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# Idea characteristics arising from individual brainstorming and design heuristics ideation methods

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**Abstract**
Ideation methods and outcomes have been evaluated in a variety of ways. Our study extends existing work through a qualitative analysis of idea characteristics based on the ideation method used. Beginning engineering students completed two short ideation sessions with a single design problem while following Individual Brainstorming and then Design Heuristics methods. We compared the resulting 1756 ideas from 186 students in response to one of two design problems (*Design a device to feed a cat or dog* or *Design a device to build a burrito*). We evaluated the ideas based on key characteristics and emergent patterns determined through thematic qualitative analysis across all ideas. This analysis identified four measures for comparing the two ideation methods: (1) number of different aspects included in each idea; (2) frequency of paradigmatic ideas; (3) variations on a key paradigmatic aspect; and (4) number of unusual aspects generated. The findings showed Individual Brainstorming supported a focus on system-level ideas, produced more typical ideas and added little variation in key design aspects. In contrast, Design Heuristics supported a focus on component-level ideas, unusual ideas, and ideas where a key aspect was a target for increased variation. The results improve our understanding of how differences in ideation methods may influence the characteristics of generated ideas and suggest guidelines for designers in the strategic selection of methods to improve ideation outcomes.

**Keywords** Design education · Design heuristics · Brainstorming · Ideation metrics · Idea generation strategies · Qualitative analysis · Engineering education

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## Introduction

Idea generation is important in any design process because when executed well, it supports the development of innovative design outcomes (Cropley, 2006). Best practices suggest that during ideation designers generate many, varied ideas without judgment of the ideas (Cross, 2008; Higgins et al., 1989; Osborn, 1957; Ulrich & Eppinger, 1995). Failed ideation can result in limited exploration of potential possible solutions, limiting opportunities for creativity and innovation (Dorst & Cross, 2001; Higgins et al., 1989; Osborn, 1957). Both practitioners and students have been shown to struggle with ideation, often generating only a few, obvious solutions (Jansson & Smith, 1991; Leahy et al., 2020; Purcell & Gero, 1996) or fixating on early ideas (Jansson & Smith, 1991; Linsey et al., 2010; Purcell & Gero, 1996; Leahy et al., 2020).

Ideation methods can support designers during idea generation to find more creative, diverse, practical, or elaborate solutions (Daly, Seifert, et al., 2016; Daly, Yilmaz, et al., 2016; Shah et al., 2003). While some research suggests particular ideation methods may lead to more creative or practical solutions, the literature does not provide consistent results with regards to the impact of using particular ideation methods. Further, the literature has not focused on the characteristics of ideas that are generated by using particular methods; rather, the literature has focused on common and broad evaluation metrics, such as creativity, novelty, diversity, and elaboration (Dean et al., 2006; Linsey et al., 2011; Shah et al., 2003).

Thus, in this study, we compared characteristics of engineering students' ideas when using two different idea generation methods—Individual Brainstorming (adapted from Group Brainstorming rules developed by Osborn (1957)) and Design Heuristics (Daly, Yilmaz, et al., 2012; Daly, Christian, et al., 2012; Yilmaz et al., 2016)—with two product design problems. Our study leveraged an inductive thematic analysis to identify differences in qualitative characteristics of ideas generated with these two different idea generation methods. A better understanding of the impact of idea generation methods on the nature of ideas may produce evidence to guide designers in their choice of methods for idea generation.

## Background

Methods to enhance idea generation success have been proposed for use in design practice and education (c.f. Fu et al., 2016). Recommended methods include Brainstorming (Osborn, 1957), analogy (Dahl & Moreau, 2002), TRIZ (Altshuller, 2005; Altshuller & Rodman, 1999), SCAMPER (Eberle, 1995), C-Sketch (Shah et al., 2001) and Morphological Analysis (Allen, 1962), as well as many others. More recent proposals include Design by Analogy (Linsey et al., 2012) and Design Heuristics (Daly, Seifert, et al., 2016; Daly, Yilmaz, et al., 2016; Yilmaz et al., 2016).

Design researchers have investigated the impact of using particular methods on multiple idea outcomes. One study focused on producing functional designs using Morphological Analysis (Allen, 1962), a method of generating new ideas by listing the necessary functions of a product and a corresponding list of potential means of achieving those functions to identify "promising" ideas (Cross, 2008). In another study of Morphological Analysis, Smith and colleagues (2012) evaluated ideas using external judges and found that morphological charts with a higher proportion of means to functions produced what they defined as "better" concepts, as rated by the judges. However, successful use of idea generation

methods may depend on expertise and training. The TRIZ approach (in Russian: Teoriya Resheniya Izobretatelskikh Zadatch or the Theory of Inventive Problem Solving) offers an extensive system for innovation in design derived from the patent literature (Altshuller, 2005; Altshulle & Rodman, 1999). A collection of techniques is condensed in TRIZ into 40 inventive principles to help solve design problems. When using TRIZ, conflicting optimizations for 39 design parameters are considered through a "contradiction matrix" informed by principles from successful designs. Few studies suggest its appropriateness for beginning designers; however, one study by Chang and colleagues (2016) employed a 6-week instructional program and found TRIZ improved creative outcomes. For those with less expertise and training, higher novelty and variety in designs. Thus, in this study, we compared characteristics have been observed (Vargas-Hernandez et al., 2013), but the simplified version of TRIZ techniques employed in that case was not specified.

Fewer studies have compared ideation outcomes using different idea generation methods. A study by Chulvi and colleagues (2013) examined idea generation outcomes using SCAMPER (Eberle, 1995) to that of the more technical TRIZ approach (Altshuller, 2005; Altshuller & Rodman, 1999). SCAMPER (Substitute, Combine, Adapt, Modify, Put to other uses, Eliminate, and Reverse) represents general strategies to transform existing ideas into new ones (Eberle, 1995). Evaluating ideas using an Analytical Hierarchy Process (Saaty, 1980) Chulvi and colleagues (2013) found ideas generated using a logical TRIZ contradiction matrix method were more novel and creative than those generated using SCAMPER. Another study compared students using one of three methods—Individual Brainstorming, Morphological Analysis, and Design Heuristics—on the same design problem (Daly, Seifert, et al., 2016). The results showed that ideas generated using Design Heuristics were the most practical and idea elaboration was higher with Design Heuristics and Morphological Analysis techniques.

Given the many existing methods and the continued innovation in idea generation methods, designers may need further guidance on how the choice of ideation method may influence design outcomes. Design educators have similarly questioned when and why specific ideation techniques may be used to advantage outcomes (White et al., 2012). Studies demonstrating improvement in design outcome measures such as novelty, variety, quantity, and rated quality (Shah et al., 2003) help to demonstrate that methods are effective; however, such global measures may not reveal how specific methods impact the *characteristics* of the designs created.

## Brainstorming

One popular design ideation method is Brainstorming. Often the term "brainstorming" is used colloquially to refer to any type of prolific idea generation without concern for quality, both in groups or individually (Paulus & Yang, 2000). However, in its original conception, Brainstorming was defined as a group activity with the aim of producing ideas following these guidelines: (1) withhold judgment of ideas, (2) encourage wild ideas, (3) generate a high quantity of ideas, and (4) combine and improve ideas (Osborn, 1957). This original Brainstorming method, developed as a group process, has also been used as an individual practice. Individual Brainstorming is a method consisting of similar guidelines adapted from Osborn's original instructions for individual use, as described by Daly, Seifert, and colleagues (2016), and Daly, Yilmaz, and colleagues (2016): postpone judgment of ideas, encourage wild ideas, aim for quantity over quality, build consecutively on ideas, and value every idea.

Brainstorming has been shown to lead to broader exploration of possible solutions (Linsey et al., 2011), increase the quantity of ideas generated (Daly, Seifert, et al., 2016; Daly, Yilmaz, et al., 2016), and allow participants to build off each other's ideas to generate new ideas (Bennis & Biederman, 1997; Galegher et al., 1990; Linsey et al., 2011). Many studies have explored impacts of using Brainstorming in group settings. For example, Parnes and Meadow (1959) evaluated the impact of Brainstorming on the quality of ideas generated. They defined quality of ideas as a combination of uniqueness and value of ideas and used raters to score each idea for uniqueness and value. The researchers found ideas generated using Brainstorming scored significantly higher in quality compared to participants not using Brainstorming. They also found that the more ideas that were produced (higher quantity), the more high-quality ideas emerged. The positive correlation between quantity and quality of ideas is reflected in many studies (e.g. Briggs et al., 1997; Gallupe et al., 1992). In another study that evaluated Individual Brainstorming, Daly, Seifert, and colleagues (2016) evaluated three different idea generation methods with first-year engineering students: Individual Brainstorming, Design Heuristics, and Morphological Analysis. They evaluated ideas using the Consensual Assessment Technique (Amabile, 1982) where raters scored ideas for creativity, elaboration, and practicality. Raters also scored participants' idea sets for quantity and diversity. They found that Individual Brainstorming led to the highest quantity of ideas compared to the other methods, but no difference in diversity or creativity compared to the other methods.

Brainstorming has in some circumstances been shown to limit productivity (Mullen et al., 1991). Group Brainstorming has been shown to produce fewer total ideas than the same number of people generating ideas individually for the same amount of time (Lewis et al., 1975). Paulus and colleagues demonstrated that people perceive they are significantly more productive than they actually are during Group Brainstorming (Paulus et al., 1993). As the majority of research has focused on Group Brainstorming, not as much is known about the impact of Individual Brainstorming on the types of ideas generated.

## Design Heuristics

Design Heuristics is a set of evidence-based idea generation strategies developed to help designers generate more diverse ideas (Daly, Christian, et al., 2012, Daly, Yilmaz, et al.2012; Yilmaz et al., 2016). Design Heuristics consist of 77 cards that represent cognitive shortcuts designers use to vary the set of ideas generated during ideation. These cognitive shortcuts were collected from protocols of engineers thinking aloud through ideation, analyses of award winning products, and a case study of a long-term design project (Yilmaz et al., 2016). The Design Heuristics were observed across multiple ideas from multiple designers with a range of experiences, indicating a useful level of abstraction in how to alter product characteristics to create new ideas.

Each Design Heuristic card includes a prompt, such as the one shown in Fig. 1. One side of each card has an abstract graphic and written description of the heuristic (left). The other side of the card includes examples of the heuristic used in two existing consumer products (right). On every card, a seating design using the heuristic is pictured to illustrate that each heuristic can apply to the same design problem. The other product on the card is from a wide range of consumer products to illustrate that the heuristics apply across applications and industries. Design Heuristics can be used in multiple ways to create new designs, such as: use one card to generate a new idea, use one card to generate multiple ideas, use multiple cards together to generate an idea, transform an existing idea using one or more cards, or use Design Heuristics in conjunction with a decomposition method like Morphological Analysis. Further, Design Heuristics can be used to support idea initiation, idea development, subcomponent design, and group idea

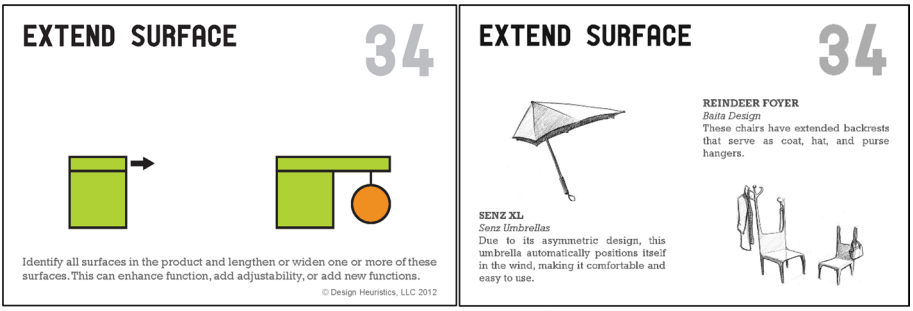



**Fig. 1** Front (left) and back (right) of one of the 77 Design Heuristic cards displaying the heuristic *Extend surface*, including written description, graphic representation, and two example products demonstrating the heuristic. (Courtesy of Design Heuristics, L.L.C.)

generation (Daly et al., 2019). A variety of approaches to using the Design Heuristic cards has been documented across multiple studies (Christian et al., 2012; Daly, Christian, et al., 2012; Daly, Yilmaz, et al., 2012; Daly, Seifert, et al., 2016; Daly, Yilmaz, et al., 2016; Leahy, Daly, McKilligan et al., 2018; Leahy, Daly, Murray et al., 2018; Leahy, et al., 2020).

Previous studies have investigated the use of Design Heuristics with practitioners and students. In one study with students, Christian and colleagues (2012) examined the use of Design Heuristics for idea generation and idea transformation in introductory engineering courses. The researchers found that in both cases, students used Design Heuristics to elaborate or further specify design ideas. Leahy and colleagues (Leahy, Daly, McKilligan et al., 2018; Leahy, Daly, Murray et al., 2018) also examined how students used Design Heuristics to transform initial ideas into new designs. They found eight types of transformation supported by Design Heuristics: enhancement of features, functions, aesthetics, settings, materials, sizes, organizations, and usability. Daly and colleagues explored how students used Design Heuristics in an introductory engineering course (Daly, Christian, et al., 2012; Daly, Yilmaz, et al., 2012). Ideas were analyzed to identify evidence of heuristic use, solution type, idea creativity, and idea set diversity, a measure of the variety of ideas within the set of ideas generated by each student. They found that ideas generated using Design Heuristics were more developed and more often considered the larger context of the product rather than having only a functional focus.

These studies describe various measures of the impact of using Design Heuristics on ideation outcomes, including number of ideas created, creativity, diversity, and novelty. However, while prior studies have identified trends in some ideation outcome measures (e.g. Daly, Christian, et al., 2012; Daly, Yilmaz, et al., 2012), there are still important questions about specific idea characteristics that might be prompted through the use of Design Heuristics. In particular, comparing characteristics of ideas generated with and without Design Heuristics on the same design problem may help to identify *how* they influence idea generation. Such an exploration may be helpful to inform design engineers' application and instruction of Design Heuristics in conjunction with or in addition to other idea generation methods.

## Ideation metrics

There are many metrics for evaluating ideas and the efficacy of ideation methods. Common metrics for evaluating ideas include quantity, novelty, quality, variety, and creativity (Amabile, 1982; Besemer, 2000; Besemer & Treffinger, 1981; Dean et al., 2006; Nagasundaram,

1995; Nagasundaram & Bostrom, 1994, 1995; Shah et al., 2003). Often, researchers leverage multiple of these existing metrics in order to evaluate ideas. For example, Shah and colleagues (Shah et al., 2003) suggest that evaluating quantity, quality, novelty, and variety explain how effective an idea generation method is at exploring possible solutions.

There are a number of ways these metrics are assessed in design outcomes. Many studies use raters to assign a score to ideas for one or more of the metrics. For example, Daly, Seifert and colleagues (2016), and Daly, Yilmaz and colleagues (2016) leveraged the Consensual Assessment Technique where raters assessed ideas for creativity, elaboration, and practicality. In another study, Chulvi and colleagues (2013) implemented an Analytical Hierarchy Process, where judges rated ideas for novelty and creativity. Ideas can be considered individually or as a set; Daly, Seifert and colleagues (2016) and Daly, Yilmaz and colleagues (2016) implemented raters to judge the diversity of a set of ideas in addition to their individual idea analysis. Some studies created scales to evaluate ideas, such as Shah and colleagues' (2003) analyses of idea variety. They created a "genealogical" categorization of how ideas fulfilled design functions and then categorized a set of ideas based on that decomposition of functions (Shah et al., 2003). In their analysis, idea sets with a higher score based on functional categorization were considered to have higher variety.

Another metric used to evaluate ideas is paradigm relatedness, defined as how closely an idea aligns with prevailing ways of thinking (Silk et al., 2016). With the paradigm representing the typical and commonly used solution type, paradigm relatedness has been used to better describe idea creativity (Nagasundaram & Bostrom, 1995). Creative ideas are defined as those that escape the dominant paradigm for solutions to a problem. Nagasundaram and Bostrom (1995) suggested ideation methods can promote paradigm-preserving, paradigm-modifying, or paradigm-neutral outcomes. Paradigm-relatedness was used as a measure of creativity and diversity of ideation outcomes in Silk and colleagues' (2016) work comparing incremental and radical shifts in design ideas in relation to the use of an ideation method.

These existing ideation metrics focus on generalizing design outcomes in order to compare ideas across design problems; however, describing ideas only in terms of metrics such as creativity, novelty, and diversity abstracts across many potentially interesting problem-specific characteristics of design. By applying inductive qualitative research methods (Creswell, 2013; Patton, 2001), context specific themes can be uncovered along with findings which may lead to new insights about how ideation methods impact idea characteristics, allowing for better understanding of ideation methods and more informed choices about when to use them.

## Research methods

The goal of this study was to evaluate emergent characteristics of ideas generated with two different ideation methods. We were guided by the research question, "What characteristics of ideas are evident when comparing ideas generated with Individual Brainstorming and with Design Heuristics?" The design of the study was aimed at enhancing the detection of differences in the characteristics of participants' ideas when using Individual Brainstorming and using Design Heuristics. Consequently, we employed a within-subjects design where each participant generated ideas for a single design problem while generating ideas using *both* ideation methods. This research design enhances the observation of how the characteristics of ideas change when using two different methods because the same designer continues ideation under both methods. This single-case AB design is helpful in

studies aimed at testing the effects of an intervention; in this study, the familiar condition (Individual Brainstorming) occurred first and the intervention (Design Heuristics) occurred second for all participants.

This research design choice creates a confound where Individual Brainstorming always occurs first in the serial order of the two sessions; however, there are reasons why this design is preferred. With each designer using both methods, important differences based on designers' past experiences, identities, and interests are held constant. Direct comparison of ideas from the same person allows a more sensitive detection of differences in performance. In studies using this interrupted time series design, the familiar process is always measured prior to the intervention requiring training and new processes. The reason is that once introduced, the new method may influence the familiar process; so logically, performing the idea generation task during Individual Brainstorming may be affected by learning to use Design Heuristics and generating ideas with that method. Brainstorming has been called an 'intuitive method' for designers (Chulvi et al, 2013), and thus plays the role of allowing self-generated ideas to emerge first. Students often need to exhaust or "get out" their own original ideas via Individual Brainstorming in order to effectively apply an idea generation method like Design Heuristics (Gray et al., 2015). As the second ideation session, the intervention is disadvantaged compared to the initial session where ideas typically come more easily than later sessions. This time series design allows a more sensitive comparison of design ideas from the same designer both before and after the intervention of Design Heuristics training. The limitations of this study design are also considered in the discussion of the study findings.

## Participants

The participants included 199 incoming first-year engineering students at a large research-focused (Carnegie Designation R-1) Midwestern university. Students were enrolled in the common-entry engineering college, but had not yet chosen a particular engineering specialty program and would not choose a specialty until their second year. There were 149 men and 50 women ranging from ages 16–20 with a mean age of 17.9 (SD = 0.47). Students voluntarily participated in a free 2-day design workshop offered to new engineering students. Students did not receive grades and were not otherwise evaluated nor compensated for participation in the program.

## Materials

Two design problems from a prior study on ideation using morphological charts by Smith and colleagues (Smith et al., 2012) were selected. In the "Burrito Maker problem," participants were asked to "Design a device to prepare a burrito," and in the "Pet Feeder problem," participants were asked to "Design a device to feed a cat or dog." The design problems we used were chosen for their accessibility, as participants likely had familiarity with (or at least could visualize) making a burrito or feeding a pet.

Participants were provided 10 concept sheets (shown in Appendix 1) and were told to record each new idea separately, with the goal for each participant to generate 10 ideas in total. Each concept sheet was numbered and provided a space to draw and to create a written description. A subset of seven Design Heuristics cards were selected at random from the set of 77 Design Heuristics for use in the study, including *Adjust function through movement, Allow user to customize*, *Bend, Change surface properties,*

*Reconfigure, Scale up or down,* and *Use multiple components for one function* (these cards are shown in Fig. 2).

## Procedure

The participants were split into two roughly equal groups in separate rooms to participate in a 75-min idea generation workshop. In each workshop, all participants in the room were assigned to work on one design problem (assigned at random) for the entire workshop. Participants in one room worked on the Burrito problem (n = 93) and the other room (n = 106) on the Pet problem (some assigned participants did not attend their scheduled workshop within the larger program). Facilitators in both rooms were trained and followed the same script in delivering the workshop. Each facilitator guided participants through the session in the sequence represented in Fig. 3. All of the participants generated ideas in two sessions using Individual Brainstorming in the first and Design Heuristics in the second.

The session began with a short introduction about the importance of idea generation in design, including best practices such as producing multiple ideas and not evaluating ideas right away. The facilitator discussed how designers try to generate a lot of diverse and creative ideas, and then synthesize, iterate upon, or eliminate ideas until arriving at a final outcome. The facilitator explained that there are idea generation methods that designers can use to help them come up with new ideas.

Next, the facilitator introduced Individual Brainstorming (Daly, Yilmaz, et al., 2016; Daly, Seifert, et al. 2016) for participants to use in the first idea generation session. Because participants worked independently in this study, we adapted Osborn's (1957) rules for Brainstorming to fit an individual working alone to generate ideas following Taylor, Berry, and Block's recommendations (Taylor et al., 1958). The guidelines provided to participants were as follows: postpone and withhold your judgment of ideas; encourage wild and exaggerated ideas; quantity counts at this stage—not quality; build consecutively on your ideas; every idea has equal worth.

Participants were then provided with the design problem and were given 25 min to generate 5 solution ideas using Individual Brainstorming. To assist participants in structuring their time and encourage them to generate multiple ideas, the facilitator prompted participants every 5 min throughout the session as a reminder to move on to their next idea. Participants were instructed that their drawings were intended to communicate their concepts, along with labels and text as needed.

Next, participants were introduced to Design Heuristics. The facilitator described how the Design Heuristics cards could be used to prompt new ideas in many ways, including (1) use a new card to generate one or more ideas; (2) combine multiple heuristics within a single idea; (3) use a single card to generate multiple ideas; (4) use a card to transform an idea; and (5) use the abstract image or the examples to inspire ideas (Daly et al., 2019).

To practice with the cards, the facilitator presented a sample design problem ("develop ideas for seating devices") and asked participants to generate ideas using the Design Heuristic card *Utilize opposite surface*. The facilitator then answered any participant questions. Then, participants worked for a second 25 min session to generate 5 more ideas for their assigned problem using the 7 Design Heuristics cards provided.

Two participants' full datasets with ideas generated during both Individual Brainstorming and Design Heuristics sessions are included in Appendix 2.

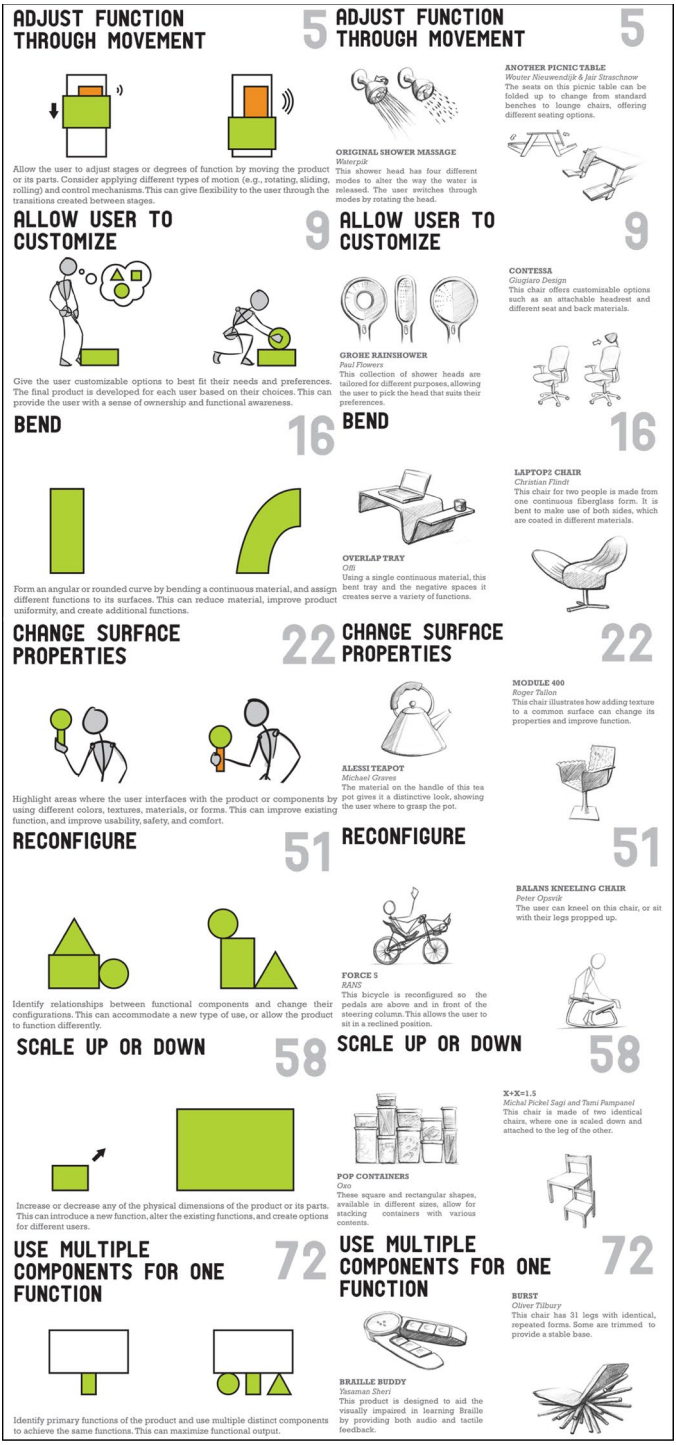



**Fig. 2** The seven design heuristics cards provided to participants in the study (Courtesy of Design Heuristics, L.L.C.)

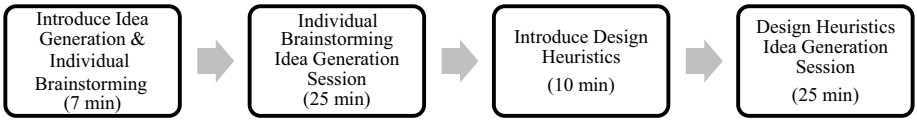



**Fig. 3** Flow chart showing experimental procedure for all participants

## Qualitative data analysis

Analysis considered both participants' drawings and transcribed written descriptions. Data for thirteen participants (6.5%) were removed from the analysis due to illegibility or completing fewer than three ideas out of the 5 requested ideas per session. Table 1 lists the total number of participants and ideas included in the final analysis, as well as the breakdown of which idea generation method was used.

To analyze idea characteristics, we adapted a genealogical variety tree method for categorizing ideas (Shah et al., 2003). Shah and colleagues used a variety tree to identify functional decompositions. We adapted the variety tree to instead evaluate emergent idea characteristics across similar ideas. We defined idea *aspects* through an inductive qualitative analysis approach as key descriptive components which make up each idea. We iteratively identified main patterns of idea aspects across ideas for both design problems, presented in Figs. 4 and 5, and defined their main qualities as shown in Appendix 3.

**Table 1** Summary of the number of participants and ideas included in analysis

| | Pet problem | Burrito problem | Total |
|---|---|---|---|
| Number of participants | 94 (50.5%) | 92 (49.5%) | 186 |
| Number of ideas generated | 886 (50.5%) | 870 (49.5%) | 1756 |
| Average number of ideas | 9.5 (1.6) | 9.9 (0.5) | 9.7 (1.2) |
| Individual Brainstorming ideas | 436 (50.0%) | 435 (50.0%) | 871 |
| Design Heuristics ideas | 450 (50.8%) | 435 (49.2%) | 885 |

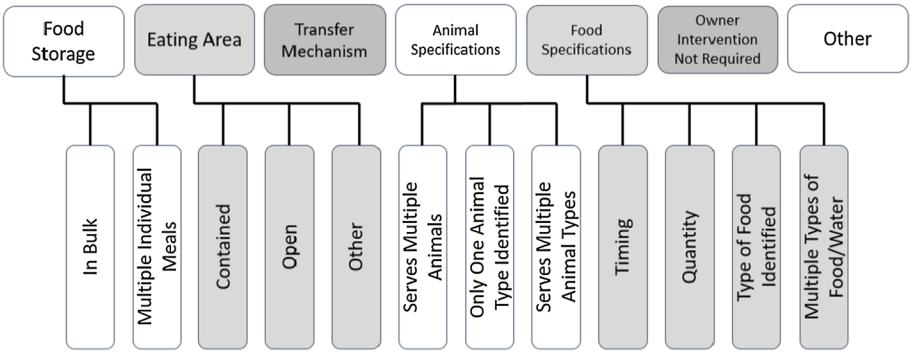



**Fig. 4** Idea aspects categorization scheme for the Pet problem

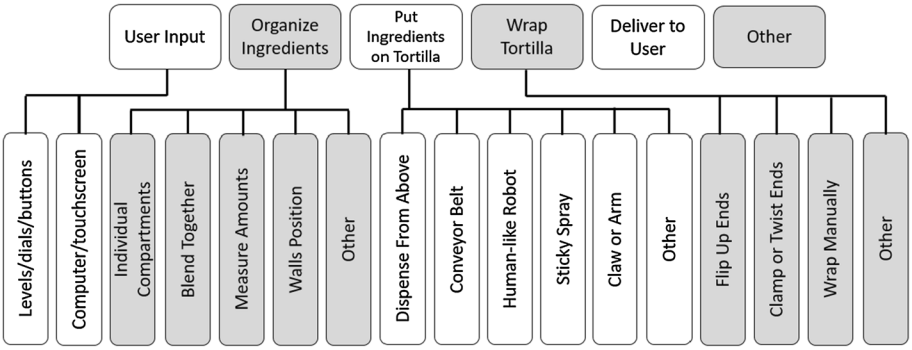
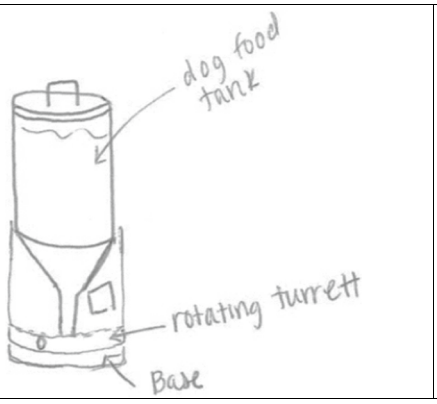



**Fig. 5** Idea aspects categorization scheme for the Burrito problem

Figure 6 contains a participant drawing and description for a solution to the Pet problem. Table 2 describes the evidence in the participant's drawing, labels, and description informing its categorization according to idea aspects categorization scheme.

Figure 7 contains a participant drawing and description solving the Burrito problem. Table 3 demonstrates what evidence was taken from the participant's drawing, labels, and description to inform how the idea was categorized according to Burrito problem idea aspects categorization scheme.

Using the idea aspects categorization scheme, two researchers independently categorized 10% of the data for each problem to determine reliability. We used the formula described in Miles and Huberman (1994) defining reliability as the number of agreements divided by the sum of agreements and disagreements between researchers. Inter-rater reliability (IRR) for the Pet problem idea aspects categorization scheme was 98.3%, and any discrepancies were argued to consensus. For the Burrito problem, the idea aspects categorization scheme IRR was similarly calculated as 89.2%, and any discrepancies were argued to consensus. Then, one researcher categorized the remaining data using the same categorization schemes.

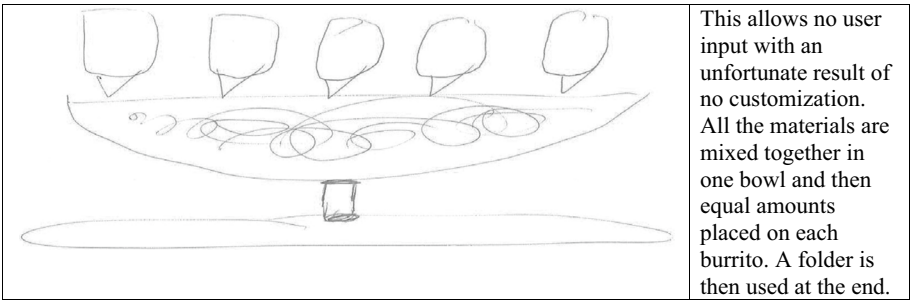



Storage food tank on top, funnels to put 1 pebble in turret, rotates "randomly" to shoot pebbles in varied distance + speeds to have dog move and run to get food. Purpose: indoor dogs that won't get much exercise. Automatic pre-set times & amounts. (P-12)

**Fig. 6** Participant idea including drawing and description for the design problem, "Design a device to feed a cat or dog"

**Table 2** Categorization of idea aspects for the participant idea in Fig. 6

| Idea aspect | Evidence |
|---|---|
| Food storage—in bulk | "Dog food tank" label and drawing; "storage food tank" description |
| Eating area—open | Eating location is defined (turret "randomly" shoots pebbles for dog to run and find) but is not contained |
| Transfer mechanism | Funnel transfers food from food storage tank down to the rotating turret, which shoots pebbles out for the dog to eat |
| Animal specifications—only one type of animal identified | Only dogs are specified in the description and labels |
| Food specifications—timing | Description references "automatic pre-set times" |
| Food specifications—quantity | Description references "automatic pre-set…amounts" |
| Owner intervention not required | The machine works automatically (as stated in description) so the owner is not required for many meals |



This allows no user input with an unfortunate result of no customization. All the materials are mixed together in one bowl and then equal amounts placed on each burrito. A folder is then used at the end.

**Fig. 7** Participant drawing and description in response to the design problem, "Design a device to build a burrito." (P-97)

**Table 3** Categorization of idea aspects for the participant idea in Fig. 7

| Idea aspect | Evidence |
|---|---|
| Organize ingredients—individually | The drawing indicates 5 separate compartments along the top which hold individual ingredients |
| Organize ingredients—other | The ingredients are "mixed together in one bowl" as shown in both the description and drawing. This method of organizing ingredients is not described by any other category, so it was categorized as Other |
| Put ingredients on tortilla—dispense from above | The description indicates that ingredients are "placed on each burrito" and the drawing indicates that ingredients are dispensed from the bowl above the burrito |
| Wrap tortilla | The description indicates "a folder is then used at the end" |

The resulting idea aspects categorization was considered in four different analyses: (1) Number of aspects considered within each idea; (2) Paradigmatic patterns of aspects repeated across ideas; (3) Number of ideas varying a paradigmatic aspect; and (4) Number of unusual ideas attending to characteristics not common in the datasets.

## Results

### Number of idea aspects considered per idea

The number of aspects represented in each idea measured how many different elements or components were considered within a single idea. This number was used as an indicator of the scope or scale of an idea. We compared the average number of aspects per idea for designs generated during Individual Brainstorming versus Design Heuristics for both design problems, as shown in Table 4. Statistical comparisons used SPSS version 27 and Excel version 16.5, and with assumptions of equal variance supported, t-tests were used to compare the means for each problem. The results show that ideas from the Individual Brainstorming session included more aspects (on average) than the ideas from the Design Heuristics session for both the Pet Feeder and Burrito Maker problems. The estimate suggests a medium to large effect size where over 70% of participants included more aspects in their Individual Brainstorming ideas.

The greater number of aspects in Individual Brainstorming ideas (on average) suggests the creation of a system with sub-components, each addressing aspects such as where food will be stored, how food will be measured, how food will be transferred to a feeding area, and how a pet will know it is time to eat. In contrast, the ideas generated with Design Heuristics addressed fewer aspects, suggesting a tighter focus on food delivery to the pet. Table 5 includes two representative examples of the scale of ideas generated using Individual Brainstorming in comparison to ideas generated using Design Heuristics. In the example, the idea on the left was generated using Individual Brainstorming and the one on the right, Design Heuristics. The idea generated with Individual Brainstorming addressed six aspects, while the idea generated with Design Heuristics addressed three aspects. The greater number of aspects represented in the idea generated with Individual Brainstorming reflects this idea as a system with many sub-components, including where food will be stored, how food will be measured, how food will be transferred to a feeding area, and how an animal will know it is time to eat. In contrast, the fewer aspects addressed in the idea generated with Design Heuristics represents a tighter focus: how food will be delivered to an animal.

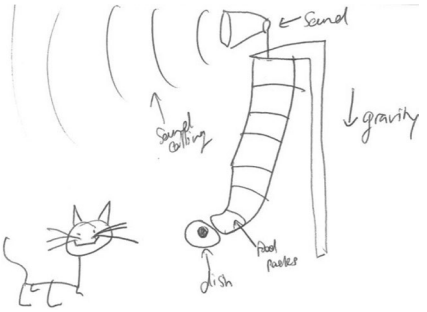
### Emergence of paradigmatic aspects

Paradigms in idea generation are defined as the prevailing or common way of thinking and perceiving (Silk et al., 2018). In the ideas generated for the Pet Feeder problem, we identified a *paradigmatic aspect* appearing often across participants. A "food bowl" aspect appeared in 82% of ideas for this problem, defining a paradigmatic aspect present as a design element in most ideas. A food bowl was often included as part of a larger system that established how pets and owners interact with it; however, in some ideas, the food

**Table 4** Average number of aspects attended to in generated ideas

| | Individual Brainstorming ideas | Design Heuristics ideas | *t* | *df* | *p* | Cohen's *d* |
|---|---|---|---|---|---|---|
| Pet problem | 4.07 (0.71) | 3.27 (0.99) | 9.1 | 93 | < .001 | .94 |
| Burrito problem | 2.37 (0.59) | 1.91 (0.50) | 6.4 | 86 | < .001 | .69 |

**Table 5** Two ideas generated by the same participant to solve the Pet Feeder design problem and the idea aspects analysis

| Idea generated with Individual Brainstorming | Idea generated with Design Heuristics |
|---|---|
|  | |
| Participant description: Gravity feeder, a pillar of measured amounts of food that get sent down after a specific period of time plays a sound to all cats/dogs (P-18) | Participant description: The surface of a ball changes to one that has holes where food can be released when chewed by dog (P-18) |
| Idea aspects attended to (6): Food storage, Eating area, Transfer mechanism, Animal specifications, Food specifications, and Owner intervention | Idea aspects attended to (3): Eating area, Transfer mechanism, and Animal specifications |

bowl itself became a *target of variation* in alternative designs. These ideas focused on changes to the food bowl rather than offering a more complete design with more aspects included. However, for the Burrito Maker problem, no aspect emerged as dominant across designs.

We also identified common *patterns* of aspects that emerged across ideas and were defined as paradigmatic. For the Pet Feeder problem, most ideas (59%) included three co-occurring aspects:

1. *Food Storage Area*: Bulk food storage or multiples of prepared meals.
2. *Contained Eating Area*: A bowl, container, or plate designated for consumption and distinct from the food storage area.
3. *Method to Transfer Food*: Often food free-falling from storage via gravity into a bowl below, a human scooping food from storage into a bowl, or a slide connecting storage and bowl.

For the Burrito Maker problem, the most frequent idea occurred in 39% of ideas and included two co-occurring aspects repeated across ideas:

1. *Organize Ingredients*: A method for identifying where the ingredients go before combining in a burrito, including individual compartments for ingredients or blending all ingredients together.
2. *Put Ingredients on Tortilla*: A method of transferring ingredients onto the tortilla; for example, dispensing ingredients from above or having a robot arm dispense ingredients.

Repetition of aspects across ideas served as an index of how often the same elements appeared across different ideas for each participant's set. Idea sets with a low score on this measure reflected more variation in the elements of designs within the set, while a high score reflected that the same design elements were used across multiple ideas.

### Variation of paradigmatic aspects

Across both design problems, there was a greater percentage of ideas generated with Design Heuristics that were outside of the dominant paradigm than with ideas generated with Individual Brainstorming. The number of ideas that were within or outside of the paradigm are listed in Table 6. In the Pet design problem, 50% of ideas generated using Design Heuristics were outside of the paradigm. In contrast, only 33.7% of ideas generated using Individual Brainstorming were outside of the paradigm. The difference between ideas generated using Design Heuristics and Individual Brainstorming was significant, $X^2$ (1, N = 886) = 25.95, $p < 0.001$, Cramer's $V = 0.17$ (Cohen, 1988). Similarly, in the Burrito design problem, 69.8% of ideas generated using Design Heuristics were outside of the paradigm, while only 51.7% of ideas generated using Individual Brainstorming were outside the paradigm. The difference between ideas generated using Design Heuristics and Individual Brainstorming was significant, $X^2$ (1, N = 870) = 30.09, $p < 0.001$, Cramer's $V = 0.19$ (Cohen, 1988). Ideas generated with Design Heuristics tended to include more designs that were unlike the standard design proposed in most ideas.

Four examples of ideas meeting the dominant paradigm criteria for the Pet problem are shown in Table 7 and four examples of ideas meeting the dominant paradigm criteria for the Burrito design problem are shown in Table 8.

Ideas that elaborated on the paradigmatic aspect in the Pet design problem described variations on a food bowl, and were generated primarily using Design Heuristics. The total number of food bowl variation ideas generated was 152. Of these, 80.3% (n = 122) of the food bowl variation ideas were generated using Design Heuristics while 19.7% (n = 30) were generated using Individual Brainstorming (see Table 9). The difference between ideas elaborating on the paradigm using Design Heuristics and Individual Brainstorming was significant, $X^2$ (1, N = 886) = 60.28, $p < 0.001$, Cramer's $V = 0.26$ (Cohen, 1988). While using Individual Brainstorming, the paradigmatic aspect of the food bowl largely remained unchanged, while Design Heuristics seemed to prompt participants to see the paradigmatic

**Table 6** The number of ideas within or outside of the paradigm in comparison to the total number of ideas for both design problems, as related to idea generation method

| | | # of Ideas generated using Individual Brainstorming | # of Ideas generated using Design Heuristics | Total ideas |
|---|---|---|---|---|
| Pet problem | Within paradigm | 287 | 220 | 507 |
| | Outside paradigm | 149 | 230 | 379 |
| | Total | 436 | 450 | 886 |
| Burrito problem | Within paradigm | 210 | 131 | 341 |
| | Outside paradigm | 225 | 304 | 529 |
| | Total | 435 | 435 | 870 |

**Table 7** Four examples of ideas within the paradigm for the Pet design problem

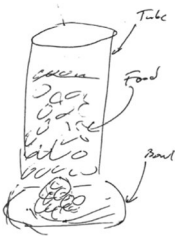
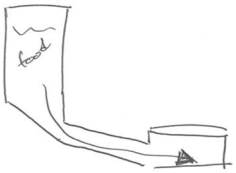
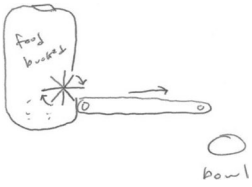
| Idea generation method used | Idea drawing | Participant idea description |
|---|---|---|
| Individual Brainstorming |  | The food fills up the bowl from falling from the chute into the bowl as the animal eats the food already in the bowl. (P-7) |
| | | This device activates a food release system at specified times. (P-10) |
| Design Heuristics |  | Gravity pushes the food down into the bowl because of the sloped piece. (P-33) |
| |  | Food is turned out of a bucket onto a conveyer belt where it is dumped into the food bowl. (P-42) |

**Table 8** Four examples of ideas within the paradigm for the Burrito design problem

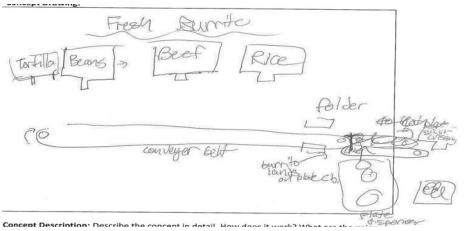
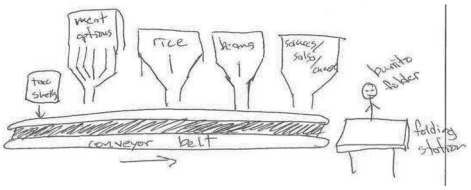
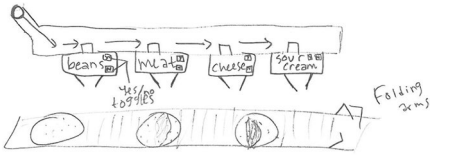
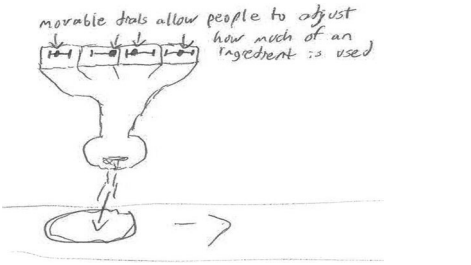
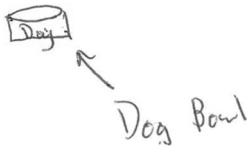
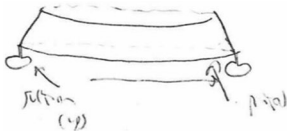
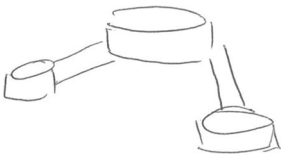
| Idea generation method used | Idea drawing | Participant idea description |
|---|---|---|
| Individual Brainstorming |  | Tortilla drops onto belt. Bean, beef, and rice dispense. Folded by crane-like machine. Drops onto plate. (P-120) |
| |  | The concept is based on a conveyer belt which different stations dispense ingredients for burritos. It's basically like an automated assembly line for building burritos (P-146) |
| Design Heuristics |  | Conveyor belt—tortillas moving, ingredients triggered by metal ball. User can select Y or N if he/she wants ingredients. Folded by mechanical arms. (P-139) |
| |  | This design allows for easy user manipulation of burrito ingredients. (P-156) |

**Table 9** Number of food bowl variations in ideas generated using Individual Brainstorming vs. Design Heuristics for the pet feeder problem

| | Number of ideas generated using Individual Brainstorming | Number of ideas generated using Design Heuristics |
|---|---|---|
| Total | 436 | 450 |
| Food bowl ideas | 30 | 122 |

**Table 10** Four examples of a paradigmatic aspect (food bowl) in ideas from four different participants

| Generated using | Idea drawing | Participant idea description |
|---|---|---|
| Individual Brainstorming |   | It's a dog bowl. (P-75) |
| | | A bowl to put food in. Also placed on a lever that can be raised or lowered. (P-44) |
| Design Heuristics |  | This is a simple bowl but it is made of heavy metal and is secured to the ground. Therefore, it won't be knocked over. (P-68) |
| |  | Attach different size bowls for different meals/ different food items. Provide several different bowls so user can customize sets. (P-82) |

aspect as a target of (or opportunity for) adding variation. Table 10 shows four examples of these bowl ideas with varying levels of details. We did not find similar elaboration on specific paradigmatic aspects in the analysis of the Burrito Maker problem.

## Generation of unusual aspects

Unusual aspects were defined as "Other" if the entire idea or an aspect of the idea were not described in the idea aspect categorization schemes (Figs. 4 and 5), unique among the set of 1756 ideas generated by participants. In the Burrito design problem, Design Heuristics led to more ideas being categorized by the "Other" category of the Burrito problem idea aspects categorization scheme in comparison to ideas generated using Individual Brainstorming. Of ideas categorized as "Other," 60.2% were generated using Design Heuristics, in comparison to 39.8% of ideas generated using Individual Brainstorming. The difference between ideas generated using Design Heuristics in comparison to Individual Brainstorming was significant, $X^2$ (1, N = 870) = 11.05, $p < 0.001$. The effect size for this finding, Cramer's $V$, was small, 0.11 (Cohen, 1988). So, use of Design Heuristics resulted in more ideas categorized as "Other," reflecting more unusual qualities in these ideas.

**Table 11** Two examples of participant drawings and associated descriptions that were categorized as "Other" for the Burrito design problem

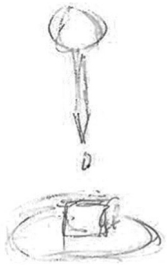
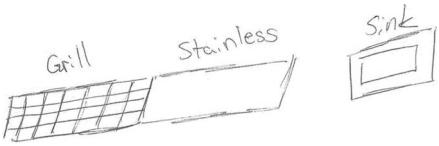
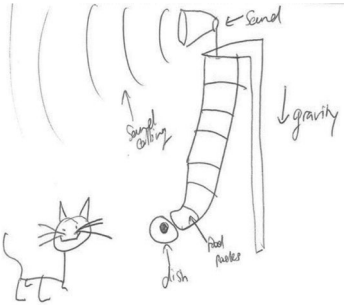
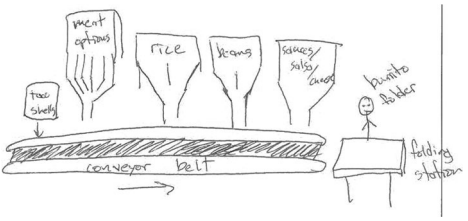
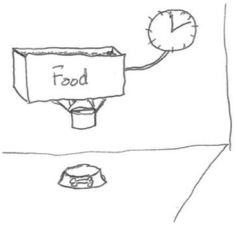
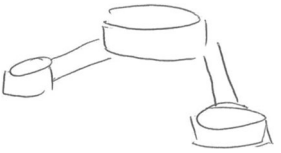
| | |
|---|---|
|  |  |
| A machine that selects a cube based on what preferences a person has for a burrito by simply hydrating the compressed cube of food, a hot steamy burrito is made. (P-98) | Different materials to know where items belong. (P-101) |

Table 11 shows two examples of participant ideas for the Burrito problem that were both categorized as "Other". The example on the left features an idea that few, if any, other participants generated and therefore it was not characterized by the categories in the Burrito problem's idea aspects categorization scheme. The idea describes a cube that is hydrated to create a burrito based on user preferences. This idea was categorized for "User Input" as it took user preferences into account, but the remaining categories did not sufficiently describe the cube hydrating process. This aspect of the idea, therefore, was categorized as "Other." The example on the right was categorized only as "Other." The idea describes a method of using different materials to know where items belong in the burrito-making process. This idea was unique among ideas generated by all participants, and therefore could not be described by the emergent categories which made up the categorization scheme. We did not find a parallel emergence of unusual aspects for the Pet problem.

In summary, our analysis revealed three key differences in ideas generated using Individual Brainstorming compared to Design Heuristics, illustrated through examples shown in Table 12:

(1) Ideas generated using Individual Brainstorming tended to focus on systems, while ideas generated using Design Heuristics tended to focus on specific components;
(2) Ideas generated using Individual Brainstorming were more similar across participants, while more unusual ideas were generated using Design Heuristics; and
(3) Ideas generated using Design Heuristics more often elaborated variations on paradigmatic aspects compared to Individual Brainstorming ideas.

**Table 12** Summary of differences in idea characteristics generated using Individual Brainstorming and Design Heuristics

| Individual Brainstorming | Design Heuristics |
|---|---|
| Focus on systems | Focus on components |
|  | |
| Gravity feeder, a pillar of measured amounts of food that get sent down after a specific period of time plays a sound to all cats/dogs. (P-18) | The surface of a ball charges to one that has holes where food can be released when chewed by dog. (P-18) |
| More typical ideas | More unusual ideas |
|  | |
| The concept is based on a conveyer belt which different stations dispense ingredients for burritos. It's basically like an automated assembly line for building burritos. (P-146) | A machine that selects a cube based on what preferences a person has for a burrito by simply hydrating the compressed cube of food, a hot steamy burrito is made. (P-98) |
| Paradigmatic aspect unchanged | Paradigmatic aspect target of variation |
|  |  |
| This device activates a food release system at specified times. (P-10) | Attach different size bowls for different meals/different food items. Provide several different bowls so user can customize sets. (P-82) |

## Discussion

In this study, we evaluated the characteristics of 1756 individual ideas to solve one of two design problems: *design a way to build a burrito* and *design a device to feed a cat or dog*. We found that participants using Individual Brainstorming were more likely to produce ideas that were systems, while Design Heuristics supported more component-level

ideas. Ideas generated using Individual Brainstorming addressed more idea aspects than ideas generated using Design Heuristics in both design problems. This pattern indicates that ideas generated using Individual Brainstorming were system-type solutions; that is, they addressed multiple aspects of the problem and how they related to each other. Many ideas generated using Individual Brainstorming, for example, incorporated food storage, a food bowl, and how food would move from storage to bowl. In contrast, idea generated using Design Heuristics tended to focus on individual aspects of the solutions, like making variations on a food bowl or on modifications to food storage.

This finding aligns with that of Daly, Seifert and colleagues (2016) and Daly, Seifert and colleagues (2016) showing ideas generated using Design Heuristics were more practical and elaborate than ideas generated using Individual Brainstorming. They found ideas generated using Design Heuristics were "more specific, and more technical," which aligns with the more detailed focus and exploration of components, rather than a "zoomed-out" view of a system. Similarly, the increased focus on specificity aligns with work identifying that Design Heuristics support elaboration and specification (Christian et al., 2012). The finding that Individual Brainstorming supports system-level exploration aligns with work identifying that Brainstorming leads to broad exploration (Linsey et al., 2011). This finding has significant implications for teaching both idea generation methods. For tasks involving initial idea generation or holistic system-level exploration, our findings suggest that Individual Brainstorming may be a more effective method to support engineers. Design Heuristics, in contrast, may be more effective during idea development or iteration on a single aspect or component of an idea.

Across both design problems, Design Heuristics helped participants to generate more ideas outside of the paradigm. The paradigm for each design problem was defined by the most frequently occurring idea across all participant ideas. Because so many participant ideas fit this paradigmatic content, the more novel ideas were reflected by unusual aspects that appeared in few, if any, other ideas generated by the participants. The Design Heuristics more effectively helped participants to break out of these paradigms, which suggests that Design Heuristics may support students in generating ideas that are more likely to be unique. As diversity of ideas is an important criteria in successful idea generation (Daly, Yilmaz, et al., 2016; Daly, Seifert, et al., 2016), this finding helps in understanding the value of using Design Heuristics during idea generation.

Design Heuristics also supported participants in seeing the paradigmatic aspect as a target of variation, in contrast to ideas generated using Individual Brainstorming, where the paradigmatic aspect was largely unchanged. As might be expected, the participants tended to think alike as they considered the problems and produced paradigmatic ideas. Further, participants tended to perseverate on this core paradigmatic idea, producing little variation across their idea set. Of the many ideas collected, only a small set showed significant differences from the core idea. These "unusual" ideas suggest that unique ideas are quite rare in the beginning stages of learning to design, and these ideas were most often prompted using Design Heuristics. The food bowl variations for the Pet problem were primarily generated using Design Heuristics. During Individual Brainstorming, the food bowl was typically paradigmatic as part of the solution. In contrast, using Design Heuristics, this paradigmatic component became the *target* of variation. Design Heuristics seem to support students in defining assumptions and prompting variations on those assumptions. Christian and colleagues similarly found that ideas generated using Design Heuristics were more elaborate (Christian et al., 2012) and Daly, Christian, and colleagues (2012) found ideas generated using Design Heuristics "went beyond basic principles."

Additionally, this finding of variation on a paradigm suggests that Design Heuristics might help students to break out of their conceptions of what an idea "must be." It may be that novice engineers believe that for an idea to "count," it has to address the entire problem presented. They might have believed an idea had to include gears, conveyor belts, and other mechanisms in order to qualify as a sufficient idea, as appeared often during Individual Brainstorming. In contrast, the food bowl ideas added with Design Heuristics were characterized by simplicity. In many cases, the entire drawing for the idea was simply a bowl sitting on the floor with small variations such as texture, height, or size. The simplicity and specificity of these ideas stand in stark contrast to the system-level ideas generated, which extended even as far as Rube Goldberg-esque machines. The difference between these ideas provides evidence that Design Heuristics encourage exploration of components rather than holistic systems.

Despite the successful analysis of a single paradigmatic aspect—food bowls—as a nexus for variations in the Pet problem, this key aspect has no parallel in the Burrito problem analysis. Perhaps due to the simplicity of the Pet design problem ("design a way to feed a cat or dog"), the variation among the observed ideas was focused on a paradigmatic aspect rather than a larger paradigmatic idea when using Design Heuristics. This tendency to generate alternative ideas was characterized by focusing on a single component rather than the entire solution for the Pet problem. This observed difference in how variation introduced by Design Heuristics differed in the two problems may be due to familiarity with the problem context, lack of knowledge about how to implement "burrito making" as a component task, or other differences in the problem. This difference in findings for the two problems points out the importance of including multiple design problems in research studies so that such differences are evident in the findings. Other design problems will likely produce other frequent patterns that are informative about how the ideas were created that go beyond the observation of a paradigmatic idea.

Ideas categorized as "Unusual" reflected more unique ideas that were not captured by the emergent idea aspects categorization scheme. In the Burrito design problem, Design Heuristics led to more ideas being categorized in the "Unusual" category of the Burrito problem idea aspects categorization scheme in comparison to ideas generated using Individual Brainstorming. Ideas categorized as "Unusual" indicate that ideas, or at least components of ideas, were not able to be described by the idea aspects categorization scheme, which described the majority of other ideas. We did not find a significant difference in ideas categorized as "Unusual" in the Pet problem, suggesting the problem context may impact the generation and categorization of unique ideas. Since ideas for the Burrito design problem generated using Design Heuristics were more likely to be categorized as "Unusual," Design Heuristics appeared to help push participants to generate ideas that were less like their own and their peers' ideas. Daly, Yilmaz, and colleagues (2012) and Daly, Christian, and colleagues (2012) also found that ideas generated using Design Heuristics were significantly more creative, and Leahy, Daly, McKilligan and colleagues (2018) found that Design Heuristics prompted more creative and unique ideas. Our findings show that one way the generation of unique ideas takes place is through a focused variation of a design aspect across multiple generated designs, producing more varied designs as a result.

The findings from this study revealed patterns in characteristics influenced by the ideation methods used. Our study design included many individual participants who generated a relatively large number of different designs (10) during the sessions. Collecting so many different ideas for the same two design problems produced a clear sense of the possible solution space considered by novice engineers. Further, using simple design problems allowed an analysis that detected similar patterns across ideas despite individual differences

in how designs were sketched and described. These two design problems, used in previous studies by Smith and colleagues (2012), revealed underlying patterns in design characteristics influenced by the specific ideation methods used. Future studies might examine patterns across many design problems to reveal other systematic phenomena resulting from idea generation approaches.

## Limitations

An important feature of this study's within-subjects design is that each designer created ideas for a single design problem while generating ideas using Individual Brainstorming first and Design Heuristics second. This design enhances the observation of how the qualities of ideas change when using two different methods, and this "interrupted time series" design was selected in order to allow the natural Brainstorming session to precede the instruction with Design Heuristics, which may have altered a Brainstorming session following it. However, the serial ordering of the two sessions may be an alternative explanation for the findings. Because Design Heuristics were always used in the second session, it is possible that occurring second caused the observed differences. If so, it would not explain why ideation performance improves later in the design sessions. Many past studies show ideation produces less variation among ideas later in a session due to increasing fixation (c.f. Janssen & Smith, 1991; Purcell & Gero, 1996; Linsey et al., 2010; Leahy et al., 2020) rather than the enhanced variation of ideas as observed in this study.

Fatigue effects may disadvantage a second idea generation session because designers have been shown to produce fewer ideas over time due to fixation, fatigue, or lack of motivation, as well as idea exhaustion (Gray et al., 2015). The sequence also allowed students to generate ideas using their own natural approach during Brainstorming before adopting the Design Heuristics method. Introducing a new method may influence one's natural process, so capturing natural idea generation before the use of a new method may avoid interference between methods. Further, as the second ideation session, Design Heuristics were more likely to be disadvantaged as students' interest and energy lagged. However, this limitation of the study design should be considered in generalizing from the study findings.

Another limitation of the study design is the absence of information about differences among the individuals who participated in the study. We do not know students' experiences with or ambitions for engineering work, their intended program of study, or whether they were international or domestic students. We had an imbalance in gender representation and likely an imbalance in race/ethnicity (although we did not ask about students' race/ethnicity), as we received participants from a university with gender and racial imbalances. It is well-documented that personal identities can influence ways of thinking and generation of new ideas (e.g. Foss et al., 2013; Jaussi et al., 2007). Variations across those and other dimensions may further inform the understanding of the impact of ideation methods. While the pedagogical workshop provided a large and diverse sample of incoming first-year engineers, it also limited the study activity to providing a single, cohesive learning experience for all students. As beginning engineers, the observed outcomes may not be applicable in understanding ideation methods with more advanced engineering students or practitioners. The two simple design problems in the study are similarly limited compared to "real world" engineering design problems. Finally, the design session was time-limited and prevented collaborative or longer-term design processes more typical of engineering projects. Therefore, the variations in idea characteristics observed in this study may be more or less implicated in design practices beyond initial conceptual design.

### Implications

Our findings showed that Individual Brainstorming led to more ideas focused on systems-level ideas while Design Heuristics supported generating variations in component-level ideas. Design Heuristics helped students to create more unique ideas outside of the dominant paradigm observed in the study. This finding suggests Design Heuristics are useful in conducting a directed exploration of specific components within a design. The heuristics may guide designers in questioning the assumptions about "standard" components to invent multiple variations, resulting in more novel designs. More generally, perhaps adopting more than one ideation method during a session increases beneficial outcomes. As more evidence emerges about the impact of ideation method on design outcomes, strategic choice of method may be identified as more beneficial to designers and engineers. Future work investigating the particular idea outcomes prompted by ideation methods can help designers to align selection of ideation method with design goals. Further, varying the ideation method may provoke varied design outcomes, leading to yet unexplored opportunities for innovation.

Another implication from this study is that designers, educators, and researchers might consider a broader collection of ways to assess ideation outcomes. In this study, we looked more deeply than the common metrics to identify qualitative differences in the impacts of ideation methods. Design researchers might incorporate context-specific measures such as emergent themes in their evaluation of ideation outcomes. These methods uncover important and emergent patterns in design not evident with more traditional methods of analysis such as creativity ratings or self-evaluation surveys. The discovery of *how* Design Heuristics changed the characteristics of resulting designs suggests more nuanced approaches to identifying the impact of design processes may lead to new findings in other idea generation contexts as well.

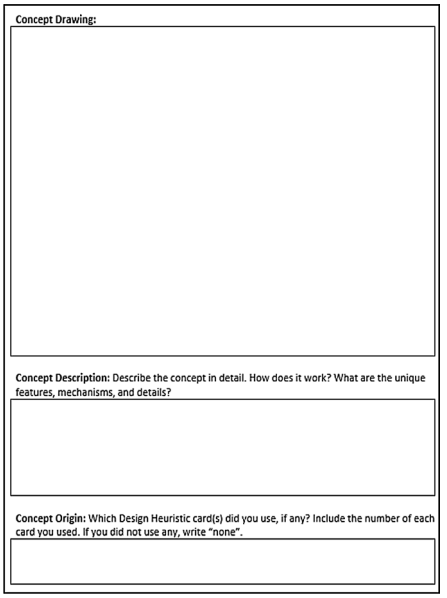
## Conclusion

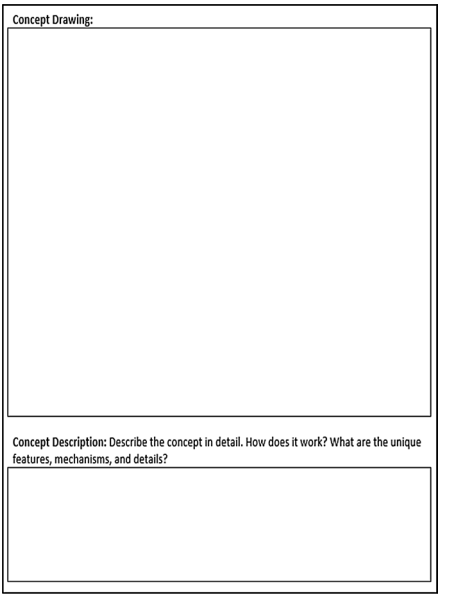
In this study, we compared a large sample of 1756 ideas generated using Individual Brainstorming and using Design Heuristics by a large sample of 186 beginning engineering students. Students generated ideas using both methods to solve one of two design problems, and we evaluated their ideas based on key idea characteristics. These emergent characteristics led to four measures of idea generation methods: (1) number of aspects per idea, (2) paradigmatic patterns of aspects across ideas, (3) elaboration on a specific paradigmatic aspect, and (4) presence of unusual aspects. We found the Individual Brainstorming session supported a focus on complete idea systems, more typical ideas, and ideas with little change in the paradigmatic aspect. Design Heuristics ideas revealed a focus on component-level ideas, unusual ideas, and variation of the paradigmatic aspect. These findings suggest ideation methods support

different outcomes in the characteristics of resulting designs. More information about the impact of ideation methods on design outcomes could support more strategic guidelines for the use of alternative methods when generating ideas.

## Appendix 1

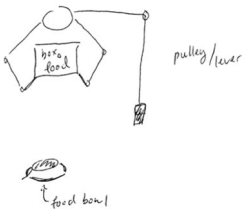
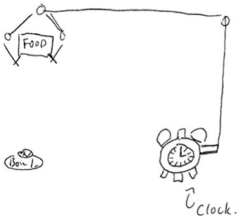
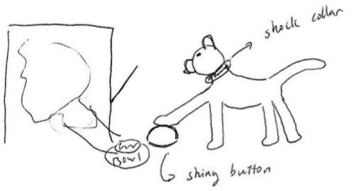
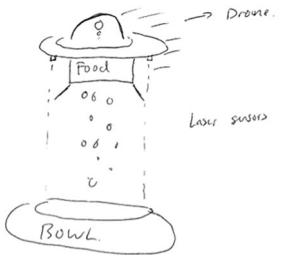
Concept sheets used by students while generating ideas using Design Heuristics (left) and using Individual Brainstorming (right), with designated space to sketch and describe the idea in writing. The Design Heuristics concept sheet includes a space to indicate the specific card used, if any, to generate that idea.

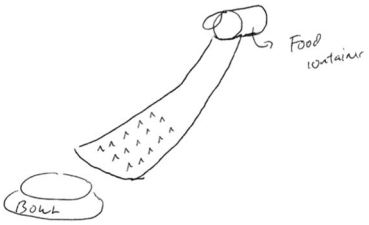
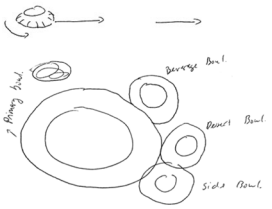
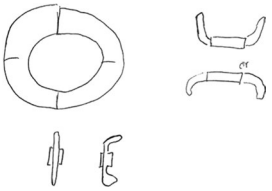


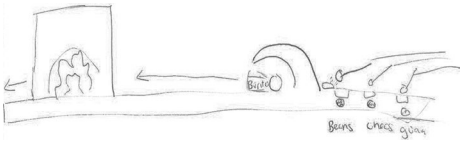
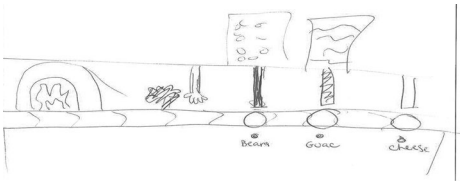
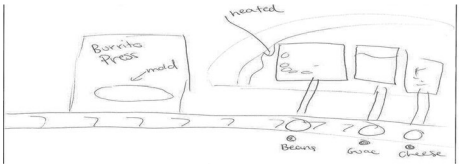
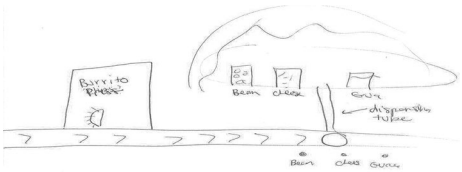
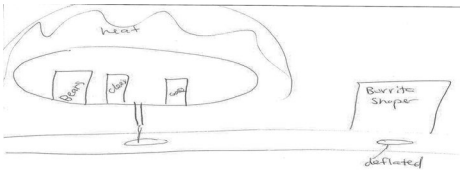



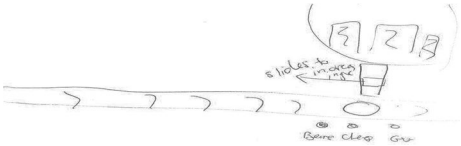
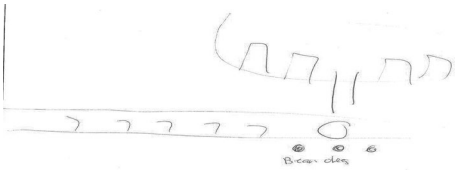
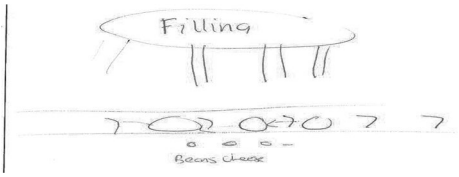
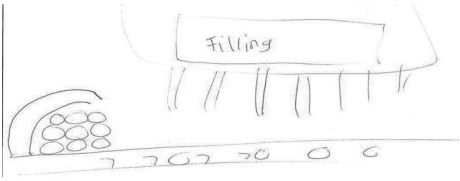
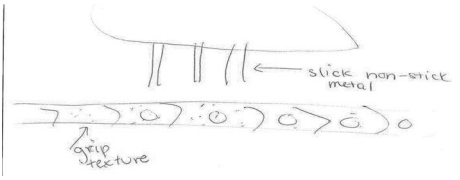
## Appendix 2

One participant's (P-199) entire dataset for the problem, "Design a device to feed a cat or dog," and another participant's (P-124) for the problem, "Design a device to build a burrito." Ideas 1–5 were generated using Individual Brainstorming, and ideas 6–10 were generated using Design Heuristics.

| Individual Brainstorming session | | |
|---|---|---|
| Idea | Description | Drawing |
| 1 | When it's time to feed the pet, someone needs to pull a lever that releases food of the desired type into the bowl. Release lever when done to stop the dropping cat food |   |
| 2 | When the clock hits feeding time, it shakes tremendously and opens the food box via pulley. When the clock stops so does the flow of food because the pulleys would have returned to their original position which kept the food box closed |   |
| 3 | Train the dog to only hit the button when it is hungry/feeding time has been reached using shock collar. The button opens a door which allows food to flow down a chute into the bowl |   |
| 4 | Drone leaves charging platform at designated times. Drone flies around room until its laser sensors match up to a bowl at which time it releases food from the box of food it is carrying. Drone charging station must be in same room as food bowl. Drone finds bowl by searching in a grid-like pattern |   |
| 5 | When a certain time is reached, a clocks hammer, instead of being used to strike bells or chimes, is used to knock over a small block. This block would have been used to pry back a slingshot that had been carrying a ball of food. Once released, this ball of food lands in the pet's bowl. | |

| Design Heuristics session | | |
|---|---|---|
| Idea | Description | Drawing |
| 6 | Attach a curved slide from the food can to the bowl. However, the surface of this slide will be extremely rough, so much so food becomes trapped and slowed by the slides' projections. The rate at which food exits the slide can be controlled to the point that throughout the day, food travels through the slide and buildup until feeding time when it is emptied by the pet |   |
| 7 | The bowl can be slid along a track where masked spots correspond with different flavors/nutrients/brands. The bowl also serves as a timer which marks how long the pet must wait until its next feeding session. To do this, the buckets of food above would be blocked until the time is up. | |
| 8 | Several auxiliary bowls can be connected to the primary one depending on need/preference |   |
| 9 | Instead of using a bowl to feed pets, use a pseudo-trough like container. This trough would be essentially one long bent and curved piece of plastic. This would allow several different pets to eat from the same container at the same time | |
| 10 | Instead of a bowl with a fixed configuration, this idea uses a plastic center and a rubber lip. This rubber lip is portable (?) and heaps all the way around the plastic. The rubber can be pulled back in both directions, stopping the mixing of foods, flavors, bacteria. Two different pets can even use it twice in the same day |   |

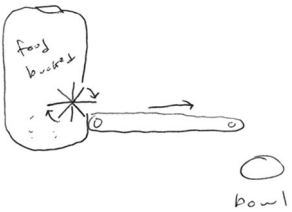
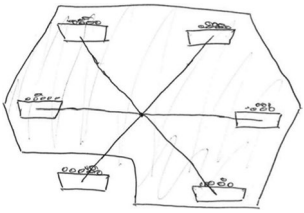
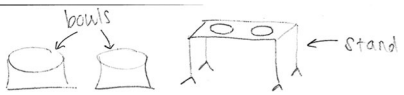
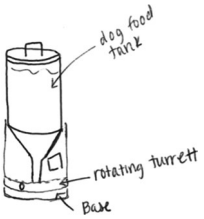
| Individual Brainstorming session | | |
|---|---|---|
| Idea | Description | Drawing |
| 1 | This device allows customer to push a button which then signal a serving of burrito filling into the tortilla by automatic spoon. As the burrito continues down the assembly line, a curved claw rolls the burrito |  |
| 2 | This concept continues the assembly line idea, but the burrito filling is dispenses just above the tortilla. In addition, a robot hand that mimics the rolling of a burrito would wrap it. Finally the burrito would be heated in the oven |  |
| 3 | Now, the burrito ingredients are heated and still dispensed from above. The burrito will enter the burrito press, where it will be molded into shape |  |
| 4 | Now, the heated ingredients rotate and are dispensed out of one tube. Then burrito is folded in half and the outsides are clipped so nothing can escape |  |
| 5 | The burrito shape makes the burrito w/o anything in it. Then, the ingredients are injected/dispersed into the burrito, filling It's inside |  |

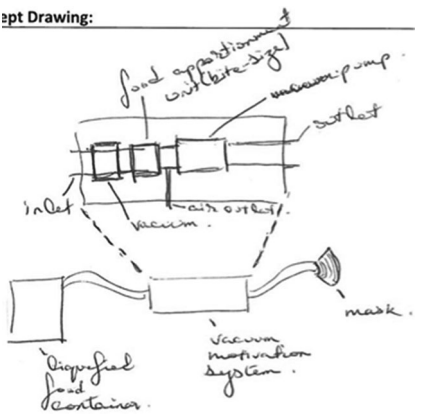
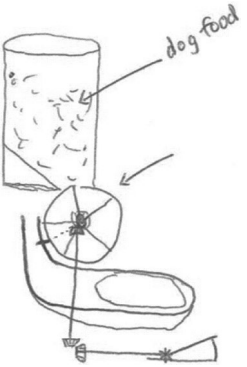
| Design Heuristics session | | |
|---|---|---|
| Idea | Description | Drawing |
| 6 | The dispenser slides to allow for a custom ingredient amount. In addition the conveyor belt moves the burrito down. The buttons also signal a shift in ingredient usage |  |
| 7 | The many option of the burrito allow customers to determine what they want and how much they want just by push a button |  |
| 8 | Multiple dispensing tubes are used to input filling into the burrito. |  |
| 9 | The oven-like shaped container optimizes heating. The curved metal at the end helps beautifully stack the burrito |  |
| 10 | The new grip texture stops anything from sliding. Also, the tubes made with non-stick metal to stop blockage |  |

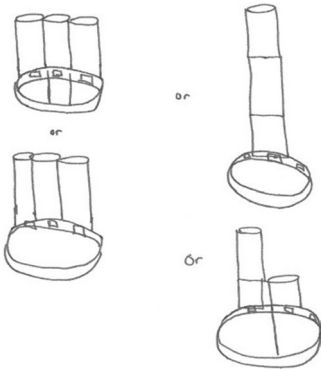
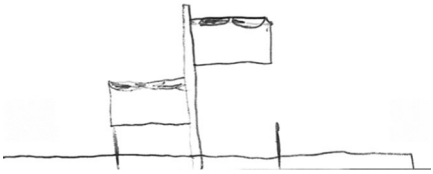
## Appendix 3

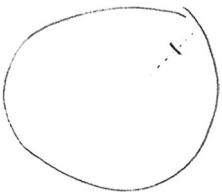
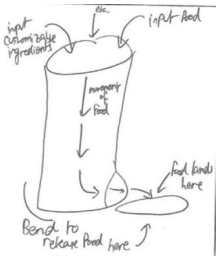
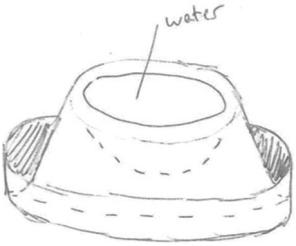
Categorization schemes for the Pet problem and the Burrito problem.

## The pet problem

| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| Food storage | In bulk | Large container or bag of food which contains more than one meal's worth of food |  "Food is turned out of a bucket onto a conveyer belt where it is dumped into the food bowl" |
| | Multiple individual meals | Multiple meals that are individually separated and prepared ahead of time |  "Fill the bowl up once every 6 days depending on how much the pet eats. The "wheel" rotates after a given amount of time once the bowl is empty" |
| Eating Area | Contained | Bowl, plate, or container which defines where food is to be eaten |  "These bowls come with a stand that the user can choose to implement or not. May be helpful for taller pets, or more attractive looks" |
| | Open | Eating area is defined, but not contained |  "Storage food tank on top, funnels to put 1 pebble in turret, rotates "randomly" to shoot pebbles in varied distance + speeds to have dog move and run to get food. Purpose: indoor dogs that Won't get much exercise. Automatic pre-set times & amounts." |

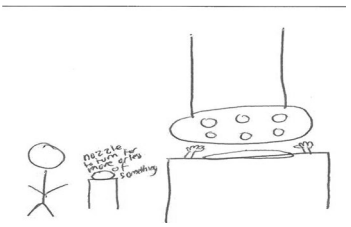
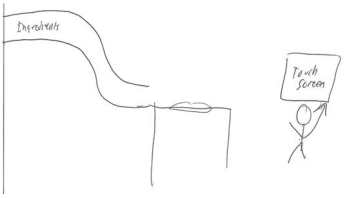
| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| | Other | Eating area which is defined but cannot be described as 'contained' or 'open' |  "FORCE FEEDING MASK: Liquefied food from a holding container into a mask-like apparatus that holds the animal's mouth. Food is moved using a vacuum system in the middle of the tube. Enough food enters at each interval for the animal to swallow but not choke" |
| Transfer Mechanism | N/A | Movement of food from storage to the eating area OR movement to access the eating area |  Dog presses on lever, 2 shaft system to spin wheel, food goes down, slide into bowl. Reqs: well trained dog (or cat, but good luck) |

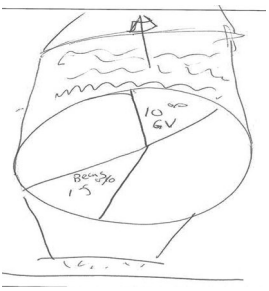
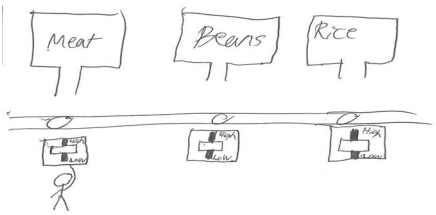
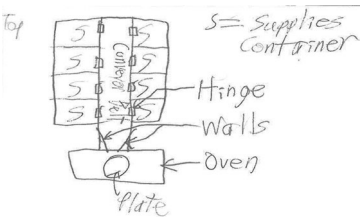
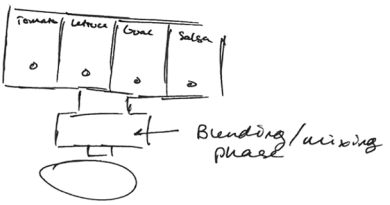
| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| Animal specifi-cataions | Serves multiple animals simultane-ously | Device serves multiple animals at the same time (type of animal is not important) |   This feeder has movable parts! With the 3 food holding cylinders, two dividers, and one basin (with three holes), you can customize your feeder to feed however many (or little) as you want |
| | Only one type of animal identified | Only one type of animal identified in either the text description or the drawing | PET FEEDER APP: Use app to facilitate the release of dog good, can also work with spoken command |
| | Serves multiple animal types | Device can function for multiple types of animals (cats, dogs, hamsters, etc.) |  This simple concept consists of two sets of bowl which are adjusted at different heights, so a dog can reach the larger one and a cat can reach the smaller |
| Food specifica-tions | Timing | Reference to how often food is given or how often food is given | The power to be programmed at expel food at certain times * amount. Door made of non-toxic metal |

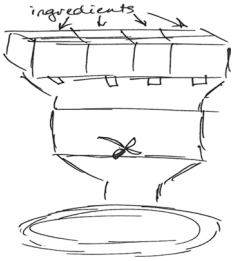
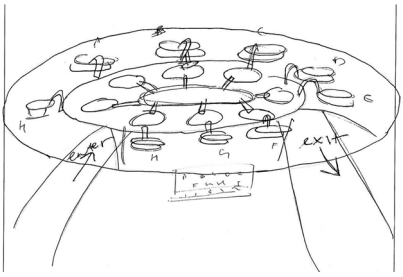
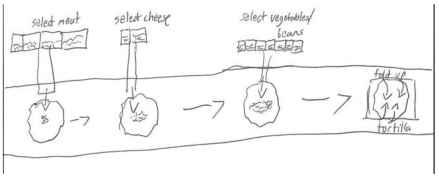
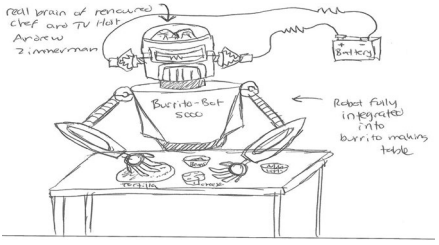
| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| | Quantity | Reference to the amount of food given, or any description/element of weight or how much food to give the pet |  "Bowl with moveable marker for expected amounts. This way, the user can enlist help of young children or those unfamiliar with typical feeding amounts to feed pets." |
| | Type of food identified | Reference to the creation, nutrients, or specific characteristics of food |   Food is released at the bottom. The food can be modified by the user adding unique ingredients. This offers customizable taste for the cat/dog. |
| | Multiple types of food/water | Device accommodates multiple types of food or water |   "Food will go around the bottom of the water bowl. All of it is one piece." |
| Owner intervention not required over multiple meals | N/A | Owner input or action was not required for the cat/dog to eat over the course of multiple meals | "Have a machine that empties dog/cat food periodically during the day for owners who forgot refill the bowl while away but can't filed only one bowl for the cat/dog that day." |

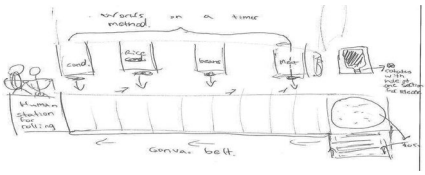
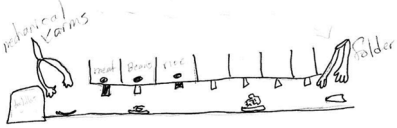
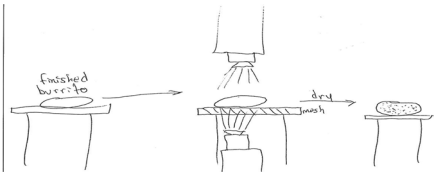
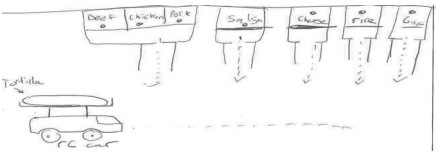
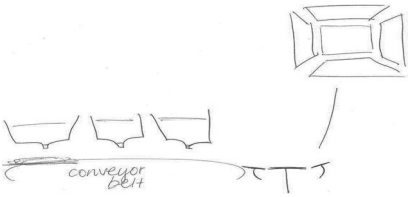
| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| Other | N/A | A key component of the design cannot be described by defined categories | "Automatic dispenser, colored like food & soft scratching post texture for cats." |

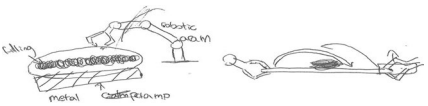
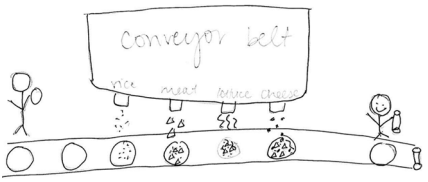
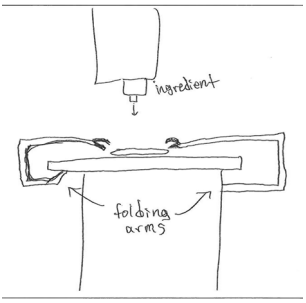
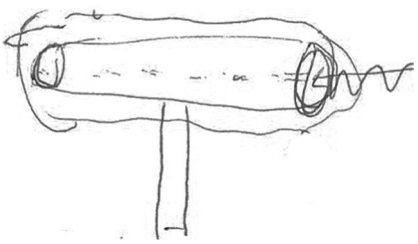
## The burrito problem

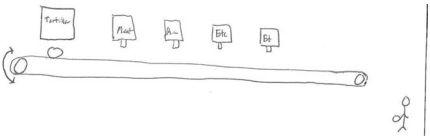
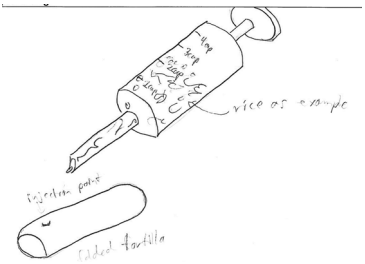
| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| User input | Physical mechanism | User input is facilitated by a physical mechanism (button, lever, nozzle, etc.) |  The ingredients that the customer wants fall from a rotating contraption over head and the customer can control how much of something through turning a nozzle then arms come up and fold the burrito |
| | Touchscreen/ computer | User input is facilitated by a touchscreen or computer interface |   The customer uses a touch screen to pick out what goes on the burrito. Then ingredients flow down a compartment onto the burrito |

| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| | Other | User input is facilitated in a way that is unique among the idea set |  The user edits a pie chart to select how much of each ingredient to put on the burrito. The machine then mixes the ingredients and drops them on the burrito |
| Organize ingredients | Measure amounts | Reference to the quantity of ingredients going on the burrito |   The user is able to adjust the quantity of the ingredient put into the burrito through the use of sliding controls |
| | Walls position ingredients | Use of walls to push ingredients into place |   Supply containers are connected to conveyor belt frame by a hinge. A lift on their opposite ends dumps supplies onto the conveyor belt. The walls center the supplies |
| | Individually compartmentalized | Individual compartments to store ingredients are identified |   The machine allows the user to select the ingredients he/she wants dispensed then mixes and/or blends them to be put on the tortilla. Can be used with concept 3 for rolling |

| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| | All ingredients blended together | Ingredients are blended together |  Tab based dispensing into a blender/mixer then onto a burrito to be rolled with a "burrito roller" |
| | Other | A method of organizing ingredients which is unique |  Enter ingredients & rotate table w/ multiple plates on it |
| Put ingredients on tortilla | Conveyor belt | A conveyor belt is used in the burrito-making process |  Tortillas travel down conveyor belt where the desired meat, cheese, and other ingredients are released as desired in layers. At end, section of belt folds onto itself to fold the burrito |
| | Human-like robot | A human-like robot which replaces the tasks a human would do |  Real brain of renown chef and TV host, Andrew Zimmerman. Robot fully integrated into burrito making table |

| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| | Dispense from above | Ingredients drop onto the tortilla from above |  Belt system w/ filling droppers on the moving tort |
| | Claw/arm | A claw or mechanical arm is used at some point during the burrito-making process |  The burrito is made on a conveyor belt. It starts with the hand placing the tortilla on the belt then it moves along & a person pushes the button for the toppings they want then the hands at the end fold it |
| | Sticky spray | A sticky spray for ingredients to stick onto the tortilla or for the tortilla to stick to itself |  The machine gives the burrito a stick coating so you can't drop it or unfold it accidentally |
| | Other | A method of putting ingredients on a tortilla which is unique |  Car is remote controlled, drives tortilla across table, customer presses button to dump ingredients on tortilla. Waiter than folds it up at the end |
| Wrap Tortilla | Flip up ends of tortilla | Reference to a mechanism which wraps the tortilla by flipping up the ends of the tortilla |  The tortilla sits on a conveyor belt under tubs w/ filling that insert the filling as it moves. It falls off conveyor belt onto a 5-plate machine that folds the sides and ends of the burritos together |

| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| | Clamp or twist ends | Reference to a method of wrapping the tortilla by clamping or twisting the ends |  Rolling station design. Clamp holds down unrolled burrito; arm then rolls one side; clamp released arm grabs other side and rolls to complete the burrito |
| | Manually wrapped | Reference to a person wrapping the tortilla |  There's a conveyor belt which drops a certain amount of rice, lettuce, cheese, salsa, and etc. on to the tortilla. There is a person at the end and who will roll up the tortilla in a burrito |
| | Mechanical arms | Mechanical arms which wrap or fold the tortilla |  The machine dumps too much of one ingredient on the tortilla and sloppily folds it into a gnarled mess. It didn't have to be a good burrito… |
| | Other | A method of wrapping the tortilla which is unique |  Burrito wraps around circular device naturally. Opens up in half, drop food in. Metal container has material that burrito sticks to. Folds ends in after |

| Category | Sub-category | Definition | Key example |
|---|---|---|---|
| Deliver to user | | Reference to any method of delivering the burrito to the user |  A moving conveyor belt moves the tortilla while the condiments are being dropped from above. Different condiments can be changed for each individual burrito. Finally, the burrito drops to the person to enjoy |
| Other | | A idea which was overall almost entirely unique |  The burrito syringe injects, into a folded tortilla, any condiment desired. It comes in many sizes to accommodate ingredients |

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**Data availability** None.

**Code availability** None.

## Declarations

**Conflict of interest** None.

**Research involving human and animal participants.** University of Michigan IRB #HUM00061138.

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