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Using Paradigm-Relatedness to Measure Design Ideation Shifts

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Abstract

The goal of this study was to explore multiple quantitative measures of design ideation shifts. We specifically investigated shifts in ideation focused on generating incremental design solutions versus radical design solutions. Utilizing Kirton's Adaption-Innovation (A-I) theory, incremental solutions were labeled as being more adaptive and radical solutions were labeled as being more innovative. We conducted a study with 23 prospective and current undergraduate engineering students. Participants first generated conceptual solutions for a design problem with minimal constraints to create a situation in which they felt free to generate ideas they naturally felt were most appropriate for the problem. Second, participants generated ideas for a different design problem that was framed either to encourage more adaptive or more innovative ideas. We coded each idea using two different versions of a paradigm-relatedness metric. The metrics assessed the extent to which an idea works within or extends beyond currently prevailing paradigms for the problem. Version 1 had two levels: (1) paradigm-preserving or (2) paradigm-modifying. Version 2 added a third intermediate level: (1) paradigm-preserving, (2) somewhat paradigm-modifying, or (3) strongly paradigm-modifying. We assessed ideation shifts quantitatively from the first to the second ideation sessions by comparing counts and proportions of both metrics. Comparing the different quantitative measures provided a test of the advantages and disadvantages of the different ways to characterize ideation shifts.

1. Introduction

Engineers face complex design problems that require unique and practical ideas to solve. To generate these ideas, engineers need flexibility to apply a range of different design approaches. Our larger project[1]—of which this study is a part—seeks to understand how to educate engineering students to be more flexible in their ideation approaches. This goal relies on the ability to characterize ideation flexibility, so that we can understand how educational tools and programs support flexibility development. Thus, the goal of the current study was to develop a measure of the extent to which an engineer's ideation outcomes shift from one problem to another, as those outcomes shifts are likely to be related to and result from a shift in ideation approach.

Understanding the range of approaches that individuals might take to solve design problems can be used to form the theoretical foundation for assessing whether individuals shift from one approach to another. Kirton's Adaption Innovation (A-I) Theory is a theory describing a spectrum for of how individuals approach and solve problems.[2] According to A-I theory, individuals have a stable cognitive style, which captures their preferences for the amount of structure that they require to feel comfortable in approaching a problem and their likely approach for going about solving the problem. Cognitive style is on a spectrum from more adaptive to more innovative. A more adaptive approach involves trying to "make things better" by generating solutions that fit within consensually agreed upon constraints and improving already existing solutions. In contrast, a more innovative approach involves trying to "do things differently", and so in this approach a designer is more likely to generate ideas that do not fit within established constraints or boundaries of a problem. Both adaptive and innovative approaches to ideation can be valuable in different design situations.[3]

A-I theory was developed to characterize the spectrum of a person's preferences and likely approaches. Relatedly, one way to characterize design ideation outcomes—the ideas that are generated as a result of an ideation process—is on the spectrum from incremental to radical.[4,5] Engineers can generate ideas that adapt and build off existing workable solutions to make incremental improvements. In contrast, they can generate more innovative ideas by considering very different approaches than what already exists to propose radical changes. This incremental versus radical spectrum for characterizing design outcomes parallels A-I's theory about differences in individual problem-solving approaches.[2,6] Thus, it may be that an individual's ability to shift from generating more adaptive or incremental ideas in one design situation to generating more innovative or radical ideas in another design situation is an indication of their capability for being flexible in their design approaches.

In idea generation, a measure of flexibility can be thought of as the ability to apply a range of approaches, choosing the approach that best aligns with particular situational characteristics (as opposed to applying the same approach regardless of alignment with particular situational characteristics). In our prior work, we utilized individual's reflections on their ideation process to qualitatively characterize their approach and how that approach changed from on situation to the next.[7] We build on that work by focusing this study on developing a quantitative measure for assessing a shift strictly in terms of the design outcomes that the individual exhibits—the ideas that they produce in different design situations. To measure an ideation shift, one first needs to understand what is someone's baseline/default outcomes in some neutral situation. Once that baseline/default is established, a shift can then be operationalized as the extent (and the ease) of the designer's shift away from their baseline/default outcomes under new conditions that call for an alternative approach. Although not a complete measure of flexibility, measuring the extent of a shift in outcomes is a foundational step toward measuring ideation flexibility. To that end, our research question for this study was: How can "flexibility" between adaptive and innovative outcomes be measured in engineering design idea generation?

2. Method

2.1. Design

Our overall research design involved a within-subjects comparison in which participants first generated ideas under a *neutral* condition and then generated ideas under a contrasting *framing* condition. The *neutral* condition provided a baseline situation for measuring how an individual preferred to approach ideation when the situation did not favor one approach to another. The *framed* condition provided a situation in which it was more appropriate to take a particular ideation approach that better aligned with the situation. The framing did vary between participants as a between-subjects contrast, with some participants receiving a framing that encouraged an adaptive ideation approach and others receiving a framing that encouraged an innovative ideation approach. However, the contrast between adaptive and innovative framings was not our main focus for this study. Instead, we focused primarily on the within-subjects contrast of the *neutral* condition versus the *framed* condition to assess the extent to which alternative measures capture the shift in idea generation that occurred under those contrasting conditions.

2.2. Participants

A total of 23 engineering students participated in the study. The participants were a subset of a larger study testing different interventions for fostering creative and flexible idea generation practices.[1] The sample consisted of eleventh grade high school pre-engineering students attending a summer engineering program hosted by a large Midwestern university (n = 13), and sophomore undergraduate engineering students enrolled in a sophomore-level mechanical engineering course at another large Midwestern university (n = 10). Only those participants from the larger study that received the intervention of *problem framing* were included in this study. Other participants from the larger study received other idea generation interventions that are reported elsewhere.[1] Participants were randomly assigned to either the *adaptive framing* condition (n = 11) or the *innovative framing* condition (n = 12).

2.3. Materials

Two design problem contexts were used in the study that we refer to as the *Snow* and *Lids* problems respectively. The design contexts have been used in prior design research,[8–10] but were adapted for this study so that each context included three versions: (1) a neutrally framed version; (2) an adaptively framed version; and (3) an innovatively framed version. More details about the development of the problem contexts and the different framed versions are available in our prior writing.[11] For the purposes of this study, the most important aspect of the problem statements was that the neutral framing was intended to serve as a baseline for how an individual preferred to approach ideation when the situation did not favor one approach over another. See Appendix A for the neutral version of both problem contexts. The two non-neutral framings were intended to encourage individuals to generate either more adaptive or more innovative ideas, respectively, to provide a situation in which it was more appropriate to take a particular ideation approach that aligned with the situation. See Appendix B for an example of the *Snow* problem context framed both adaptively and innovatively.

2.4. Procedure

Students were randomly assigned to either the *adaptive framing* condition or the *innovative framing* condition. In both conditions, the students participated in two sequential ideation sessions. First, all participants were given a brief introduction to the role of idea generation in the design process, and then each student was given a neutral version of one of the two design problems. The students had 20 minutes to generate ideas individually for this first ideation session. The students were instructed to record each new idea on a separate page using a structured idea sheet with designated space for visual sketches and for verbal descriptions. After a short break, the students participated in the second ideation session. Participants who were randomly assigned to the *adaptive framing* condition received an adaptively framed design problem, and participants who were randomly assigned to the *innovative framing* condition received an innovatively framed design problem. Participants were given whichever problem context they had not been given in the first ideation session. To minimize the potential for an order effect, we counterbalanced the order of the problem contexts, such that some participants received the *Snow* problem first and the *Lids* problem second, and others received them in the reverse order. Students were again given 20 minutes to generate ideas.

3. Paradigm-Relatedness Coding of Ideas

3.1. Two-Level Paradigm-Relatedness Code

A paradigm-relatedness coding scheme was developed based on prior research.[12,13] This coding scheme was applied to each idea individually with the goal of characterizing each idea as either paradigm-preserving or paradigm-modifying. Consistent with the prior research, the coding scheme consisted of considering for each idea the following potential indicators of paradigm-relatedness:

1. *Focus* – did the idea directly address the problem as given (paradigm-preserving) versus focus on a solution for a larger problem (paradigm-modifying)?
2. *Assumptions* – did the idea work within the underlying assumptions of the problem (paradigm-preserving) versus alter those underlying assumptions (paradigm-modifying)?
3. *Elements* – did the idea utilize elements that are commonly found in or associated with the problem (paradigm-preserving) versus elements that are not commonly found in or associated with the problem (paradigm-modifying)?
4. *Relationships* – did the idea maintain expected ways that a user would interact with elements in this type of problem or maintain expected ways that elements interact with each other (paradigm-preserving) versus propose unexpected ways for a user to interact with elements in this type of problem or propose unexpected ways for elements to interact with each other (paradigm-modifying)?

The coders considered all of these indicators in determining their overall code for an idea as either *paradigm-preserving (PP)* or *paradigm-modifying (PM)*. There was no strict rule about the exact number of indicators coded as PM that were necessary and sufficient to justify the overall code as also being PM. There is precedent in the ideation metrics literature for not being explicit about the exact relationship between sub-dimensions and an aggregate code, as often coders are asked to consider those multiple sub-dimensions, but then to use their judgment to make a final holistic rating that takes them all into account.[12] In our case, we felt that it was important for coders to be able to exercise some discretion on the overall paradigm-relatedness code, so that the overall code would be related to the indicators but would not be entirely defined by them. In practice, ideas that were coded as PM on none of the indicators were coded as PP on the overall code. Ideas that were coded as PM for two or more of the indicators were most often coded as PM on the overall code. The borderline cases tended to consist of ideas that were coded as PM on exactly one of the indicators. In those cases, the coders had to make a holistic judgment as to whether the idea was overall PM or PP.

3.2. Three-Level Paradigm-Relatedness Code

In the course of completing the coding, we recognized that some ideas were difficult to code as either PP or PM. More specifically, we noticed that some ideas that we coded as paradigm-preserving did have some paradigm-modifying aspects to them, in addition to other ideas that we coded as paradigm-modifying but that were not very strongly paradigm-modifying. These distinctions were not captured in our original two-level paradigm-relatedness code, so to capture them, we developed an additional three-level paradigm-relatedness code with the following levels: *paradigm-preserving (PP)*, *paradigm-modifying (PM)*, or *strongly paradigm-modifying*

(PM+). Generally, ideas that were paradigm-modifying on exactly one of the indicators were coded as PM, but not PM+. Ideas that were paradigm-modifying on more than one of the indicators were typically considered PM+. Otherwise, the ideas were coded as PP. But as in the two-level overall paradigm-relatedness code, the raters were able to exercise their own judgment about each case.

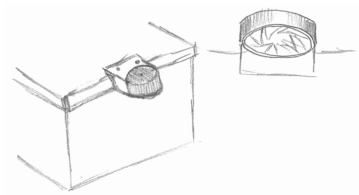
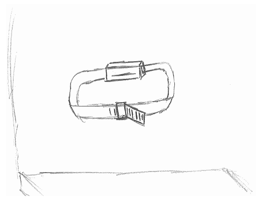
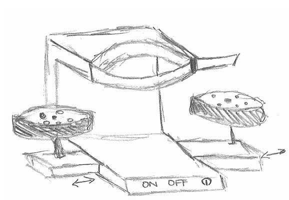
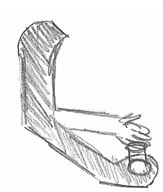
3.3. Coding Procedure

To minimize coding bias, ideas were blinded and randomly ordered so that coders would not know the experimental condition (adaptive or innovative), the ideation session (neutral or framed), or the participant from which each idea was generated. Two researchers were trained on the coding scheme by independently coding a subset of the ideas. To determine the inter-rater reliability of the coding scheme, we calculated the Cohen's kappa between their coded datasets. A Cohen's kappa exceeding a value of 0.60 was deemed sufficiently reliable as this indicates substantial agreement.[14] The coders worked with a third researcher to clarify the coding scheme and then recoded the subset of the data until the coding was reliable. After establishing reliability for the coding scheme, the coders each coded the full dataset independently. The two coders then discussed all remaining disagreements and established a consensus code, which was the final agreed-upon code used in all subsequent analyses. The final inter-rater reliabilities across the full dataset were $\kappa = 0.76$ and $\kappa = 0.64$ for the *Snow* problem context for the two-level and three-level paradigm-relatedness codes respectively, and $\kappa = 0.75$ and $\kappa = 0.64$ for the *Lids* problem context. Although in the end all four of the codes were sufficiently reliable, the inter-rater reliabilities suggest that the three-level PR code may be more difficult to reliably code as compared to the two-level PR code.

3.4. Coding Example

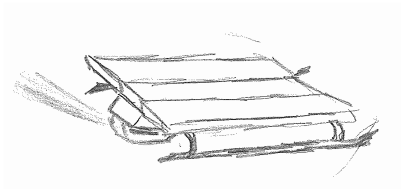
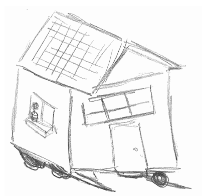
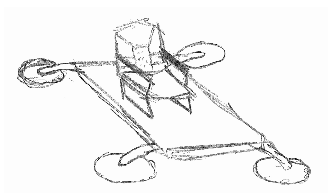
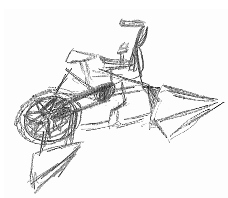
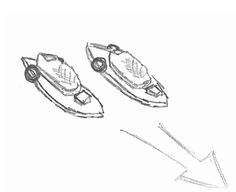
To illustrate the paradigm-relatedness coding, we provide the following example of Participant 338. This participant received the *Lids* problem for the neutral ideation session and generated four ideas, which are summarized in Table 1 below. Three of the ideas were adaptations of common ways to open lidded containers using a vice grip and so were all coded paradigm-preserving (PP). The final idea was more paradigm-modifying (PM) as it involved developing a mechanical extension to a person's arm in order to "improve bilateral task performance," which is not a common element used for opening containers. The assigned codes were consistent for both the two-level and three-level paradigm-relatedness measures, indicating that most of the ideas were clearly paradigm-preserving and that the mechanical arm extension idea, although uncommon, was paradigm-modifying but not strongly so.

Table 1. Ideas generated by Participant 338 in the neutral ideation session and the paradigm-relatedness codes assigned to each idea.

Idea Number	Idea Drawing	Idea Description	Two-Level PR Code	Three-Level PR Code
1		Rubber Teeth	PP	PP
2		Mounted Vice	PP	PP
3		Vice with Wheels	PP	PP
4		Mechanical Arm Extension	PM	PM

Participant 338 was assigned to the innovatively-framed condition, and so received the innovatively-framed *Snow* problem for the second ideation session. During the framing ideation session, this participant generated five total ideas, which are summarized in Table 2. Four of the five ideas were coded as paradigm-preserving using the two-level PR code. Using the two-level PR code to compare the set of ideas generated in the neutral session to the set of ideas generated in this framed session suggests this participant did not make much of a shift in ideation approach. However, the three-level PR code supports a different conclusion. Inspecting the three-level PR codes indicates that many of the ideas generated in the innovatively-framed ideation session have some paradigm-modifying aspects to them. Three of the five ideas were coded as PM, and one additional idea was coded as strongly paradigm-modifying (PM+). This example illustrates how the three-level PR code may possibly be more sensitive to shifts in ideation approaches.

Table 2. Ideas generated by Participant 338 in the innovatively-framed ideation session and the paradigm-relatedness codes assigned to each idea.

Idea Number	Idea Drawing	Idea Description	Two-Level PR Code	Three-Level PR Code
1		Powered Sled	PP	PP
2		Cabin on Skis and Wheels w/ GPS	PP	PM
3		Hovercraft	PM	PM+
4		Bike w/ Snow Pads	PP	PM
5		Snowshoes w/ Wheels	PP	PM

4. Calculating the Paradigm-Relatedness Shift Metrics

Our primary goal for this study was to capture the extent to which a designer shifts their ideation approach from their baseline approach to an approach suited to a particular type of problem. We were specifically interested in the extent to which participants shifted their ideation approach from the neutral ideation session to the framed ideation session in terms of the paradigm-relatedness of their ideas. To measure this shift, we considered two possible metrics: one in terms of counts of ideas and the other in terms of proportions of ideas.

4.1. Counts

4.1.1. Two Level

Our first metric approach was to evaluate the level of shift using changes in the number of paradigm-preserving ideas versus paradigm-modifying ideas. In this metric, a shift toward a more innovative approach would include generating a greater number of paradigm-modifying ideas in the framed ideation session compared to the neutral ideation session. Since we did not control for the number of ideas participants generated, we also considered a smaller number of paradigm-preserving ideas in the framed ideation session as indicating a shift toward a more innovative approach. Taken together, we measured the extent of the shift toward a more innovative approach as:

$$\begin{matrix}\textit{Count Shift}\\ \textit{Score}\\ \textit{(2 level)}\end{matrix} = \left(\begin{matrix}\textit{Number of}\\ \textit{PM Ideas in}\\ \textit{Framing}\end{matrix} - \begin{matrix}\textit{Number of}\\ \textit{PM Ideas in}\\ \textit{Neutral}\end{matrix}\right) - \left(\begin{matrix}\textit{Number of}\\ \textit{PP Ideas in}\\ \textit{Framing}\end{matrix} - \begin{matrix}\textit{Number of}\\ \textit{PP Ideas in}\\ \textit{Neutral}\end{matrix}\right)$$

Returning to Participant 338 from the examples of the PR codes above, we can now quantify that participants’ shift score as follows:

$$\begin{matrix}\textit{Count Shift Score}\\ \textit{(2 level)}\end{matrix} = (1-1) - (4-3) = -1$$

An interpretation of this shift score is that the participant made a shift towards a more adaptive approach (since the value is negative). This is consistent with the nature of this metric as the number of PM ideas stayed the same from neutral to framing, but the number of PP ideas increased (3 at neutral to 4 at framing). The increase in number of PP ideas suggests that the participant may have taken a slightly more adaptive approach to the framed problem.

4.1.2. Three Level

To calculate a shift score for the three-level PR code, we needed to take into account that more PM ideas may indicate a subtler or smaller shift than more PM+ ideas. To do this, we gave full weight to the change in PM+ ideas and the change in PP ideas, but assigned a partial weight to changes in PM ideas as represented in the following formula:

$$\begin{matrix}\textit{Count Shift}\\ \textit{Score}\\ \textit{(3 level)}\end{matrix} = \left(\begin{matrix}\textit{Number of}\\ \textit{PM+ Ideas in}\\ \textit{Framing}\end{matrix} - \begin{matrix}\textit{Number of}\\ \textit{PM+ Ideas in}\\ \textit{Neutral}\end{matrix}\right) + \left(\begin{matrix}\textit{Number of}\\ \textit{PM Ideas in}\\ \textit{Framing}\end{matrix} - \begin{matrix}\textit{Number of}\\ \textit{PM Ideas in}\\ \textit{Neutral}\end{matrix}\right) / 2 - \left(\begin{matrix}\textit{Number of}\\ \textit{PP Ideas in}\\ \textit{Framing}\end{matrix} - \begin{matrix}\textit{Number of}\\ \textit{PP Ideas in}\\ \textit{Neutral}\end{matrix}\right)$$

Returning to Participant 338 again, we can now calculate the three-level shift score as follows:

$$\underset{(3\ level)}{\textit{Count Shift Score}} \quad = \quad (1 - 0) \quad + \quad (3 - 1) / 2 \quad - \quad (1 - 3) \quad = \quad +4$$

Interestingly, the three-level shift score suggests that the participant made a fairly strong innovative shift, which is not consistent with the two-level shift score. This difference may be explained by the participant generating a number of ideas that fell on the boundary between paradigm-preserving and paradigm-modifying, and so it was only possible to observe that shift using the finer-grained distinctions available in the three-level PR code.

4.2. Proportions

4.2.1. Two Level

It is possible that in some cases developing a shift score based on counts of ideas may overstate the level of a shift that may be less the result of a shift in ideation approach and more the result of simply generating more or fewer ideas. To account for this, we also considered quantifying ideation shifts in terms of proportions of ideas codes as paradigm-preserving or paradigm-modifying.

$$\begin{matrix}\textit{Proportion} \\ \textit{Shift Score} \\ \textit{(2 level)}\end{matrix} = \left(\begin{matrix}\textit{Proportion of} \\ \textit{PM Ideas in} \\ \textit{Framing}\end{matrix} - \begin{matrix}\textit{Proportion of} \\ \textit{PM Ideas in} \\ \textit{Neutral}\end{matrix} \right) - \left(\begin{matrix}\textit{Proportion of} \\ \textit{PP Ideas in} \\ \textit{Framing}\end{matrix} - \begin{matrix}\textit{Proportion of} \\ \textit{PP Ideas in} \\ \textit{Neutral}\end{matrix} \right)$$

Again, we can use Participant 338 as an example and calculate the two-level shift score using proportions as follows:

$$\begin{matrix}\textit{Proportion Shift} \\ \textit{Score (2 level)}\end{matrix} \quad = \quad (1/5 - 1/4) \quad - \quad (4/5 - 3/4) \quad = \quad -0.1$$

Like in the two-level shift score using counts, this two-level shift score using proportions indicates that this participant made a small adaptive shift.

4.2.2. Two Level

Similar to the shift scores using counts, we might expect that the three-level shift score using proportions would indicate a strong innovative shift. The three-level shift score using proportions is again a straightforward extension of the formula using counts:

$$\textit{Proportion Shift Score (3 level)} = \left(\textit{Proportion of PM+ Ideas in Framing} - \textit{Proportion of PM+ Ideas in Neutral} \right) + \left(\textit{Proportion of PM Ideas in Framing} - \textit{Proportion of PM Ideas in Neutral} \right) / 2 - \left(\textit{Proportion of PP Ideas in Framing} - \textit{Proportion of PP Ideas in Neutral} \right)$$

Returning to Participant 338 one more time, we can now calculate that participants' three-level shift score using proportions as follows:

$$\textit{Proportion Shift Score (3 level)} = (1/5 - 0/4) + (3/5 - 1/4) / 2 - (1/5 - 3/4) = +0.925$$

Indeed, as predicted, this shift score indicates a large shift to a more innovative ideation approach as the proportion of PP ideas went way down while the proportion of PM and PM+ ideas increased.

Taken together, these shift metrics using the two-level or three-level PR code and either counts or proportions may provide alternative ways to analyze the level of ideation shift observed across all participants in the study.

5. Comparing the Paradigm-Relatedness Shift Metrics

We now return to the question of how to measure the ideation flexibility of individual designers using shifts in the paradigm-relatedness of their ideas. The breakdown of ideas for each participant is illustrated below. Figure 1 illustrates the count shift scores and Figure 2 illustrates the proportion shift scores for both the two- and three-level PR codes. Each figure separates the participants in the *adaptive framing* condition from the participants in the *innovative framing* condition. The first bar for each participant represents the breakdown of ideas in the *neutral* (*N*) ideation session and the second bar represents the breakdown of ideas in the *framed* (*F*) ideation session. The participant IDs are at the top of each pair of bars, with the shift score in parentheses. The participants are sorted by their shift score with the lower shift scores to the left, representing a more adaptive shift, and the higher scores on the right, representing a more innovative shift. The left-right sorting is only for ease of interpretation along a spectrum, such that a placement more on the right of the spectrum does not imply any greater value than a placement more to the left, as both more adaptive and more innovative shifts are considered to be equally valuable even if they are different from each other.

One way to compare the different metrics is to assess the extent to which they are correlated with each other. A higher correlation may indicate that the metrics are assessing the same thing, whereas lower correlations may mean that sensitive to very different aspects of ideation shifts. Table 3 presents the correlations among the four metrics. The count and proportion shift scores are highly correlated with each other, suggesting that the distinction between counts and proportions may not differentiate different types or levels of shifts. Comparing across Figures 1 and 2 leads to the conclusion that the ranking of participants is similar using either the count or proportion metrics. Some notable differences include that in the proportion shift score many of the participants are measured as having no shift at all because they generated all PP ideas at both the neutral and the framed ideation sessions. This happens less often in the count shift score since the number of PP ideas often changes from one session to the next. Since we want the shift score to represent a change in approach, it is possible that the count shift score is too reliant on changes in the quantity of ideas.

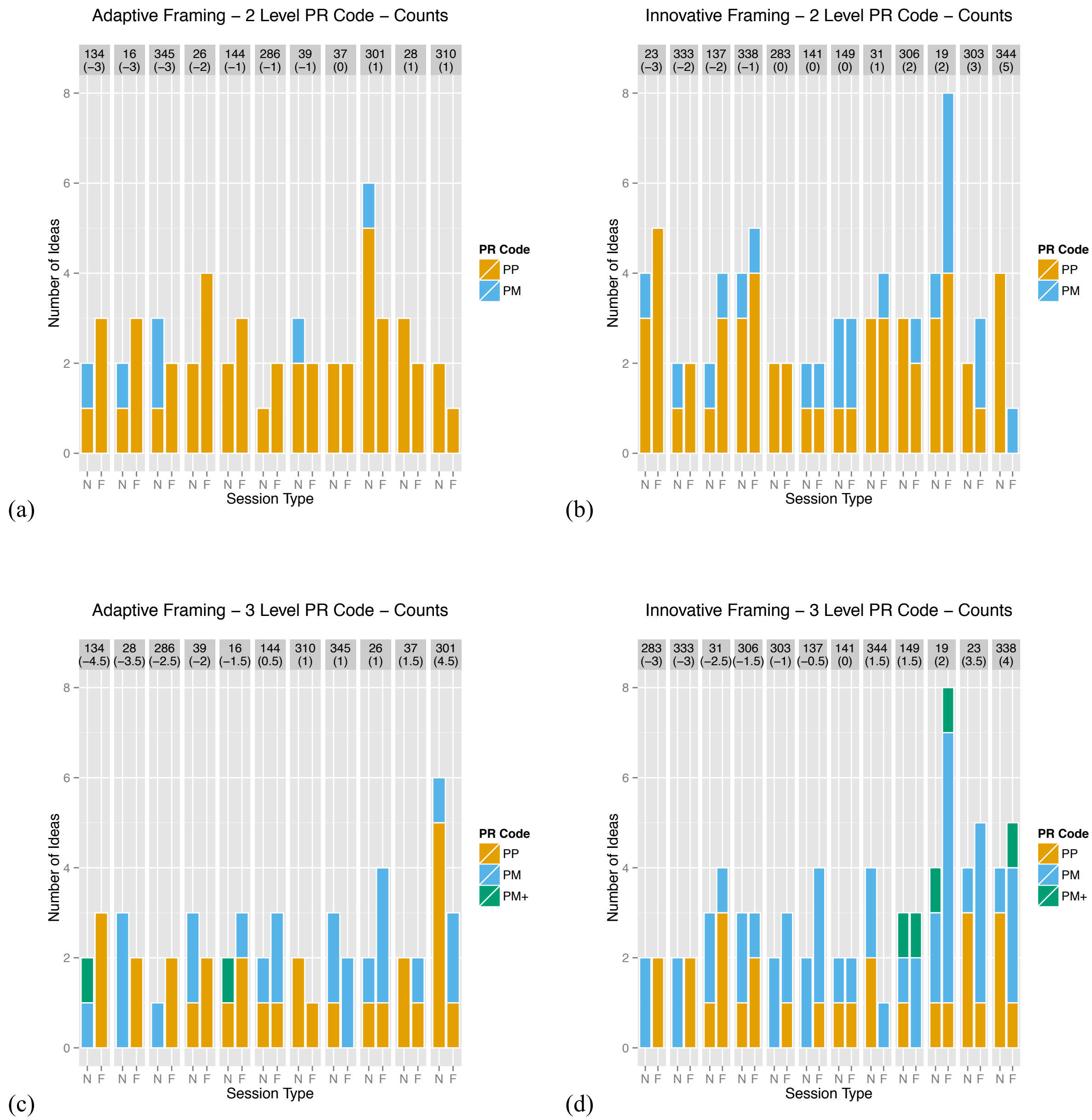
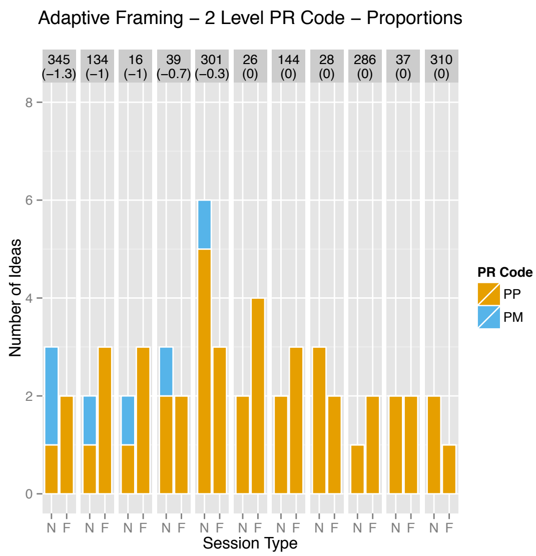
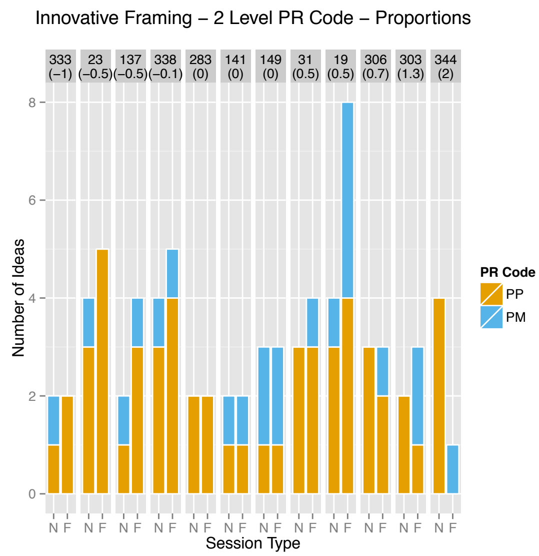


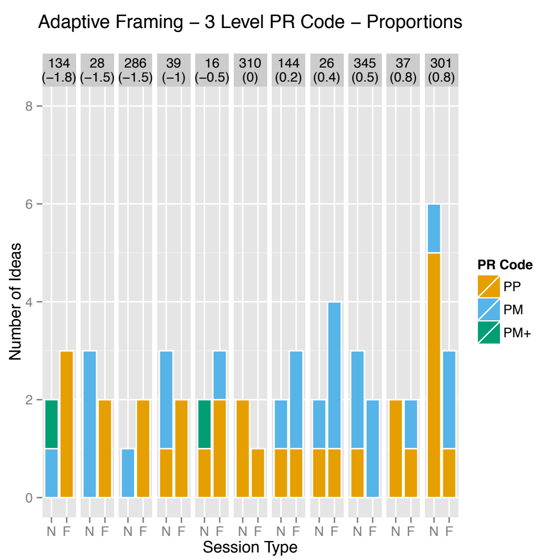
Figure 1. Count shift scores by participant for two level paradigm-relatedness code in (a) the adaptive framing condition and (b) the innovative framing condition; and count shift scores for three level paradigm-relatedness code in (c) the adaptive framing condition and (d) the innovative framing condition. All are sorted from lowest shift score (left) to highest shift score (right) with the Participant ID at the top and the shift score in parentheses.



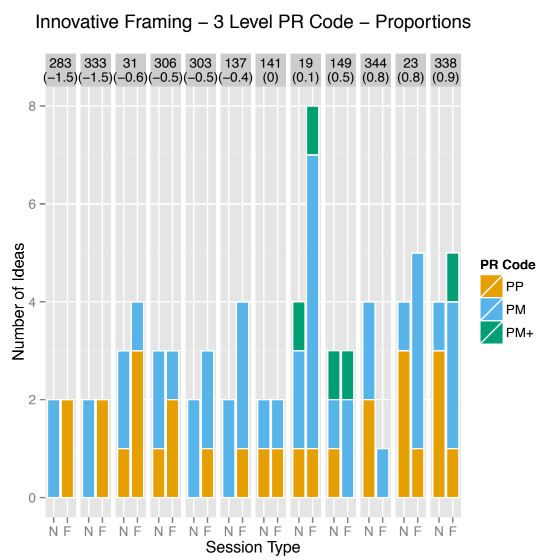
(a)



(b)



(c)



(d)

Figure 2. Proportion shift scores by participant for two level paradigm-relatedness code in (a) the adaptive framing condition and (b) the innovative framing condition; and proportion shift scores for three level paradigm-relatedness code in (c) the adaptive framing condition and (d) the innovative framing condition. All are sorted from lowest shift score (left) to highest shift score (right) with the Participant ID at the top and the shift score in parentheses.

Another notable difference between the count and proportion shift scores can be seen in Participant 301. This participant has a negative proportion shift score since they generated one PM idea in the neutral ideation session and no PM ideas in the framed ideation session. In contrast, they have a positive count shift score since although the number of PM ideas does decrease, the number of PP ideas decreases by a larger amount. The case of Participant 301 and the participants with generate only paradigm-preserving ideas in both sessions suggests that the count shift score may overvalue decreases in number of PP ideas. Absent other changes, decreasing the number of PP ideas may not indicate a substantial shift in ideation approach. Given that the proportion and count shifts are so highly correlated, it may make sense to use only the proportion shift score in order to protect against shifts that are due only to changes in the number of PP ideas rather than true changes in ideation approach.

The two-level and three-level shifts scores are not highly correlated with each other. This may mean that these metrics are distinct and are picking up on different types of changes in ideation approach. Participant 338 (described in detail earlier) is a good example of the differences between these metrics. Because Participant 338 generated ideas that are on the border between paradigm-preserving and paradigm-modifying, the two-level shift score did not capture that shift. This may suggest that the three-level PR code and associated shift score together provide a more sensitive measure of ideation shifts.

Table 3. Correlations among the four shift metrics.

	Count Shift Score (2 level)	*Count Shift Score (3 level)*	*Proportion Shift Score (2 level)*	*Proportion Shift Score (3 level)*
Count Shift Score (2 level)	1			
Count Shift Score (3 level)	0.12	1		
Proportion Shift Score (2 level)	0.91	0.14	1	
Proportion Shift Score (3 level)	0.14	0.94	0.21	1

6. Conclusion

In this study, we have proposed and considered a number of ways to quantify the level of shift in ideation approach taken by students engaged in conceptual design. Our findings revealed that no single measure captured the full extent of participants' shifts. For example, the two-level code was more reliably coded across raters and worked for observing large shifts, but didn't capture subtle shifts, especially when the designers generated ideas on the boundary between paradigm-preserving and paradigm-modifying. Another finding was that looking at changes in proportions of ideas helped to isolate shifts in approach that were distinct from changes in the quantity of ideas generated. However, it may be that the proportion shift scores underestimate subtler shifts that are better assessed by looking at changes in raw counts.

This work is an important step in developing a way to measure design ideation flexibility. The multiple measures proposed here provide an opportunity to begin to examine flexibility in different ways across larger datasets. By quantifying shifts in approaches, we can get closer to operationalizing the quality of flexibility that many agree to be of value for fostering in engineering student, but that few have a way to incorporate formally. With the shift measures proposed here, engineering educators may be better able to recognize and describe what counts as flexibility, while also better evaluating interventions designed to improve flexibility.

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A. Problem Contexts

Snow **Neutrally Framed**		***Lids*** **Neutrally Framed**
Low-Skill Snow Transporter		*One-Hand Opener for Lidded Food Containers*
Today skis and snowboards are widely used as personal transportation tools on snow. But to be able to use them, a lot of skill and experience are required that a user cannot normally learn within one day. Moreover, skis and snowboards cannot run uphill easily. It would be better if there were other options of personal tools for transportation on snow, which still allowed the user to control direction and braking, but did not require much time to learn how to use.	**Context**	The local rehabilitation center helps to treat thousands of stroke patients each year. Many individuals who have had a stroke are unable to perform bilateral tasks, meaning they have limited or no use of one upper extremity (arm/shoulder). A common issue the hospital has observed with their stroke patients is in their ability to open jars and other lidded food containers. The ability to open lidded food containers is particularly important for patients who are living on their own, in which case they often don't have help around for even basic tasks. A solution to helping them open lidded food containers with one hand would go along way in helping the patients to maintain their independence.
Design a way for individuals without lots of skill and experience skiing or snowboarding to transport themselves on snow.	**Need**	Design a way for individuals who have limited or no use of one upper extremity to open a lidded food container with one hand.
Develop solutions for this problem. Be sure to write each solution on a different piece of paper, and use drawings to sketch your ideas. It's important that you do your best and continue working for the full time of the activity.	**Goals**	Develop solutions for this problem. Be sure to write each solution on a different piece of paper, and use drawings to sketch your ideas. It's important that you do your best and continue working for the full time of the activity.

Figure 3. Neutrally framed versions of the ***Snow*** *(left) and* ***Lids*** *(right) problems.*

B. Problem Framings

Snow Adaptively Framed		Snow Innovatively Framed
Low-Skill Snow Transporter		*Low-Skill Snow Transporter*
Today skis and snowboards are widely used as personal transportation tools on snow. But to be able to use them, a lot of skill and experience are required that a user cannot normally learn within one day. Moreover, skis and snowboards cannot run uphill easily. It would be better if there were other options of personal tools for transportation on snow, which still allowed the user to control direction and braking, but did not require much time to learn how to use.	**Context** Same as neutrally-framed version	Today skis and snowboards are widely used as personal transportation tools on snow. But to be able to use them, a lot of skill and experience are required that a user cannot normally learn within one day. Moreover, skis and snowboards cannot run uphill easily. It would be better if there were other options of personal tools for transportation on snow, which still allowed the user to control direction and braking, but did not require much time to learn how to use.
Design a way for individuals without lots of skill and experience skiing or snowboarding to transport themselves on snow. **Your solutions should focus on improving existing designs or adapting familiar ways of approaching the problem or similar problems.** Consider constraints such as weight and size in your solutions, so users could carry it and be able to bring it with them in their car. Also think about how the solution is powered given that it should make it easier for people to go up hill as well as downhill, but should be reasonably affordable.	**Need** Added criteria and constraints	Design a way for individuals without lots of skill and experience skiing or snowboarding to transport themselves on snow. **Your solutions should focus on creating totally new designs or developing totally new ways of approaching the problem.** Don't be concerned about a particular size or weight of your solution, and feel free to choose any materials you desire, as those sorts of constraints might be able to be worked out in the future.
Develop solutions for this problem. Focus on developing **practical** solutions. Try to develop solutions that are cost-effective and immediately workable. Be sure to write each solution on a different piece of paper, and use drawings to sketch your ideas. It's important that you do your best and continue working for the full time of the activity.	**Goals** Explicit about type of ideas most valued	Develop solutions for this problem. Focus on developing **radical** solutions. Try to develop solutions without concern for cost or immediate workability. Be sure to write each solution on a different piece of paper, and use drawings to sketch your ideas. It's important that you do your best and continue working for the full time of the activity.

Figure 4. Comparison of adaptively and innovatively framed versions of the ***Snow*** *problem.*