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Iterative transformations for deeper exploration during concept generation

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Abstract
Engineering designers often generate multiple concepts to increase novelty and diversity among early solution candidates. Many past studies have focused on creating new concepts "from scratch;" however, designers at every level become fixated on their initial designs and struggle to generate different ideas. In line with prior work on design transformations, we propose a concept generation process of *iterative transformation* to create new ideas by intentionally introducing major changes in form, nature, or function to an existing concept. A study of this concept generation process recruited beginning engineering students likely to benefit from an alternative to "blank slate" generation. Working alone in a single test session, students generated an initial concept for a presented design problem. Then, they were instructed to generate another concept by transforming their initial design into a new concept and repeated this process to create three more concepts. In a second design round, students were asked to consider 7 Design Heuristics strategies to prompt possible transformations for their concepts. Beginning again with their initial concept, each student generated another set of four transformed concepts using iterative transformation. The analysis considered 60 initial concepts and 476 transformed concepts with and without the use of Design Heuristics. We created *Design Transformation Diagrams* to observe links (sequential, non-sequential, or both) between transformed concepts within each set of four concepts and between the two sets. Three patterns across the diagrams were identified: Fully Sequential, Sequential with Deviation, and Divergent. When aided by Design Heuristics, transformations included more non-sequential links, suggesting synthesis, refinement, and extension of other prior concepts, and resulting in more varied and distinct transformations. This iterative transformation process may support more diversity in concepts generated through a deeper exploration of related concepts without requiring an escape from the influence of existing concepts. Concept generation strategies like Design Heuristics may support engineering students as they learn to expand their early exploration of design concepts.

Keywords Design education · Concept generation · Design Heuristics · Idea development · Transformation · Engineering education

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Introduction

Ideally, concept generation results in many varied solutions to a design problem (Cross, 2008; Higgins et al., 1989; Osborn, 1957). There are many different approaches to generating concepts; for example, designers may be inspired by concepts from analogous contexts (Dahl & Moreau, 2002; Linsey et al., 2012), combine multiple prior concepts into new ones (Allen, 1962; Finke et al., 1992), or transform existing concepts (Leahy et al., 2019; Singh et al., 2009). Designers at all levels have been shown to struggle with generating novel ideas that are different from existing concepts (Cropley, 2016). The existence of a concept, whether presented as an example solution (Jansson & Smith, 1991) or newly generated (Leahy et al., 2020), causes "fixation" on the early idea, limiting the ability to generate different concepts (Crilly, 2015).

To support creating different ideas, concept generation methods, including individual and group Brainstorming (Osborn, 1957; Wilson, 2006), TRIZ (Altshuller, 1999, 2005; Ilevbare et al., 2013), Morphological Analysis (G. Smith et al., 2012), SCAMPER (Eberle, 1996), and Design Heuristics (Daly et al., 2012; Yilmaz et al., 2016b) can be leveraged. Concept generation methods can support the initial generation of concepts as well as refinement and expansion of initial concepts. Past research has often focused on design tools to support concept generation in creating many original concepts "from scratch" (Edelman et al., 2022; Goucher-Lambert & Cagan, 2019; Kramer et al., 2015).

However, fewer studies have explored concept generation processes where existing concepts are intentionally transformed into new, different ideas. Working with an existing design incorporates fixation by explicitly permitting the consideration of the past design while setting a goal to add major changes in form, function, or nature to construct a *different* design. Similarly, Leahy et al. (2019) identified "idea transformations" as created new ideas by changing functions and features of a prior concept. The term "transformation" has been previously employed to describe lateral (breadth) and vertical (depth) movements within a problem space of designs (Goel, 1995; Haupt, 2018).

In the present study, we extend the use of idea transformations as a way to generate additional ideas during concept generation (Leahy et al., 2019) to propose an *iterative transformation* process. Rather than attempting to generate a wholly new concept, a designer may repeatedly transform a current design through intentional choices to introduce major differences that distinguish a new concept from existing ones. The process can be performed iteratively, taking the current design as a starting point and pursuing changes to it, resulting in yet another different concept. In this iterative transformation process, designers are guided to focus on *differences* between created designs, and fixation becomes a grounding for deeper exploration of related alternative designs. The set of concepts generated through iterative transformation tracks the deeper investigation of related designs (vertical transformations in Goel's (1995) and Haupt's (2018) terms) using intentional variation to discover novel designs. This process of iterative transformation may help designers push toward novelty and diversity through deeper, rather than broader, exploration of a potential solution space (Goel, 1995).

In a study with beginning engineers, we investigated an iterative transformation process for conceptual design, and assessed the resulting concept sets for novelty and diversity. Students first freely generated an initial design for a presented engineering problem, then were instructed to follow an iterative transformation process to create four more concepts. Next, after a short training on the use of Design Heuristics to transform concepts, students were asked to begin again with their initial concept and create a second set of four concepts using iterative transformation enhanced by suggestions from Design Heuristics for variations to try. The analyses examined differences in concept components within each individual's concept set series as well as between their two sets. Iterative transformation processes (with and without Design Heuristics use) during concept generation may support beginning designers in expanding their consideration of alternative solutions.

Background

Creativity is important for developing novel concepts, or design ideas, early in an engineering design process (Cropley, 2015a). Faculty report they view creativity as very important in engineering (Kazerounian & Foley, 2007), yet students report few opportunities for learning how to be creative (Kazerounian & Foley, 2007; Waller, 2016; Wilde, 1993). Past research documents a lack of training and participation in creative problem solving and abstract thinking in engineering education (Cropley, 2020; Cropley & Cropley, 2000; Valentine et al., 2019). Multiple studies suggest engineering students need opportunities to practice creative processes throughout the curriculum (Carpenter, 2016; Cropley, 2015b; Cropley & Cropley, 2000; Daly et al., 2014; Higuera Martínez et al., 2021), and incorporating approaches to explore ideas can contribute to these needed opportunities.

Concept generation in early design

Concept generation is an early stage of an engineering design process, also called conceptual design (McNeill et al., 1998; Suwa et al., 2000). Successful concept generation can be a pathway to innovation in problem solving and design work (Goldschmidt & Tatsa, 2005; Hay et al., 2017; Silk et al., 2019), and unsuccessful generation limits the potential for creativity (Cropley, 2006). Successful concept generation involves thorough exploration of the solution space (Newell & Simon, 1972), defined by all potential and feasible options (Goel & Pirolli, 1992). To explore the space of potential designs, recommended practices suggest producing many and diverse concepts, and delaying evaluation and judgment (Cross, 2001; Osborn, 1957). For example, a study of engineering design competitions showed that creating alternative problem descriptions during concept generation produced more innovative solutions (Studer et al., 2018). The production of many concept designs provides options to consider (Guilford, 1959; Osborn, 1957; Pahl et al., 2007; Zenios et al., 2009), increasing the potential for creative design outcomes (Brophy, 2001; Liu et al., 2003).

Generating an initial design may come easily; however, initial concepts are often obvious and the least novel solutions. It is important for designers to push beyond these initial concepts to uncover a diverse set of design concepts. However, the constraints of human memory often produce design fixation (Crilly, 2015; Cross, 2001; Jansson & Smith, 1991; Purcell & Gero, 1996), where a presented example continues to influence the generation of later alternatives. Even when the presented solution has undesirable elements, designers at both novice and expert levels have been shown to continue to include them in later designs (Jansson & Smith, 1991). Further studies showed even higher levels of fixation on initial concepts when the designers generated those concepts themselves (Crilly, 2015; Leahy et al., 2020), supporting the finding that engineering designers prefer their own initial concepts (Purcell & Gero, 1996; Smith et al., 1993; Ullman et al., 1988; Youmans &

Arciszewski, 2014). Design fixation works against generating larger and more diverse concept sets to consider.

Concept generation methods

To help designers avoid fixation on initial designs, a variety of concept generation methods have been proposed. Osborn (1957) introduced the brainstorming technique for group idea generation as the intentional practice of generating many different ideas, combining and building upon them, and encouraging wild ideas. Individual brainstorming has been shown to produce more candidate designs than other methods (Daly et al., 2016). Alternative approaches, such as analogical thinking (Dahl & Moreau, 2002), lateral thinking (De Bono, 1975), and “medgi,” (mapping, educating, disrupting, gestalting, and integrating) (Edelman et al., 2022), propose approaches to thinking about a design problem that can prompt solution ideas. “TRIZ,” or The Theory of Inventive Problem Solving, provides specific strategies for resolving design conflicts based on patent analyses (Altshuller, 1999, 2005). A comparative study found TRIZ produced useful ideas, but Brainstorming produced more novel concepts (Chulvi et al., 2013).

For beginning designers who may need more support in early concept generation, methods with prompts provide specific directions to designers, such as Eberle’s (1996) SCAMPER categories (Substitute, Combine, Adapt, Modify and Magnify, Put to other uses, Eliminate, and Rearrange), which may be helpful in pointing in a specific direction for solution creation. Design Heuristics offer guidance drawn from practicing designers to guide generation using "cognitive shortcuts;" for example, one heuristic is "repeat," capturing a pattern where different design elements are intentionally made similar within a design (Daly et al, 2012; Yilmaz et al., 2016b). A major empirical effort identified 77 Design Heuristics observed in use during product design (Yilmaz et al., 2016b), long-term design projects (Yilmaz & Seifert, 2011), and engineering design problems (Daly et al., 2012). Using Design Heuristics has been shown to help beginning (Daly et al, 2016; Murphy et al., 2017, 2022; Yilmaz et al., 2010) and advanced engineering students (Daly et al., 2012; Kramer et al., 2014), as well as expert practitioners (Yilmaz et al., 2013), in generating more varied design characteristics and more novel and useful ideas (Daly et al., 2012; Yilmaz & Seifert, 2011; Yilmaz et al., 2016a).

Concept transformation during generation

Attempting to generate a new concept wholly different from existing ones is quite challenging because designers fixate on designs already generated (Leahy et al., 2020). Leahy et al. (2019) defined *idea transformations* as modifications of prior solution ideas to create new concepts by changing functions, characteristics, or features of prior ideas into different solutions. A transformation of a previous concept into a new one can result in minimally or drastically different concepts. Murphy et al. (2022) identified aspects of concept designs where more nuanced characteristics defined differences between concepts, such as pet food bowl concepts with differing characteristics distinguishing them. Concepts may be built from a precedent using a wide variety of transformations, ranging from incremental to combinatorial to "sacrificial reframing" (Gonçalves & Cash, 2021). Further differentiation of alternative concept generation processes may better explain the generation of different ideas.

We propose an approach to early idea generation, *iterative transformation,* where designers work directly with an existing concept to intentionally change it into a new and "different" concept (Leahy et al., 2019); then, this process is repeated iteratively to produce more new ideas. Iterative transformation focuses on major changes to key design features without requiring creation of a new design that does not have any overlap with existing ones. Iterative transformation may be helpful by allowing a designer to remain fixated on concept features while exploring levels of detail and flexibly working between abstract and concrete ideas. This process fits within the types of transformations in problem space exploration proposed by Goel (1995). Transformations are movements within the problem space during design, with lateral moves reflecting broader search and vertical moves from one idea to a more specific version of the same idea suggesting greater depth of exploration (Chen & Zhao, 2006; Haupt, 2018). However, the use of transformation here—as creating a new conceptual design by changing an existing one—differs from that of design transformations of "transforming products" (Singh et al., 2009), where design transformations are strategies for creating multipurpose functions through enclosing, flipping, or folding to fit varying needs, fulfill multiple functions, and adapt to differing contexts (Weaver et al., 2010).

More generally, previous work has identified iterative processes during concept generation where generated concepts are produced through combining, building upon, classifying, synthesizing, and modifying previous concepts (Chan & Schunn, 2015; Deo et al., 2021; George et al., 2013). Brainstorming also calls for idea combinations and building upon other's ideas (Osborn, 1957). Previous research has linked influential ideas arising during concept generation with later ideas (Goldschmidt & Tatsa, 2005) through Goldschmidt's linkography method (Goldschmidt, 2016). Analysis of ideas within design sessions including multiple designers traced earlier concepts as influencing later concepts in a session. Beyond returning to past ideas, an iterative transformation process may help designers focus on creating designs that are different in a meaningful way, without the need to create wholly new concepts that have no overlap to existing ones.

Design Heuristics

Engineering students benefit from explicit instruction on how to engage in intentional divergent thinking practices (Daly et al., 2014; Kowaltowski et al., 2010; Ogot & Okudan, 2006). The Design Heuristics method for concept generation has been shown to facilitate students' creativity by encouraging the generation of more, and more diverse, concepts in the early stages of design (Daly et al., 2012). Design Heuristics have also been documented as supporting the transformation of existing concepts into new ones (Leahy et al., 2019). For beginning designers with little experience, generating even partial changes to concepts to create different ones may be challenging. Adding prompts from Design Heuristics may provide support in executing an iterative transformation process.

The Design Heuristics method resulted from empirical studies exploring how designers created variations in designs for a problem (Yilmaz et al., 2016b). Each heuristic serves as a cognitive shortcut or "rule of thumb" to use in creating a design (Crovitz, 1970; Newell & Simon, 1972; Newell et al., 1958; Reitman et al., 1964; Simon & Newell, 1958). Each of these 77 heuristics were identified empirically by observing its use across designers, problems, and solutions in multiple studies (see Yilmaz et al., 2016b for an overview). To support the use of these heuristics during design, the heuristics were incorporated into a set of 77 cards with separate cognitive prompts suggesting ways to introduce variations within concepts (Yilmaz et al., 2016b). An example heuristic, *Repeat*, is shown in Fig. 1 with the front of a card describing the heuristic with a visual image, and the back of the card describing two example products that display the use of that heuristic.

While Design Heuristics have been mainly studied in initial concept generation, some studies have focused on transformative design. Design Heuristics were found useful by engineering students in both generative (creating an idea from scratch) and transformative (working from an existing idea) roles during concept generation (Christian et al., 2012). Leahy and colleagues (2019) explored whether students were able to produce multiple variations of their own existing concepts using Design Heuristics prompts. Students first generated five concepts working independently, and then used Design Heuristics to build on any of their concepts to create five new ones. The transformed concepts included changes to enhance aesthetics, add features and functions, describe specific settings and materials, and change sizes, organization, and usability.

Method

The goal of this study was to explore relationships among the concepts generated by novice engineering students during two concept generation sessions, one unaided and one aided by using Design Heuristics. Students were instructed to begin with an initial concept they created, and then to transform that concept into a new concept. They continued creating new concepts by transforming the existing concept eight times, four without and four with Design Heuristics. The study examined how novice engineers' concepts changed during iterative transformations when unaided and when aided by Design Heuristics.

Participants

Participants included incoming first year engineering students at a large Midwestern University in North America. The optional day-long workshop introduced concept design generation for engineering design problems. The study took place during a one-hour session of the workshop, and all attendees were invited to participate. Students were informed that their participation in the study was voluntary and that they could withdraw from it at any time. No compensation for participation was offered.

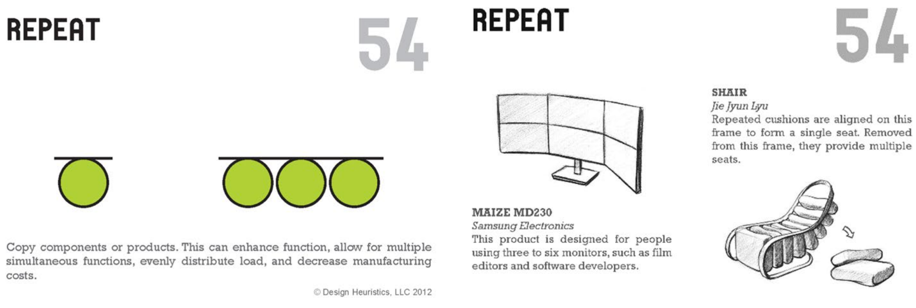


Fig. 1 Example Design Heuristics card for the *Repeat* heuristic detailing its use (front) along with product design examples (back) (Design Heuristics, L.L.C., 2012)

For this analysis, we selected 60 students' data at random from a larger pool of 165 students. The sample included 9 females and 51 males, with an average age of 18.7 (SD = 0.5). No other demographic information was collected.

Materials

Two design problems from previous studies were selected for the study based on their accessibility for students and appropriate length for a one-hour session: the Solar Cooker problem (Daly et al., 2012) and the Vertical Reach problem (Daly et al., 2016), shown in Table 1.

Data collection

Students attended a 55-minute workshop held in two separate rooms and led by trained facilitators following a script. Students in each room were assigned to work on either the Vertical Reach (n = 30) or the Solar Cooker (n = 30) problem. First, facilitators described concept generation processes, including design space exploration and recommended practices for concept generation, such as generating multiple and diverse concepts, using drawing to document design concepts, and delaying judgment of concepts. Then, students were asked to generate an initial concept for their assigned design problem and given five minutes to work. Students identified this initial concept (or selected their "favorite" generated concept if they generated more than one) by labelling it "Concept 0." Students were asked to represent it with a drawing and written description, including how it worked and noting features, mechanics, and details, on a provided concept sheet (shown in Appendix 1).

Next, students were introduced to concept transformation as a concept generation method. The process was defined as starting with an existing concept as a base and then building or developing it to make it better and explore alternatives. Facilitators provided an example of two concept transformations (Fig. 2) of a three-legged table concept transformed into a four-legged table, and a subsequent concept where the table was transformed into a chair.

To begin the first (unaided) concept generation session, students were instructed to work independently to transform their initial concept (Concept 0) to create a new concept. After generating their new concept (Unaided 1, or U1), they repeated this transformation process

Table 1 Design Problems

Vertical Reach	Many full-grown adults are constrained to a sitting position or have limited vertical reach, including paraplegics (people with paralyzed legs), the elderly, stroke victims, people recovering from leg or back injuries, people who have muscle or nerve disabling disorders, or little people. Limited vertical height can make many day-today tasks (such as reaching an overhead cabinet or changing a light bulb) a significant challenge. Your task is to design devices that would help people to overcome these height-constraining disabilities. Focus on conceptual designs. Technical specifications can be postponed to a later stage. Please consider both functions and the structural variety of the concepts.
Solar Cooker	Sunlight can be a practical source of alternative energy for everyday jobs, such as cooking. Simple reflection and absorption of sunlight can generate adequate heat for this purpose. Your challenge is to develop products that utilize sunlight for heating and cooking food. The products should be portable and made of inexpensive materials. It should be able to be used by individual families, and should be practical for adults to set up in a sunny spot. Focus on conceptual designs. Technical specifications can be postponed to a later stage. Please consider both functions and the structural variety of the concepts.

Fig. 2 Example concept transformations provided to students

using their new concept (U1) as a base to generate the next concept (U2). Students were given 20 minutes to generate a total of four new concepts by transforming each concept into a subsequent concept. Facilitators instructed students to record their designs on the concept sheets provided, including placing each separate concept on a new numbered page and including a sketch and a written description. Students were prompted every five minutes to continue creating new concepts, each time building from the previous concept, as indicated on the concept sheets.

Next, students were instructed on how to use Design Heuristics as an aid in creating new designs. Facilitators explained that one heuristic can be used to generate one or multiple new concepts, or heuristics can be combined together into a single concept. Given the short session length, students worked with a subset of 7 of the 77 cards, so as to not overwhelm students with the large deck. These seven cards were selected prior to the session at random from a shuffled deck. The 7 cards included in this study were *Add motion*, *Change geometry*, *Expand or collapse, Impose hierarchy on functions*, *Reduce material*, *Repeat*, and *Use repurposed or recycled materials* (these cards are shown in Appendix 2). Students then completed a short example exercise to practice applying a Design Heuristic card.

Then, during a second 20-minute concept generation session, students were asked again to begin with their initial concept (Concept 0), transform it using Design Heuristics, and then iteratively transform subsequent concepts with Design Heuristics, to generate four additional concepts (Concepts A1 - A4). Students were again prompted at 5-minute intervals to continue creating new concepts and record their sketches and descriptions of each on a concept sheet, where they also noted any Design Heuristics they used when creating each concept. This sequence of activities is summarized in Fig. 3, including Concept 0, concepts generated unaided in the first session (labeled U1 through U4), and concepts generated using Design Heuristics in the aided second session (labeled as A1 through A4).

Data analysis

The data for this study were first organized from the initial worksheets students used during the workshop, including all concept drawings, descriptions, and student-identified Design Heuristics, and de-identified. One researcher reviewed a subset of 20 students' data from both design problems to become immersed in the data. Utilizing previous categories developed for transformation types (Leahy et al, 2019), we then coded for the types of transformations evident. We then expanded upon this coding scheme inductively using descriptions of concept changes during transformations, following the example of identifying key concept characteristics by Murphy et al. (2022). The descriptions included identifying

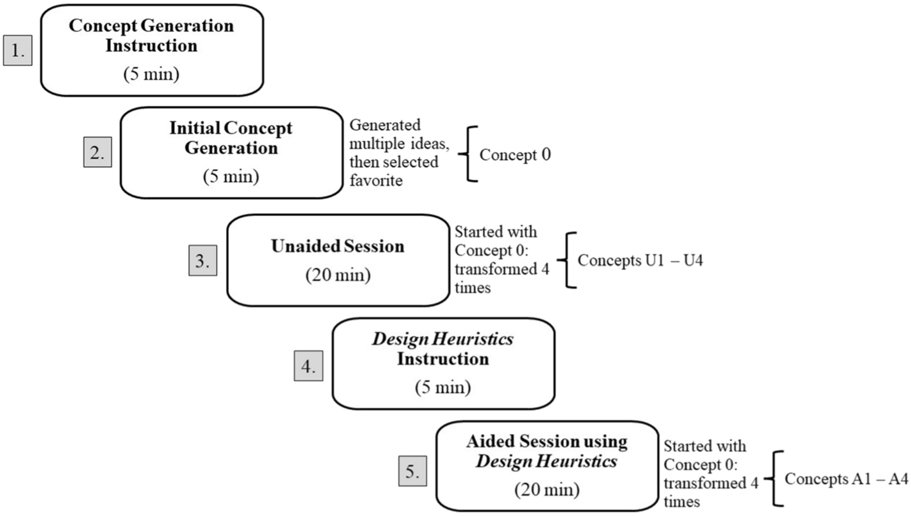


Fig. 3 Experimental procedure with indications of when Concept 0, Concepts U1–U4, and Concepts A1–A4 were produced in the process

functions, aesthetics, language, sketched characteristics, and written or sketched differences between concepts. The shared characteristic relationships between pairs of concepts represented in drawings or written descriptions were summarized to describe each concept in sequence.

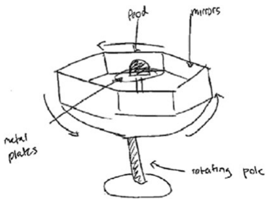
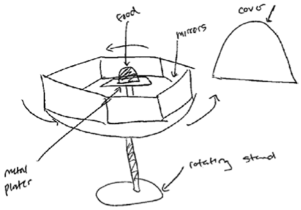
Links between concepts

After characterizing concept differences, we extended the coding scheme to specify how latter concepts were related to prior concepts. We identified and coded for two types of links between concepts: *sequential links* and *non-sequential links.* Two concepts were linked sequentially when they were generated in serial order and shared mutual characteristics. Specifically, sequential links were identified through (1) students' use of phrases such as "same as before," "only difference is," "adding," "longer," etc. to indicate the connection from the current concept to the prior sequential concept; and (2) features and characteristics of the design sketch carried over from the immediately previous concept and redrawn in the new concept sketch. For example, in Table 2, Student 13's Concept A3 was identified as *sequentially linked* from Concept A2 based on the repetition of the mirror bowl, rotating pole, mirrors, and metal plate. Student 13's full data set is included in Appendix 3.

Non-sequential links between two concepts were identified when (1) characteristics in the design sketch were from a previous concept other than the immediately prior concept as written or drawn; or (2) the student specifically named a previous concept as connected to a new concept. Non-sequential links were defined by the *first* introduction of a characteristic only. Later concepts also showing that change were not counted as non-sequential links. For example, if Concept U1 had mirrors, then Concepts U3 and U4 had mirrors, Concept U3 would count as having a non-sequential link to U1, while Concept A4 would *not* be considered a non-sequential link.

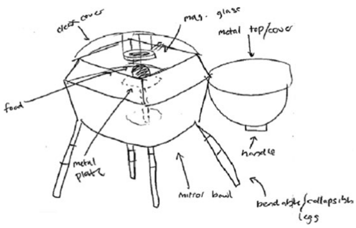
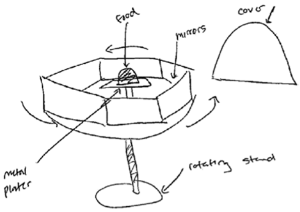
As shown in Table 3, the same Student 13 produced a later concept, Concept A3, during the aided session that appeared to carry over a feature from Concept U3; specifically,

Table 2 Two concepts from Student 13 during the Aided session illustrate a sequential link between Concept A2 and Concept A3 for the Solar Cooker problem. The changes in the concept from the prior are bolded in the description

Concept Number	Student's Written Description	Student's Concept Sketch	Design Heuristic Applied
A2: Second Concept in Aided Session	The mirror oven is supported by a **pole that allows the oven to be easily spun** for a more even cook; (in sketch) food, mirrors, metal plates, rotating pole		*Add Motion*
A3: Third Concepts in Aided Session	**Cover** must be removed before access to oven can occur; food, mirrors, cover, metal plates, rotating stand; (in sketch) food, mirrors, cover, metal plater, rotating standing		*Impose Hierarchy on Function*

a metal cover for the cooker. Because these two concepts were not procedurally adjacent in sequential order, Concept A3 was defined as having a *non-sequential link* from Concept U3. Non-sequential links could connect two non-consecutive concepts from the same

Table 3 Student 13's unaided Concept U3 and aided Concept A3, illustrate a non-sequential link. Bold words indicate distinct transformed features for that concept

Concept Number	Student's Description	Student's Concept Sketch	Design Heuristic Applied
U3: Concept 3 in the Unaided Session	Has **metal top/cover** to retain heat and keep cooked food warm. **Bendable/collapsible** legs for portability and **handle** for portability; clear cover, mag. Glass, metal top/cover, **handle**, food, metal plate, mirror bowl, bendable/collapsible legs		N/A
A3: Concept 3 in the Aided session	**Cover** must be removed before access to oven can occur; food, mirrors, cover, metal plates, rotating stand		*Impose Hierarchy on Function*

session, or link concepts between the unaided session to the aided session with Design Heuristics.

We analyzed the complete study data from 60 students using this transformation coding scheme to identify the type of links (sequential or non-sequential) occurring in each new concept. The procedure implied 8 sequential links, but in practice, concepts could be linked to multiple prior concepts non-sequentially. We organized concepts by whether they had sequential links, a combination of sequential and non-sequential links, or only non-sequential links. The expected outcome implied by the procedure was sequential links between concepts, so identifying non-sequential links was therefore unexpected and unusual.

Design transformation diagrams

To facilitate analyses, we created *Design Transformation Diagrams* to represent observed connections between concepts in both concept generation sessions for each student. These diagrams provided a visual summary of the changes to concepts over the course of the concept generation sessions while preserving the serial order of their generation over time. Each diagram summarized one student's complete set of concepts generated in both the unaided and aided sessions and identified the sequential and non-sequential links observed between concepts. Additionally, we examined the concepts in the Design Transformation Diagrams by counting the number of concepts that had 1) only sequential links, 2) sequential and non-sequential links, and 3) only non-sequential links for each student. We employed the Design Transformation Diagrams to observe patterns within and across students' work and to capture any differences in transformations across concept generation sessions when unaided and when aided with Design Heuristics.

Results

Concept generation

The number of concepts students generated, including initial concepts and transformed concepts with and without Design Heuristics, appeared similarly across problems and across concept generation sessions, as shown in Table 4.

Table 4 Concepts generated from an initial concept in two serial sessions, one unaided and one aided by Design Heuristics

Design Problem	Number of Students	Initial Concepts (C0)	Unaided Transformations (U1, U2, U3, U4)	Transformations Aided by Design Heuristics (A1, A2, A3, A4)	Total Number of Concepts
Solar Cooker	30	30	119 Avg = 3.19 SD = 0.18	120 Avg = 4.0 SD = 0	269
Vertical Reach	30	30	120 Avg = 4.0 SD = 0	117 Avg = 3.9 SD = 0.3	267
Total	60	60	239	237	536

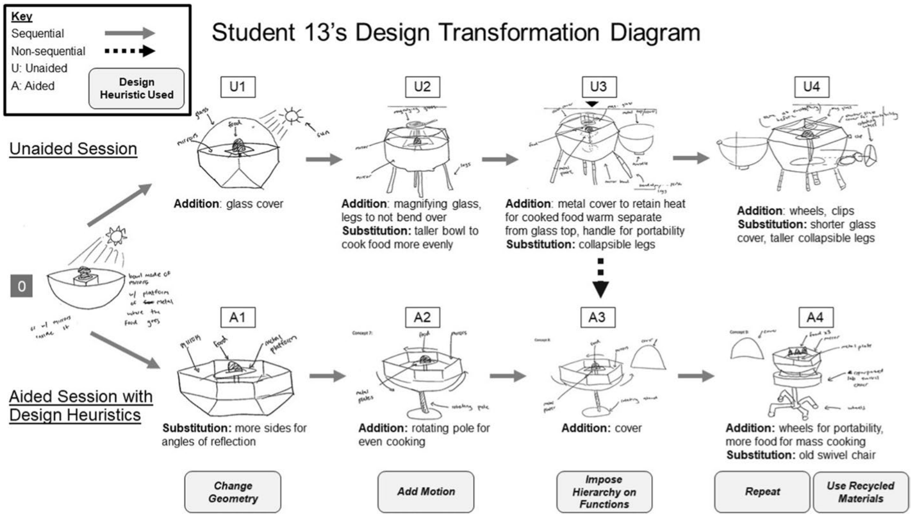


Fig. 4 Student 13's Design Transformation Diagram highlights how each of their concepts changes from the prior concept. The specific design characteristics changed in each concept are summarized beneath each sketch. Solid arrows denote sequential links (relationships to the immediately preceding concept in the series). Dotted arrows denote changes based in earlier concepts (non-sequential links). Students' self-reported use of Design Heuristics is noted below each concept

Given that concept generation quantity appeared similar in two different problem contexts and in the two types of concept generation sessions (aided and unaided), we proceeded to analyze the qualities of concepts generated without reference to differences that may have arisen from producing a varying numbers of concepts. To observe the links between concepts created during transformations, we examined the Design Transformation Diagrams; an example is shown in Fig. 4. The diagrams show connections between concepts in both the unaided and aided sessions. Sequential links are shown as solid arrows; for example, from Concept U1, adding a glass cover created Concept U2. This Design Transformation Diagram from Student 13 also shows one non-sequential link, shown as a dotted arrow, between concepts: Concept A3 draws from Concept U3 by reintroducing a metal cover to keep cooked food warm, connecting U3 in the unaided session with A3 in the aided session out of serial order.

In the following sections, we describe in detail the types of Design Transformation Diagrams observed in the study: Fully Sequential, Sequential with Deviation, and Divergent, describe the qualities of transformations with sequential and non-sequential links, and compare trends across the unaided and aided sessions to answer our research question.

Design transformation diagrams

The Design Transformation Diagrams revealed differences in students' concept generation sessions as they transformed existing concepts to generate new ones. Table 5 summarizes these differences. One transformation pattern observed in the Design Transformation Diagrams was *Fully Sequential*, where each concept was based in the immediately prior concept. Other diagrams showed concepts that appeared to be *Sequential with Deviation* in

Table 5 Design Transformation Diagram Types

Diagram Types	Number of Student Diagrams	Percentage of Student Diagrams	Description
Fully Sequential	11	18.33%	Only sequential links appear between concepts, where each concept is connected in numerical order to its immediately prior concept
Sequential with Deviation	34	55.66%	Up to two non-sequential links appear between concepts, with the remaining majority as sequential links
Divergent	15	25%	Three or more non-sequential links occur between concepts, regardless of the number of sequential links, and non-sequential links replace sequential links for some concepts

their links, with one or two connections outside of sequential order. A third set of Design Transformation Diagrams appeared to be *Divergent* in the links between concepts, with three or more concepts linked outside of serial order. Additional examples of each type of Design Transformation Diagram for each design problem are provided in Appendix 4.

Fully sequential design transformation diagrams

Eleven students' concept collections (out of 60, or 18.33%) were categorized with Fully Sequential Design Transformation Diagrams, with three students working on the Solar Cooker problem and eight on the Vertical Reach problem. These diagrams included only sequential links in both concept generation sessions. A detailed representative example of the Fully Sequential diagram of Student 52 (who worked on the Vertical Reach design problem)

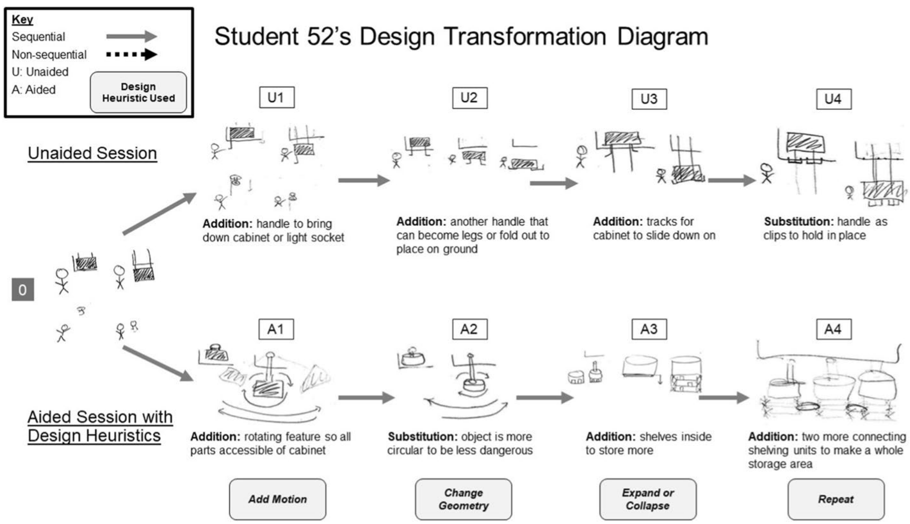


Fig. 5 Example of a Fully Sequential Design Transformation Diagram for the Solar Cooker problem showing eight transformations (solid arrows)

is shown in Fig. 5. Their initial Concept 0 described "cabinets [built] inside that bring it down to face or chest level. If it's a light the whole socket comes down." This concept was transformed into Concept U1 by the addition of a handle to bring down the cabinet or light socket. Concept U2 added another handle as an additional component with dual functionality to become "legs or fold out to place on the ground." Concept U3 changed to tracks "for the cabinet to slide down on." Concept U4 added dual functionality where the handles acted as clips to hold the cabinet in place. Of these four transformations in the unaided session, three discussed "handles" specifically. As a result, Fully Sequential Design Transformation Diagrams suggested a series of additive changes across concepts in a series, where the core design remained with a refinement or addition of components in each new iteration.

When using Design Heuristics in the second concept generation session, students used these cards to modify their concepts in ways that were not evident in the unaided session, as evidenced by the characteristic changes between concepts. With Design Heuristics, the nature of the incremental changes appeared to expand towards user interactions, user safety, and storage concerns. The use of Design Heuristics helped Student 52 to push their concept in new directions not attempted in the unaided session. When using Design Heuristics, Student 52 used *Add Motion* from their initial Concept 0 to create a rotating cabinet to make "all parts accessible," and considered a specific user with limited range of motion. Concept A2 used *Change Geometry* to create a "less dangerous" circular cabinet surface easier and safer to use. Concept A3 included added shelves using *Expand or Collapse*. Concept A4 used *Repeat* to create two connecting shelving units as a storage area. These concepts appeared more varied in their changes than those in the unaided session, and Design Heuristics appeared to promote specific design features tied to usability, storage, and safety.

Sequential with deviation design transformation diagrams

For both design problems, Sequential with Deviation Design Transformation Diagrams were the most common among students (34 of 60 students, or 55.66%). These diagrams

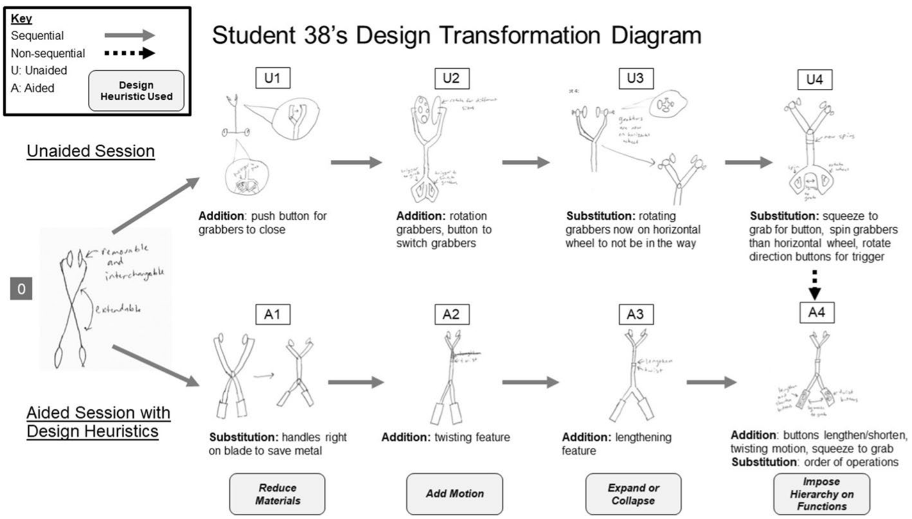


Fig. 6 Example student's transformation diagram for the Vertical Reach problem depicting a Sequential with Deviation idea development process

were defined by the presence of one to two non-sequential links with sequential links between concepts. The students whose concepts were categorized as Sequential with Deviation tended to build additive changes during the unaided session, then added a non-sequential link or two to combine characteristics of previous concepts and push their concept into a different direction in the aided session with Design Heuristics. Non-sequential links occurred within and across sessions but occurred more frequently in the aided session with Design Heuristics. A common example of a Sequential with Deviation Transformation Diagram is shown in Fig. 6.

Student 38 created Concept 0 for the Vertical Reach problem as a tool "like pliers, people can grab things with them," with "removable and interchangeable, extendable" features and functions. In transforming their initial Concept 0 to Concept U1, they added a push button to close the device more easily. Then from Concepts U1 to U2, multiple characteristics changed so the button could switch between grabber options and rotate the head of the device for better use. Concept U3 changed the grabbers to rotate on a horizontal wheel "to not be in the way." Concept U4 added multiple functional changes so the grabbers can spin, and the user must squeeze the handle to grab items. The handle was transformed to rotate the grabbers to spin when in use and change out the type of grabbers with triggers. The additive changes in the unaided session suggest more complexity and extension of one task rather than exploration of other potential alternative tasks of the device.

In the aided session with Design Heuristics, Student 38 used Design Heuristics cards to extend the given concept in new ways. In Concept A1, *Reduce Materials* led to smaller handles "right on the blade instead of looping around, saving material." Concept A2 used *Add Motion* to create a twisting feature distinct from the earlier iterations during the student's unaided concept transformations. In Concept A3, the student added a lengthening feature not previously considered. The changes in the aided session appeared to be less complex and more conceptually different from each other and the unaided session in how the device could be used and how it was made. With Concept A1, there was a consideration of saving material for potential cost, manufacturing, or sustainability benefits, depending on the designer's intention. Additionally, the twisting and lengthening features of Concepts A2 and A3, respectfully, seemed to provide more reach and access to items in harder to reach places, compared to the unaided session, where the focus was more on the different ways mechanically the item could be grabbed.

To this sequential pattern, a single non-sequential link between Concepts U4 and A4 appeared. Drawing upon their most complex design concept (U4), Student 38 combined "squeezing" to grab an item with *Impose Hierarchy on Functions*. The resulting Concept A4 added electronic buttons to lengthen and shorten the grabbers, a button to twist the grabbers, and an order of operations for use: "first lengthen, then squeeze, then twist if needed. Move left to right." These characteristics of Concept A4, with both sequential and non-sequential links, illustrate students' use of prior concepts combined with Design Heuristics to transform their concepts in a more distinct and diverse way than done in any previous concept.

Divergent design transformation diagrams

Fifteen students' concept collections (25%) were classified as Divergent Design Transformation Diagrams, with ten solving the Solar Cooker problem and five the Vertical Reach problem. Divergent Design Transformation Diagrams featured the most distinct and diverse changes from the initial concept to the final concepts, particularly in sessions aided

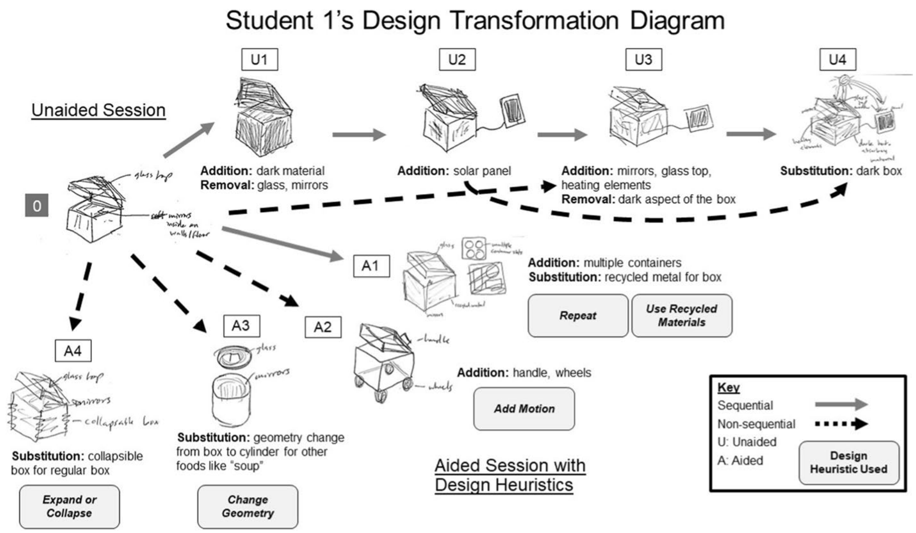


Fig. 7 Student 1's Divergent transformation diagram with majority non-sequential transformations

with Design Heuristics. Students' concept transformations in this category had at least three non-sequential links and concepts were more distinct from each other as well as distinct from their initial concept, having more evident differences in features, functions, and applications. Student 1's concepts, shown in Fig. 7, provides a typical example of diverse and distinct transformations from concept to concept in a Divergent Design Transformation Diagram.

Student 1's initial concept (Concept 0) depicted a "box [with] hinge, glass top for sunlight to come through, mirrors reflect heat/light inside." Concepts U1 and U2 connected through sequential links, with U1 adding a material change to absorb heat while removing the glass and mirrors. Concept U2 added a solar panel. A non-sequential link occurred with Concept U3, where previous characteristics of glass, mirrors, and original material from Concept 0 were combined with the solar panel from Concept U2 (a sequential link). The dark material from U2 was removed from U3 and reintroduced in U4 (noted in written description). In analyzing the links and characteristics of Concepts A1–A4, the concepts appeared distinct and varied in functionality as if alternatives for Concept 0. Frequently, a more sequential pattern in the unaided session changed to more non-sequential transformations in the aided session. With Design Heuristics, new concepts included multiple containers for cooking food (*Repeat*) and recycled materials (*Use Repurposed or Recycled Materials)* in Concept A1; *Add Motion* leading to wheels from Concept 0 and a handle for portability in Concept A2; *Change Geometry* to cylindrical container "for other things like soup" in Concept A3; and *Expand or Collapse* substituting collapsible box in A4. These changes reveal how Design Heuristics pushed students to consider more variety in their concept transformations beyond additive functions and include different tasks and options in the design to supplement the main problem objective.

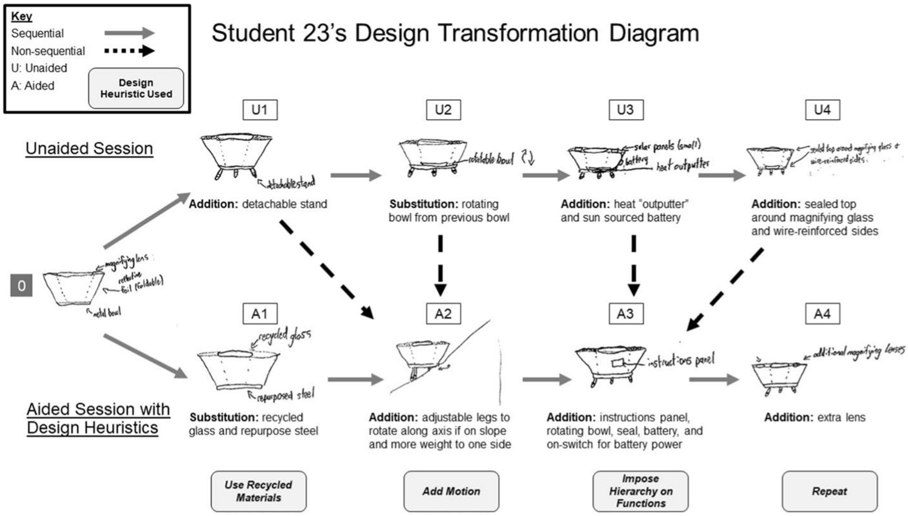


Fig. 8 Student 23's Divergent Design Transformation Diagram

Comparison of unaided and aided with Design Heuristics sessions

Analysis revealed distinct differences in concepts transformations in the unaided compared to aided concept generation sessions. For example, consider the Design Transformation Diagram from Student 23 shown in Fig. 8. Over the course of the unaided session, Student 23 added a detachable stand to their metal bowl system, substituted a rotating bowl, added a "heat outputter," a sun-sourced battery, small solar panels, sealing around a magnifying glass, and wire reinforced sides, which were of the most common features and functions in the unaided session of the Vertical Reach problem. The final concept (U4) of the unaided session had features and functions to supplement the main objective of the problem: to retain, capture, and even increase heat capabilities of the device. The Design Transformation Diagrams for Students 13, 38 (Fig. 6), and 52 (Fig. 5) showed similar patterns of adding new features to supplement the main objective of the given problem leading to the final concept during the unaided session (U4) through iterative transformations.

However, during the aided session, findings suggest that using Design Heuristics to aid in the transformations prompted more non-sequential links between concepts, resulting in more varied and distinct transformations, addressing other tasks and objectives beyond the main problem. For instance, Student 23 utilized repurposed glass and steel in Concept A1, adjustable legs and weight distribution of the device to fit different angles of terrain and environments in Concept A2, and in Concept A3, an instructional panel is provided "to ensure user correctly sets up legs" and an "on-switch for battery power can be indicated" for usability purposes. These features were distinct and novel within the concept set, prompted by the Design Heuristics cards and non-sequential links Student 23 used, and were not observed in the unaided session.

Transformations of novel and distinct features and functions, as well as more meaningful purpose and context for the changes in concepts, is a pattern that often occurred in the aided session, usually in combination with non-sequential links, and most prevalently for students with Divergent Design Transformation Diagrams, evident in the examples of

Student 1 (Fig. 7), and Student 18 and Student 39, which are shown in Appendix 4. Student concepts were more visually different from each other in terms of added features (switches, sound notification systems, or movement), feature substitutions (material used, component lengths, geometry, or multi-functionality), and how the device would benefit the user (ease of use, access, comfortability, or portability).

The most common transformations specific to each session are featured in Table 6. The unaided session concepts typically had functions and features directly related to the main task of the problem: increase heat intensity (mirrors, magnifying glass, reflective surfaces), heat absorption and retainment (substituting for black and insulating materials), and grabbing or extension mechanisms to increase height or grasping capabilities (claws, telescoping poles/arms, adjustable height). The aided session concepts frequently had features and functions related to reduction of material for weight or use ("light", "less material"), sustainability (rechargeable batteries, recycled materials), ease of use (order of operations in how to set up the device, use it, or instructions for the user), safety (fence, locking mechanism, belt/harness) and portability/compactness (by changing geometry, wheels, carrying handle, folding, hinges) often prompted by the Design Heuristics card(s). Additionally, use of sustainable materials in concepts was *only* evident in the aided session. Further, both sessions made use of more power and electrical features, however, the unaided session concepts commonly had power as related to the system and button/switches on devices, while the aided session concepts had more complex features with sensors, computers, and external controls to the system.

Non-sequential links during the aided session also drew from previous concepts in the unaided session, leading to richer recombination of features in the aided session concepts. During this concept transformation, the concept changes may or may not have benefitted from additional prompting by the Design Heuristic cards to generate new features or values for a concept. Of course, there were more prior concepts to draw from in the aided session (as it always came second); however, if desired, students could have drawn from Concepts 0, U1, U2, as non-sequential links for U4, for example. The examples of distinct transformations combining sequential and non-sequential links, or purely non-sequential links, differentiated the concept transformations observed during the aided session compared to the unaided session.

Based on these findings from the Design Transformation Diagrams, we considered differences in the appearance of links to each concept as an indicator of extended concept combinations. Because students were instructed to build new concepts using the just-previous concept, the occurrence of non-sequential links may indicate an extension of the transformation process to broaden concepts beyond what was necessary. Figure 9 shows a comparison of the proportion of transformed concepts with only sequential links, those with both sequential and non-sequential, and those with only non-sequential incoming links by session for both design problems.

While concepts in the unaided session had both sequential and non-sequential links or only non-sequential links, a significant proportion of the non-sequential links occurred in the aided session with Design Heuristics. A test of association (Cramér, 1946) showed a significant relationship between session and concepts with non-sequential links, Pearson's χ^2 $(2, N=476)=59.48$, $p<0.001$, $\Phi=0.354$.

Additionally, we observed how many students had non-sequential links in transforming their concept and the associated session, as shown in Fig. 10. This relationship between session and concepts with non-sequential links was significant, χ^2 $(3, N=60)=36.667$, $p<0.001$, $\Phi=0.782$, indicating a strong link between usage of non-sequential connections by students and the session aided with Design Heuristics.

Table 6 Common transformations specific to the unaided and aided with Design Heuristics sessions

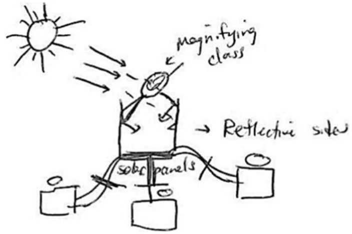
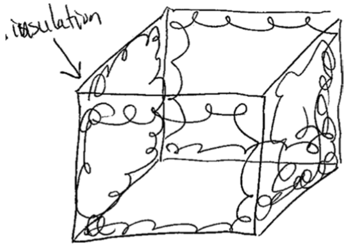
Session	Most common types of transformations		Example
Unaided	Functions and features related to main task	Increase heat intensity	 Addition of magnifying glass Participant 5, Concept U3
		Heat absorption and retainment	 Addition of insulation Participant 17, Concept U2

Table 6 (continued)

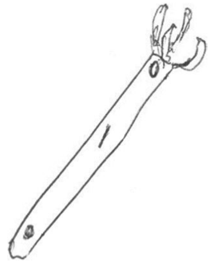
Session	Most common types of transformations	Example
	Grabbing mechanism	 Additional claw Participant 112, Concept U3
	Extension mechanism	 Substitution of telescoping legs for original legs Participant 94, Concept U2

Table 6 (continued)

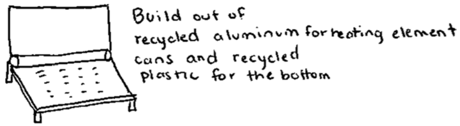
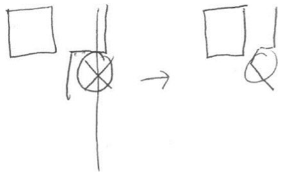
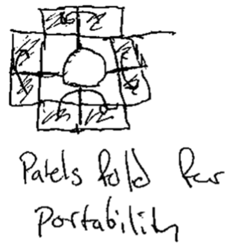
Session	Most common types of transformations	Example
Aided	Reduction of material	 Reduced chair weight and thickness "so need less to lever to raise up and move around" Participant 121, A1 *Reduce Material*
	Sustainability	 Substituted recycled materials for previous Participant 25, A1 *Use Repurposed or Recycled Materials*
	Ease of use	 Legs of wheelchair retract so user can get closer to the cabinet Participant 111, Concept A3 *Expand or Collapse*

Table 6 (continued)

Session	Most common types of transformations	Example
	Portability/Compactness	 "the squares fold together" Participant 12, Concept A2 *Add Motion*

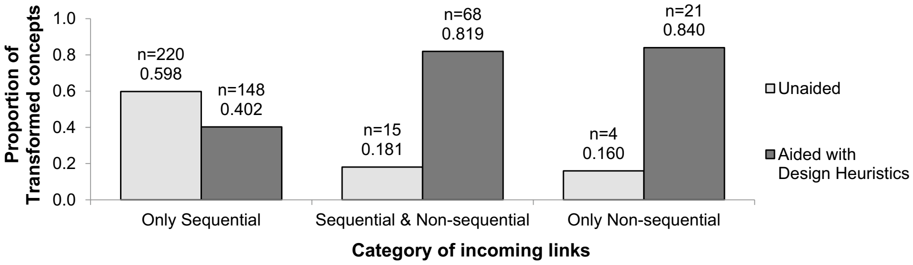


Fig. 9 Proportions and counts of transformed concepts with respect to each category of Only Sequential, Sequential and Non-sequential, and Only Non-sequential incoming links by unaided and aided with Design Heuristics across design problems

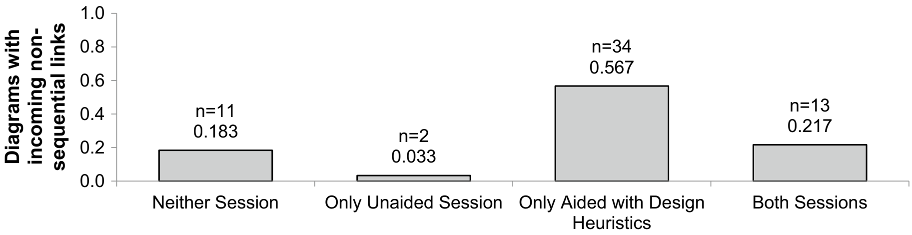


Fig. 10 More students demonstrated non-sequential links between concepts in the aided with Design Heuristics session

From these results, we observed that the aided session with Design Heuristics prompted more non-sequential links to synthesize, refine, and push on concepts in new ways. Additionally, Design Heuristics elicited more distinct and meaningful iterative transformations, creating diverse and novel student concepts.

Discussion

This study investigated how first-year engineering students transformed early concepts to form new ones with and without the aid of Design Heuristics across two different design problems. We created Design Transformation Diagrams to provide a new way to visually understand how students approached concept generation using transformations. We examined the Design Transformation Diagrams to understand how students changed their concepts over the concept generation sessions. The diagrams demonstrated that students transformed concepts in varying ways, and that students' transformation processes changed depending on whether they were aided with Design Heuristics. The diagrams provide a powerful tool to analyze concept generation sessions, potentially revealing links across concepts and ways of transforming concepts across other contexts and in combination with other concept generation methods. We identified three types of Design Transformation Diagrams in students' concept generation sessions, from most to least frequent, Sequential with Deviation, Divergent, and Fully Sequential. Most frequently, students went beyond the expected strictly sequential processes to combine connections to other, non-sequential concepts.

During the unaided transformation session, students developed their concepts in additive and mainly sequential ways in response to the problem task. When aided by Design Heuristics, students transformed their concepts in more non-sequential ways by recombining characteristics of concepts from their unaided session and/or by introducing new characteristics not used in the unaided session. Visser (2006) discussed this type of idea as reuse, where designers use sources of previous designs to combine, modify, and adapt to create and improve on new concepts, which may or may not lead to innovation solutions (Eckert & Stacey, 2000). We found that sequential links consistently took place during both the unaided and aided transformation sessions, whereas non-sequential links occurred significantly more often during the transformation session aided by Design Heuristics.

When students built upon characteristics of their concepts using Design Heuristics through non-sequential links, they pushed on qualities of solutions by *varying component characteristics* and *combining characteristics* to create new and different concepts than in the unaided session. We expected based on the instructions that students would *only* transform their concepts using the previous sequential concept. Yet, we observed that 49 of 60 students had at least one non-sequential link during the concept transformation sessions, and 34 of these occurred *only* in the aided session, implying students pushed on their initial concept through their later concepts. Designers are unlikely to forget their previous ideas and likely to use their expertise and lived experiences to inform the problem they are trying to solve, while using the resources available to develop and push on their concepts in new ways until they have exhausted their options (Goel, 1995). Design Heuristics are more likely to support a method of combining, synthesizing, and generating new changes when transforming concepts. Gonçalves and Cash (2021) discussed how forelinks and backlinks between concepts allowed them to identify 8 clusters of ideas, such as incremental ideas that made small additions to concepts, tangent ideas that had no backlinks and very few forelinks, and more connected ideas, such as bridging ideas, which had multiple forelinks and backlinks, as well as combinatorial ideas, which connected many previous ideas from a session. This categorization among concepts parallels our work, with the unaided sessions in our study including more incremental and hindsight ideas (a type of bridging idea with more backlinks), while the aided session with Design Heuristics included mostly bridging ideas, especially balanced, foresight, and combinatorial ideas.

The links between concepts observed in our study and the use of Design Heuristics seemed to encourage more exploration of the solution space through a deeper dive into the evolution of a concept, producing more alternatives, more feasible options, and reducing fixation on the initial concept, all recommended concept generation practices (Crilly, 2015; Cross, 2001; Jansson & Smith, 1991; Leahy et al., 2020). For example, during Student 1's aided session, non-sequential links led to distinct and varied concepts with different functionality and purposes (Fig. 7). Student 23 utilized non-sequential links in multiple ways: in Concept A2, they improved upon previous characteristics with new applications in different environments and versatility of the device, and in Concept A3, they improved the user experience by providing instructions and an on-switch for the battery (Fig. 8). These non-sequential links and use of Design Heuristics cards appeared to produce positive outcomes by pushing students to explore the solution space further with more diverse concepts, and combine and synthesize characteristics across concepts. Research emphasizes the importance of helping novices move away from linear design processes towards more systematic and iterative concept generation processes (Atman, 2019). Many studies value supporting students in divergent thinking during design (Norman & Verganti, 2014; Silk et al., 2019; Valle & Vázquez-Bustelo, 2009).

Design Heuristics helped to prompt a diversity of changes and design components considered by students. Research has illustrated the value of both incremental and radical design changes (Silk et al., 2019), and both types of design changes can be creative depending on the context and characteristics of the processes used (Valle & Vázquez-Bustelo, 2009). Student 52's Fully Sequential Design Transformation Diagram could be an example of this incremental creative change (Fig. 5). In using *Add Motion*, Student 52's first transformed concept, Concept A1, was changed to a rotating cabinet that could be accessible from all sides. In Concept A3, the card *Expand or Collapse* prompted the student to add more shelves inside of the cabinet in order to store more. Both changes in concepts were not previously thought of in the student's unaided session. In the unaided session, Student 52 did change how the concept was used through multiple ways to bring down the cabinet, but in the aided session, the initial concept was developed by changing a larger diversity of aspects of the design, such as through rotation, geometry change of the system, including shelving, and expanding storage capacity to make a whole storage area. Additionally, using Design Heuristics more frequently resulted in uncommon concept features and functions not evident in the unaided session, such as recycled materials, and were more frequent when using Design Heuristics, such as ease of use, sustainability, reduction of material, and portability/compactness of the design, and even prompting more context for the design, such as for purposes of safety of the user, use of the device in a variety of environments, or cost and manufacturing considerations.

These differences in the two sessions suggest that adding Design Heuristics to concept generation sessions may change the qualities considered in transforming concepts. Access to multiple cards may encourage students to rethink and overcome fixation of a design feature, such as a handle, to consider more variation in changes made. Design Heuristics seem to encourage usability goals in product design and incorporate larger concerns such as safety, ease of use, and sustainable design. Further, adding support from a concept generation tool may encourage deeper rather than superficial changes to create more differences in the designs generated. Deeper changes reveal intentional decision making by a designer to elaborate on details and features, and creating connections from previous ideas, as described by vertical transformations (Haupt, 2018).

Design Transformation Diagrams provided a successful visualization tool to highlight how an initial concept changed over time, what changed and stayed constant during the evolution of a concept, and how each concept was linked to previous ones. These diagrams are comparable to linkographic methods (Goldschmidt, 2016) in identifying "critical moves" and creative links between concepts. They are also similar to process network graphics linking divergent concept creation and convergent concept judgement through nodes of backlinks and forelinks (Gonçalves & Cash, 2021). Our diagrams expand on these ideas to include the students' concept sketches and summarized changes within the graphics showing connections between concepts. The Design Transformation Diagrams captured both cross-session and within-session idea development to reveal how concepts were connected and how Design Heuristics helped to push students to consider new concepts in different and original ways.

Given that novice engineers have been shown to move linearly through design processes rather than benefit from iteration in design (Atman et al., 2007), the iterative transformation method presented here may serve to motivate more varied design generation processes. Pulling in non-sequential links may help designers push back on problem definitions and reframe them through inspiration from previous concepts. The transformation process creates a set of related concepts the designer may consider as a conceptual repertoire, allowing the comparison of common and unusual concepts within the set. Recombination of concept characteristics through iterative changes—especially in coordination with Design Heuristics or other assistive methods—appeared to help students expand the available concepts and options "at hand" for potential selection.

Limitations

This study's methodology was limited by the use of a single design task conducted by individual students. Thus, the sessions included no information gathering, work in teams, or lengthy design sessions as might be found in practice settings. Students first completed an iterative transformation session on their own, followed by a second session using Design Heuristics to assist with generation. This "AB" design paired a baseline phase followed by a repetition including the intervention, allowing the comparison of performance by the same individuals in two tasks. In order to avoid interfering with natural approaches to the task, the unaided session always occurred first. As a result, students had generated more prior concepts to refer back to during the aided session using Design Heuristics. Session order may account for more non-sequential transformations occurring during the second, aided session compared to the unaided session. Comparing natural choices to methods for developing initial concepts is important for comparing the benefits of alternative approaches (Daly et al, 2016).

The data collected were limited in that the information gathered for each concept varied based on the extent of students' descriptions, which in some cases provided limitations in interpreting all of the changes students considered from one concept to the next. Additionally, the study did not include an examination of concept feasibility, cost, creativity, or other design outcomes, thus limiting the ability of the study to make claims about the impact of the varying ideation approaches of ultimate design outcomes. Finally, the limited sample of students from one university engineering program may not reflect outcomes with other student groups, and no information about diversity within the student sample were available.

Implications

Implications from this study apply to design and engineering pedagogical practices and the understanding of idea development based on initial concepts and concept generation. The use of transformations to generate more concepts may encourage novice engineers and designers to overcome attachment to their first concepts as they iteratively explore, revise, and refine the available solutions, components, and characteristics of generated concepts. This approach encourages producing and combining multiple changes from an initial concept for further analysis, selection, and decision making, while preventing paralysis removal of judgment by providing structure to concept iteration and building sound practices for generating multiple concepts. Even when engineering students feel they lack new directions or inspirations to draw from, they can be successful in creating "something from nothing" by building out concepts through iteration and engaging more creatively.

One research implication of this work is that future studies may benefit from the use Design Transformation Diagrams to visualize how concepts change over a design session or over time, and even to compare the effect of different concept generation tools on idea development. Research has shown communication through representations of alternatives is important in design (Schmidt et al., 2012) and may encourage engagement with team members and stakeholders (Newman & Landay, 2000; Tang, 1991). Design Transformation Diagrams may be beneficial for student designers and design practitioners to track their concept generation processes, inspire new concepts, or communicate within teams or with other stakeholders about their concept generation processes and help make decisions or comparisons among concepts.

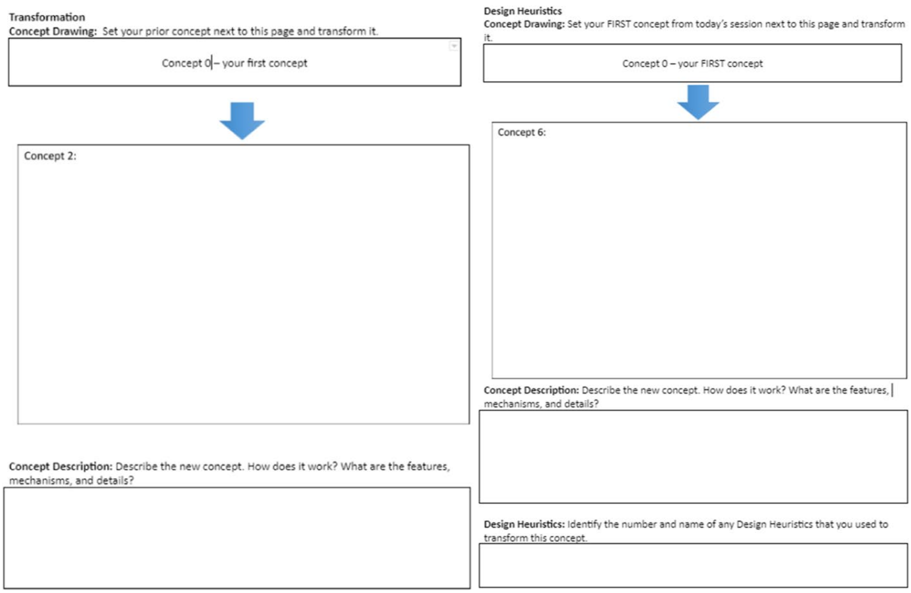
Future studies of iterative transformations during concept generation will be beneficial in understanding students' developing skills in concept generation. Iterative transformation may provide an easier process for refining and expanding initial concepts and expand exploration of concept generation methods and potential solutions.

Conclusion

In this study, we explored how students transformed their initial concepts for a design problem to identify connections between concepts unaided and aided by Design Heuristics. Using a novel visual analysis tool, Design Transformation Diagrams, we identified three different diagram types, revealing patterns among concept transformations, and how students changed their concepts over the sessions. These emergent relationships revealed using Design Heuristics during transformation prompted more non-sequential links to synthesize, refine, and push on concepts in new ways. Additionally, Design Heuristics elicited more distinct and meaningful transformations, creating more diverse and novel concepts. As students report feeling limited in their ability to create creative concepts for engineering design projects, building in exposure to methods like iterative transformation in design, manufacturing, and other technical classes may help to build student confidence as they approach future design problems. Concept generation methods such as Design Heuristics may help students in developing and iterating on concepts, supporting their successful generation of quality designs. Students may be encouraged to explore generating different and diverse concepts to increase creativity in engineering and influence design outcomes.

Appendix 1

Concept sheets were provided for each concept generation task: unaided (left) and aided with Design Heuristics (right). Starting from the previous sequential concept, the student was asked to transform it into a new design. Both sheets provided a section to sketch the new concept as well as a written description for how the concept worked, including features, mechanisms, and details. The Design Heuristics concept sheet also asked the student to identify the Design Heuristics card(s) they used to transform the concept.



Transformation
Concept Drawing: Set your prior concept next to this page and transform it.

Concept 0 – your first concept

Concept 2:

Concept Description: Describe the new concept. How does it work? What are the features, mechanisms, and details?

Design Heuristics
Concept Drawing: Set your FIRST concept from today's session next to this page and transform it.

Concept 0 – your FIRST concept

Concept 6:

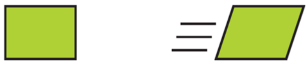
Concept Description: Describe the new concept. How does it work? What are the features, mechanisms, and details?

Design Heuristics: Identify the number and name of any Design Heuristics that you used to transform this concept.

Appendix 2

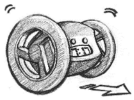
Seven Design Heuristics cards (selected at random) were provided to each student in the second design task: *Add motion*, *Change geometry*, *Expand or collapse, Impose hierarchy on functions*, *Reduce material*, *Repeat*, and *Use repurposed or recycled materials* (Design Heuristics, L.L.C., 2012). The front of each card is shown on the left and the back on the right of each panel.

ADD MOTION 2



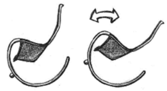
Add motion as part of the product's function. This can improve function, change user interaction, or add playfulness.

ADD MOTION 2



CLOCKY
Nanda Home Inc.
This alarm clock can jump off a table and roll along the floor while ringing.

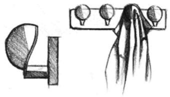
KEINU
Eero Aarino
This chair allows the user to rock forward and backward.



CHANGE GEOMETRY 20

Alter the typical or expected geometric form of the product or its components while maintaining function. This can redefine user interactions, make the product more intuitive, and suggest new product functions.

CHANGE GEOMETRY 20



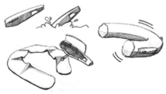
TRUFORM
Vishaal Verma
Instead of pointed hooks, this coat rack has rounded, soft hooks that distribute weight evenly and leave clothes unmarred.

CHAIR
Michael Wolk
These chair legs are designed to be triangular instead of rectangular, creating a unified look with the seat.

EXPAND OR COLLAPSE 32

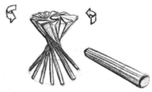
Allow the volume or area of the product or its parts to get larger or smaller. Consider the use of fluids, inflatables, flexible materials, and complex joints. This can improve portability and storage options, and allow adjustability.

EXPAND OR COLLAPSE 32



RESCUE STICK
Sungjoon Kim, Jangwoon Kim, Sook-kyung Lee, and Keunhwan Pack
This flotation device automatically inflates when it touches water.

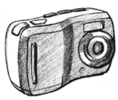
ONE SHOT
Materialise.MGX
This stool can be collapsed into a staff by twisting, providing compactness for storage.



IMPOSE HIERARCHY ON FUNCTIONS 38

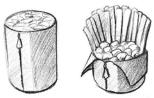
Present the functions of the product in a set order to assist in using the product. Make the steps for each function clear; for example, access to the second function only occurs after the first. This can increase safety, make the product more intuitive, and guide the user through the product's functions.

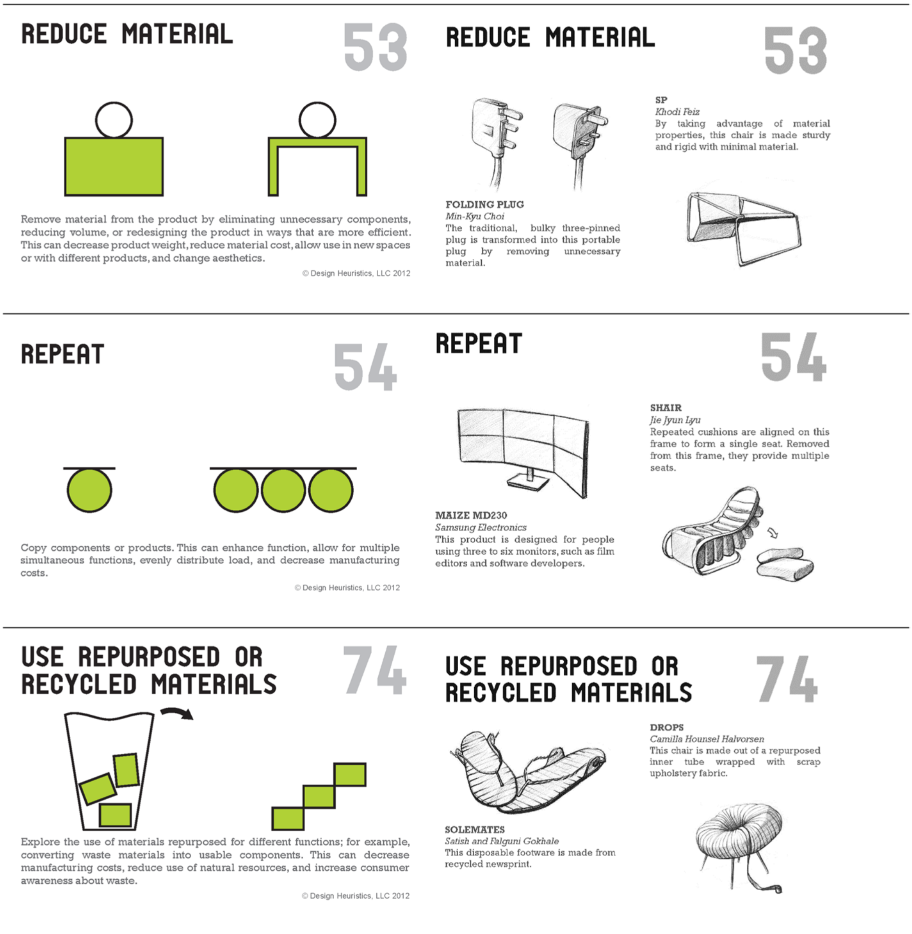
IMPOSE HIERARCHY ON FUNCTIONS 38



EASYSHARE ONE
Kodak
After a picture is taken, this camera can print the picture or send it to others.

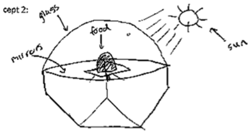
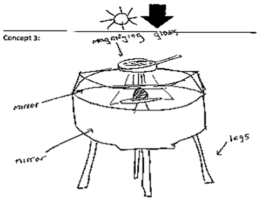
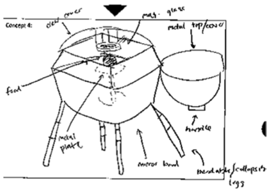
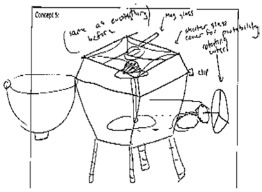
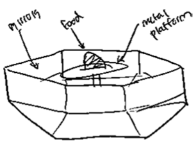
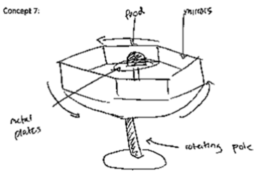
ZIP-UP
Kim In-bo
This chair can be manipulated into a cushy seat by following a set of steps: Unzip the cover, fold down some cushions, and then have seat.

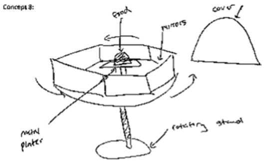
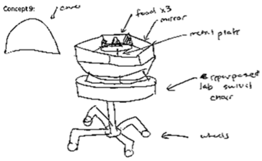




Appendix 3

Data collected from a student (Student 13) for the Solar Cooker problem, including initial concept, unaided transformations, and aided transformations using Design Heuristics. Each concept included a sketch, description including any writing (transcribed for clarity) on the sketch, and any Design Heuristics cards noted as applied. Numbers within descriptions denote unique concept features, with first mention in bold, to illustrate the change in concept qualities over transformations.

Concept Number	Description	Concept Sketch
0: Initial Concept	Food is placed inside a (**1) mirror bowl** so the sunlight all converges into the middle of the bowl onto a (**2) metal platform** that will also heat up with the sunlight; bowl made of mirrors w/ platform of metal where the food goes	
U1: Unaided	(1) Mirror bowl: reflects light and focuses it on the food. (2) Metal platform: warms up in sunlight to heat food. (**3) Glass cover:** keeps same heat inside the bowl; glass, mirrors, food, sun)	
U2: Unaided	(1) Mirror bowl (4) **extends farther up** so the light can cook the food more evenly. **(5) Add magnifying glass** to better focus the light. **(6) 4 legs** for easier access so you don't have to bend down. (3) Glass dome; magnifying glass, (1) mirror, mirror, legs	
U3: Unaided	Has **(7) metal top/cover** to retain heat and keep cooked food warm. **(8) Bendable/collapsible** (6) legs for portability and **(9) handle** for portability; (3) clear cover, (5) mag. Glass, (7) metal top/cover, **(9) handle**, food, (2) metal plate, (1) mirror bowl, (8)(6) bendable/collapsible legs	
U4: Unaided	**(10) Added wheels** so that the metal platform can be rotated easily so then food is evenly cooked no matter where the light is, **(11) taller** (6) legs**, (12) clip** to keep top closed; same as everything before, (5) mag. Glass, **(13) shorter** (3) glass cover for portability, (10) rotating wheel, (12) clip	
A1: Aided with Design Heuristic, *Change Geometry*	**(14) Has more sides** for more angles of reflection; (1) mirrors, food, (2) metal platform	
A2: Aided with Design Heuristic, *Add Motion*	The mirror oven is supported by a **(15) pole that allows the oven to be easily spun** for a more even cook; food, (1) mirrors, (2) metal plates, (15) rotating pole	

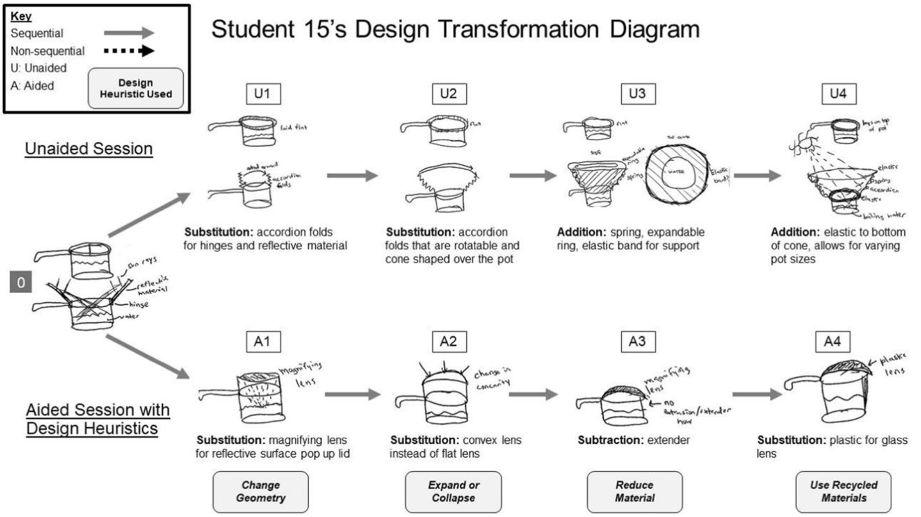
Concept Number	Description	Concept Sketch
A3: Aided with Design Heuristic, *Impose Hierarchy on Function*	(7) Cover must be removed before access to oven can occur; food, (1) mirrors, (7) cover, (2) metal plates, (15) rotating stand	
A4: Aided with Design Heuristics, *Use Recycled Materials* and *Repeat*	Wheels for portability, reuse an **(16) old swivel chair** as a rotating platform, more food at once for mass cooking; (7) cover, food × 3, (1) mirror, (2) metal plate, (16) repurposed lab swivel chair, (16) wheels	

Appendix 4

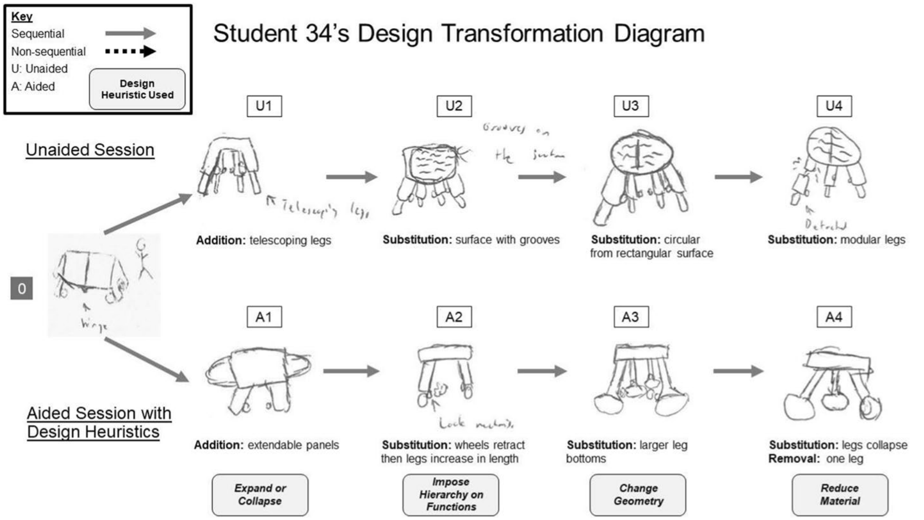
Additional examples of individual students' Design Transformation Diagrams. The diagrams are labeled by type: Fully Sequential, Sequential with Deviation, and Divergent. A different student's work is shown with each of the two problems (the Solar Cooker and the Vertical Reach Design Problems).

Fully Sequential

Solar Cooker Problem

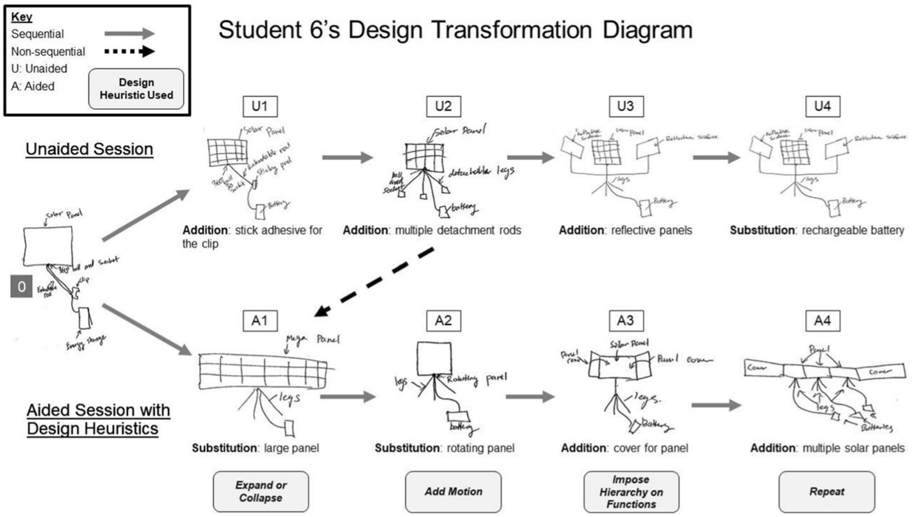


Vertical Reach Problem

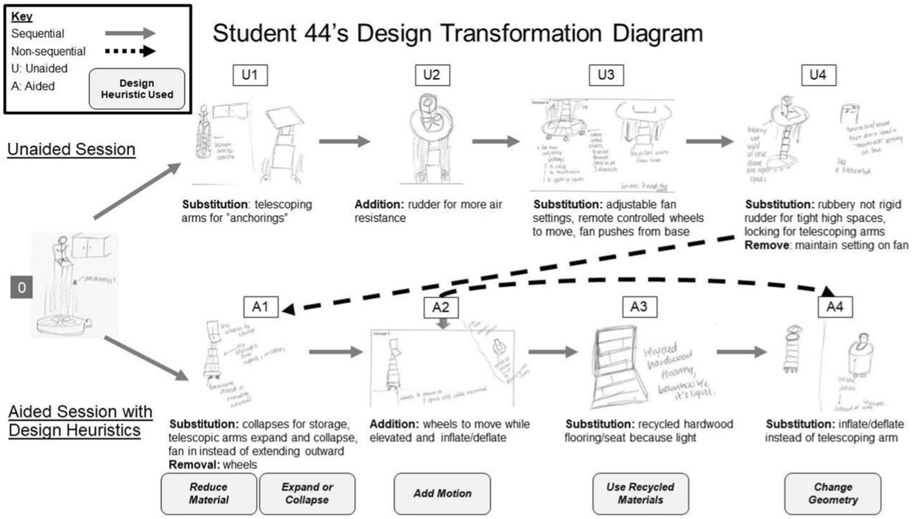


Sequential with Deviation

Solar Cooker Problem

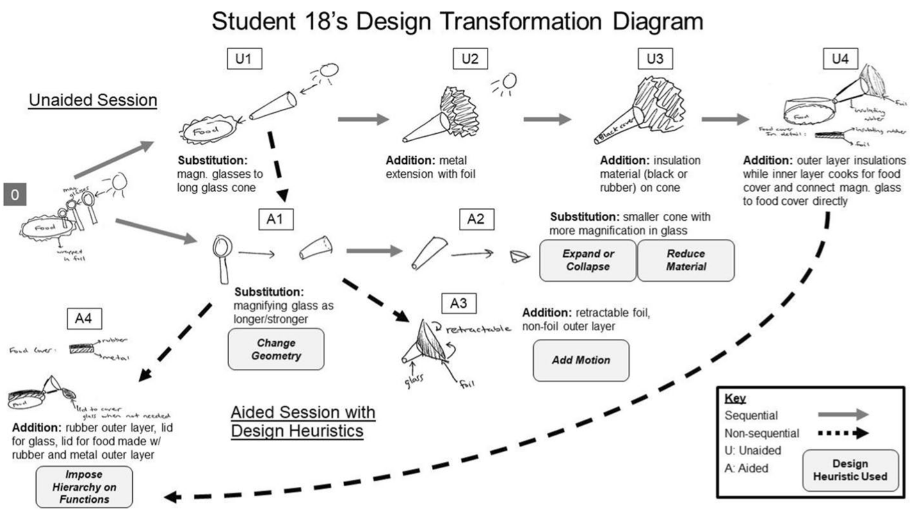


Vertical Reach Problem

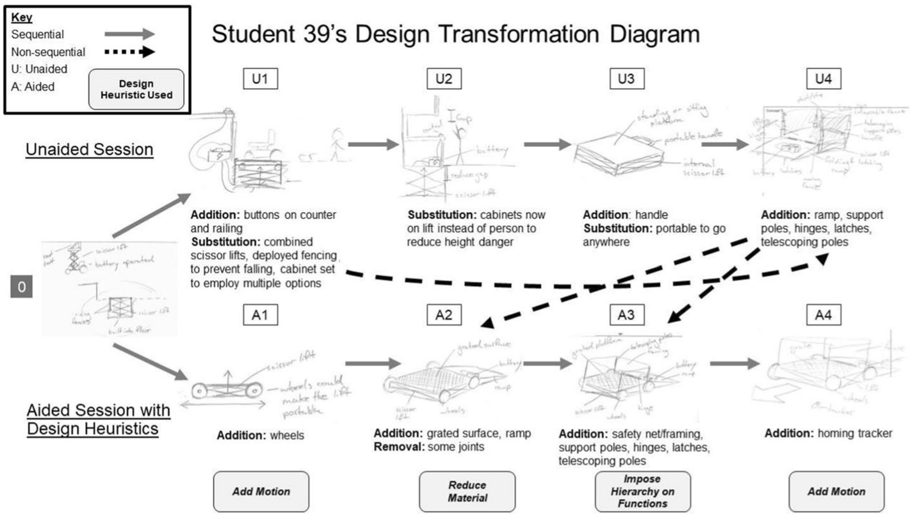


Divergent

Solar Cooker Problem



Vertical Reach Problem



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Data availability None.

Code availability None.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Human Subjects Participation University of Michigan IRB # HUM00061138.

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