aligns with common sense (i.e., people who are "more different" will have more to talk about), as well as Kurtzberg's work [52]. In a design ideation context, the significance may be greater, as the increased number of topics may indicate a more thorough exploration of the design space; if so, then this finding (along with Finding 2a) argues for maximizing cognitive style diversity in design teams. Without assessing each generated topic carefully in terms of design metrics and mapping them onto the design space, however, we cannot be certain of this claim; further research will be necessary to understand whether the increased number of discussion topics corresponds to a more extensive search of the design space or

**Table 7 Summary of key findings**

| Formal finding | Research question | Brief interpretation |
|---|---|---|
| *Finding 1*: A-I cognitive style (at both individual and team levels) did not correlate with IDN response behaviors | RQ1 | Individuals/teams of all cognitive styles/climates were equally likely to respond in all the ways encompassed by IDN (e.g., blocking, overcoming, deflecting, moving, etc.) |
| *Finding 2a*: A-I cognitive style (at both the individual and team levels) did not correlate with the occurrence of ideas or unique ideas | RQ2 | When allowed to generate solutions in their preferred ways, individuals/teams of different cognitive styles/climates were equally likely to generate similar numbers of ideas and unique ideas |
| *Finding 2b*: Maximum cognitive gap of the team was positively correlated with the number of topic segments in team discussion, as well as the depth of linked segments | RQ2 | The greater the cognitive diversity of the team, the greater the number of topics discussed (total, linked, and unlinked); in addition, teams with greater cognitive diversity revisited topics more often |
| *Finding 2c*: The more adaptive teams had greater position specificity in their high probability interaction sequences than the more innovative teams | RQ2 | Teams with more adaptive cognitive climates tended to exhibit more focused interaction sequences in generating ideas/unique ideas than more innovative teams |
| *Finding 3a*: Several specific interaction behaviors (IDN symbols) were more strongly associated with the occurrence of ideas and unique ideas | RQ3 | The presence of certain specific interaction responses (e.g., Yesand, Move, Question) in a team discussion was linked to more ideas/unique ideas from the team |
| *Finding 3b*: The interaction (IDN) sequences associated with the occurrence of ideas/unique ideas were highly varied across teams, with most sequences tending to be broad rather than specific | RQ3 | While certain specific interaction responses (e.g., Yesand) were linked to more ideas/unique ideas, the ordering of these interaction responses varied widely |

not. Nevertheless, in different ways, both Findings 2a and 2b support the desirability of cognitively diverse (style) teams.

The last three findings (Findings 2c, 3a, and 3b) can be integrated to shed light on interaction response behaviors and sequences in design concept generation. While cognitive style did not correlate with the number of ideas/unique ideas generated (Finding 2a), Finding 3a revealed that certain interaction behaviors (e.g., Deflection, Yesand, and Question) *did* support a team's increased ideation output *independent of team cognitive style composition*. Interestingly, the ordering of these interaction behaviors varied widely (Finding 3b), although the more adaptive teams did follow more focused interaction sequences than the more innovative teams (Finding 2c). The implications of these findings relate to how design teams might be taught to interact, as well as the feedback they receive when engaged in concept generation. If, for example, a design team wants to increase their idea/unique idea output, techniques for encouraging their use of specific interaction behaviors could be introduced and practiced, while also assessing the resulting concepts to determine how much of the design space was explored. The development and validation of these techniques remain as areas for future research.

## Limitations and Future Work

(1) *Number of teams*: While a sample size of $N = 14$ at the group level is not trivial and significantly expands our previous work [27], it is not large enough to guarantee that all significant effects were detected. Further investigation of the relationships among cognitive style, interaction behaviors, and design outcomes with more teams of varying types, sizes, characteristics, configurations, and contexts will be important to further confirm (or refute) our latest findings.

(2) *Limited cognitive parameter*s: Not all cognitive parameters were included in our analysis. Specifically, individual cognitive characteristics were assessed in terms of cognitive style only, and the range of cognitive styles did not span the entire A-I spectrum. The individuals participating in the teams also had some variations in cognitive level (e.g., disciplinary backgrounds, years of experience), but these variations were not considered. Such cognitive level diversity may 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 our analysis. For example, while we included IDN interaction patterns in our analysis, we did not include time-based patterns of interaction (e.g., turn-taking) that might also mediate the occurrence of ideas/unique ideas in design teams. In addition, it is possible that other types of individual characteristics (e.g., language or cultural differences) may have led to participants misreading others' intentions, which could subsequently lead to different interaction behaviors than would otherwise occur. Such potential misperceptions and their impact should be explored further in future work.

(4) *Low ecological validity*: The teams of our study were engaged in a 30-min 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/or their concept generation. In particular, the short timeframe may have led participants to exhibit a narrower range of interactions than a longer timeframe would allow, as well as fewer ideas/unique ideas. In addition, the academic setting of the experiment limits the generalizability of our results to some extent and should be addressed through future studies of teams operating in different contexts.

**Building on the Cognitive–Behavioral Model of Design Team Performance.** Taken together, we may ask what the results of this study mean for design team performance in general; additionally, what types of studies might be conducted to further develop the cognitive–behavioral model of design team performance introduced here? First, our findings highlight the importance of forming cognitively diverse design teams (at least in terms of cognitive style). In addition, they suggest that specific interaction behaviors should be encouraged or taught as a means to increase the occurrence of ideas/unique ideas during team concept generation, whatever the team composition may be. Table 8 shows the key parameters investigated in this study that were implicated in a potential relationship; notably, all of the cognitive style parameters occurred at the team level. Taken together, these relationships suggest that an IMOI framework-based model could be developed with KAI cognitive style parameters as inputs and specific IDN interactions as mediating behavioral sequences influencing the development of design outcomes.

**Table 8 Key relationship parameters among cognitive style, interaction behaviors, and design outcomes**

| Level | Cognitive style | Interaction behaviors | Design outcomes |
|---|---|---|---|
| Team | Maximum cognitive gap | — | Topic segments |
| Team | — | Specific behaviors | Ideas/unique ideas |
| Team | Mean KAI score | Specificity of sequences | — |

Second, in this analysis, we focused mainly on revealing the existence of relationships between individual cognitive characteristics and team interaction behaviors (the first two elements of the IMOI model) in design concept generation. In future work, we plan to gather data from engineering design teams in industry who are addressing more complex design problems. This will give us an opportunity to analyze individual cognitive characteristics, interaction behaviors, *and* design outcomes at a greater level of ecological validity to develop the IMOI framework-based model even further. The design outcomes will be measured not only in terms of the occurrence of ideas, but also in terms of the quality of the deliverables with respect to, e.g., novelty, usefulness, elaboration, and paradigm-relatedness [80]. In addition, investigation of the relationship between individual cognitive characteristics and interaction behaviors in other stages of the design process (e.g., concept selection) will be important in future work, as suggested by the findings of Toh and Miller [81]. Such future studies will help us overcome the limitations of this study and continue the development of a comprehensive cognitive–behavioral model of design team performance with increased generalizability.

## Conclusions

This research builds upon previous work in collaborative design with a sharper lens turned on team interactions than has previously been achieved. Measuring interactions in addition to outcomes and studying the relationship between designer characteristics and their interactions to expand our understanding of design team performance are both novel contributions to design research. Furthermore, this study considered design teams engaged in a creative activity, in comparison to other types of teams that might be studied in other fields (e.g., management). Finally, while other researchers have investigated personal attributes that may impact team interaction behaviors, none have done so through the development of a cognitive–behavioral model. Our findings are important for setting up a theoretical framework that can support research in this area and help establish a common language across research efforts in the domain of design team interactions.

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