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A Comparison of the Types of Heuristics Used by Experts and Novices in Engineering Design Ideation

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Abstract

This study explored the use of heuristics in the design space by novice and expert engineers in the initial ideation of a design solution. Verbal protocol analyses were conducted with four engineering students and four professional engineers as they generated ideas to solve a design problem. Overall, both experts and novices used various types of heuristics. Although novices' heuristics tend to focus on improving the function of the design, experts' heuristics tend to focus on improving both function and form. The implication is that the deliberate teaching of design heuristics, along with other strategies, will help in the development of generative skills of students, stimulating more creative and innovative designs. Validated design heuristics can be integrated within engineering design content at appropriate grade levels to aid in building the repertoire of heuristics used by engineering and technology education students.

***Keywords*:** Experts; design space; heuristics; novices; problem space; solution space; verbal protocol analysis

> We make decisions and judgments every day [on uncountable matters of our lives]—if we can trust someone, if we should do something (or not), which route to take, how to respond to someone's question [, which strategy to use to solve a problem]—the list is endless . . . . Thankfully, our mind makes things easier for us by using thinking strategies known as heuristics. (Dale, 2015, p. 93)

Heuristics guide human judgment and decision making. In short, heuristics are the shortcuts for problem solving that specify simple strategies for assessing and manipulating information and provide us with effortless quick responses in some decision-making tasks (Dale, 2015).

> The term heuristic is of Greek origin and means, "serving to find out or discover." Einstein included the term in the title of his Nobel prize-winning paper from 1905 on quantum physics, indicating that the view he presented was incomplete but highly useful (Holton, 1988, pp. 360–361). (Gigerenzer & Gaissmaier, 2011, p. 454)

Our brain has a limited capacity to process all the information that bombards our sensory system, and we would not function effectively if our brain tried to analyze all information in order to arrive at a decision (Cherry, 2019). Quite often, “when we are trying to solve a problem [such as a design problem] or make a decision, we often turn to mental shortcuts when we need a quick solution” (Cherry, 2019, “Why Do We Use Heuristics,” para. 2). “A heuristic is a mental shortcut that allows people to solve problems and make judgments quickly and efficiently” (Cherry, 2019, para. 1). “Heuristics play important roles in both problem-solving and decision-making” (Cherry, 2019, “Why Do We Use Heuristics,” para. 2). It allows us “to think through the possible outcomes of a decision quickly and arrive at a solution that will work for your unique problem” (Cherry, 2019, “Why Do We Use Heuristics,” para. 6).

Literature Review

Heuristics and Problem Solving

There are many definitions of heuristics. A heuristic is often described as a cognitive strategy that “assesses a target attribute by another property (attribute substitution) that comes more readily to mind” (Kahneman & Frederick, 2002, as cited in Gigerenzer & Gaissmaier, 2011, p. 454). “Research in psychology describes heuristics as simple, efficient rules to explain decision making, judgments, and problem solving, especially when faced with complex problems with vague information” (Nisbett & Ross, 1980, as cited in Yilmaz, Daly, Seifert, & Gonzalez, 2011, p. 4; see also Kahneman & Frederick, 2002; Gigerenzer, Todd, & ABC Research Group, 1999; Tversky & Kahneman, 1974). Others (e.g., Shah & Oppenheimer, 2008) refer to heuristic as a cognitive process aimed at effort reduction. Shah and Oppenheimer (2008) propose[d] that all heuristics rely on one or more of the following methods for effort-reduction:

> 1. Examining fewer cues.
> 2. Reducing the difficulty associated with retrieving and storing cue values.
> 3. Simplifying the weighting principles for cues.
> 4. Integrating less information.
> 5. Examining fewer alternatives. (p. 209)

Gigerenzer and Gaissmaier (2011) defined a heuristic as “a strategy that ignores part of the information, with the goal of making decisions more quickly, frugally, and/or accurately than more complex methods” (p. 454).

The classical explanation of heuristics is that they allow people to save effort but often at the cost of accuracy. Therefore, in problem solving, the use of heuristics does not guarantee an accurate solution or the best solution. Humans, therefore, rely on heuristics because information search and computation cost time and effort (Shah & Oppenheimer, 2008; Gigerenzer & Gaissmaier, 2011). According to Mangal (2007), some common heuristics used to solve problems are: “sub-goal analysis,” “means-ends analysis,” “working backward,” and “using an analogy” (p. 290). In *sub-goal analysis*, “a complex problem is reduced to a series (or hierarchy) of smaller, more easily solvable problems” (p. 390). In *means-ends analysis*, “while solving a problem, it is always better to have a proper analysis of the nature of the problem in perfect coordinated with the means, materials, and resources at hand” (p. 390). The goal, the strategy, and the outcome that is desired are all “issues [that] should be carefully analyzed with respect to the means available for coping with these issues” (p. 390). In *working backward*, the problem solver begins at the goal and moves back to the initial problem. *Using an analogy* allows the problem solver to limit his or her solutions to situations, artifacts, or experiences that have something in common with the present problem. Usually, the focus is not on surface similarities but on underlying meaning.

Researchers have identified some domain-specific heuristics in education. For example, Klahr (2000) highlighted several heuristics used to search the experimental space by both students and adult scientists but acknowledged that there were developmental differences in how these heuristics were used. According to Klahr (2000), “the four principle heuristics” were: (a) “use the plausibility of a hypothesis to choose experimental strategy” (p. 113), (b) “focus on one dimension of an experiment or hypothesis” (p. 114), (c) “maintain observability” (p. 115), and (d) “design experiments giving characteristic results” (p. 115).

Heuristics and Engineering Design

Engineering design has several definitions that are influenced by the various specialties within the field of engineering. However, using a somewhat eclectic or global definition, Koen (2003) defines “engineering design, or the engineering method, . . . [as] the use of *heuristics* to cause the best change in a poorly understood situation with the available resources” (p. 28). Koen’s definition implies that engineering design situations are usually poorly understood initially. This may not be the situation in all design cases; none-the-less, heuristics are important, and indeed essential, problem-solving strategies that are used by designers. Koen further indicated that

> A heuristic has four definite signatures that make it easy to recognize:
> 1. A heuristic does not guarantee a solution,
> 2. It may contradict other heuristics,
> 3. It reduces the search time for solving a problem, and
> 4. Its acceptance depends on the immediate context instead of on an absolute standard. (p. 29)

He grouped heuristics under five major categories:

> 1. Some simple rules of thumb and orders of magnitude
> 2. Some factors of safety
> 3. Some heuristics that determine the engineer’s attitude toward his work
> 4. Some heuristics that engineers use to keep risk within acceptable bounds
> 5. Some miscellaneous heuristics that do not seem to fit anywhere. (pp. 65–66)

According to Koen (2003), “the terms *rule of thumb* and *order of magnitude* are closely related, often used interchangeably, and usually reserved for the simplest heuristics,” for example, someone estimating “the size of a room by knowing the order of magnitude for standard column spacing” (p. 66). Another example would be: “The yield strength of a material is equal to a 0.2 percent offset on the stress-strain curve” (p. 66). Factor of safety heuristics are used because there are uncertainties in calculated values used by engineers. So, a factor of safety allows for a degree of error, for example, “use a factor of safety of 1.2 for leaf springs” calculations (p. 68). Attitude determining heuristics refer to the general attitude or behavior of the designer when confronted with a problem. Two examples of this type of heuristic are: “quantify or express all variables in numbers” (p. 70) and “work at the margin of solvable problems” (p. 72). “Because the engineer will try to give the best answer he can, . . . some risk of failure is unavoidable” (p. 73). Risk controlling heuristic are used to reduce these risks. An example of a risk-controlling heuristic is: “Use feedback to stabilize engineering design” (p. 77). Miscellaneous heuristics are those that “do not seem to fit under any of the previous categories” (p. 79). Examples include: “break complex problems into smaller, more manageable pieces” and “design for a specific time frame” (p. 79).

In a study designed to empirically validate design heuristics, Yilmaz, Daly, Seifert, and Gonzalez, (2011) “characterized three types of cognitive design heuristics that prompted different types of movements in the design space”: local, transitional, and process.

> - *Local* heuristics define characteristics and relationships of design elements within a single concept . . . .
> - *Transitional* heuristics provide ways to transform an existing concept into a new concept . . . .
> - *Process* heuristics prompt a designer’s general approach to idea generation . . . . They serve as cognitive tools used to initially propose ideas by directing the designer’s navigation of the solution space. (p. 5)

Table 1
Examples of Local, Transitional, and Process Heuristics (Yilmaz et al., 2011)

Heuristic	Description
Local	
Attach components with different functions	Adding a connection between two parts that function independently
Attach the product to another existing item	Utilizing an existing product as part of the function of the new product
Attach the product to the user	The user becomes part of the product's function
Compartmentalize	Separating the product into distinct parts or compartments with different functions
Transitional	
Change the geometrical form	Using different geometrical forms for the same function and criteria
Split	Taking a piece of the previous concept to generate a new concept
Substitute	Replacing the material, form, or a design component with another to achieve the same function
Process	
Contextualizing	Changing the context in which the product would be used, and using that context to inspire a concept that satisfied the nature of the context
Problem Restructuring	Shifting or redefining what the actual problem is and generating products that satisfy the identified real problem
Constraint Prioritizing	Putting more emphasis on certain criteria than others and using the emphasized criteria to focus and guide concept development

Redesigning	Re-designing existing products with similar functions
Simplifying	Generating and building on the simplest way to solve the problem

Note. This table is adapted from Tables 3 and 4 in Yilmaz et al. (2011) on pp. 11–13.

In their study with engineers and industrial designers, Yilmaz et al. (2011) proposed that the use of “specific design heuristics [local, transitional, and process] would help designers explore new types of potential designs, leading to the generation of innovative solutions” (p. 6). They found

> that heuristics are effective in generating diverse concepts. Design heuristics may, at times, be sufficient to stimulate divergent thinking. Furthermore, the study reveals some differences between these two types of designers in how they approached this open-ended, novel design problem. Specifically, we found that engineers produced a more diverse set of designs from among all of the concepts generated. Industrial designers, however, generated more design concepts in the same period [, but these designs were less diverse]. (p. 20)

In their study, and like the study before, they coded heuristics that served both as local and transitional heuristics. According to Yilmaz et al. (2011), “local and transitional heuristics are listed together because the same heuristic can be used for defining the relationship of the elements within one design concept, or as a transition in moving from one concept to a new one” (p. 10). Table 2 illustrates heuristics that were both local and transitional. Process heuristics were those applied by the designers to the idea generation process as a whole. They reflected a designer's general approach to ideation within the session, and the heuristics observed do not include all possible heuristics for the design task. However, they represent a set of possible heuristics appropriate for idea generation for this design problem.

Table 2
Heuristics That Are Both Local and Transitional (Yilmaz et al., 2011)

Heuristic	Description
Adjust functions by moving parts	By moving the product's parts, the user can achieve a secondary function
Change the configuration of elements	Performing different functions based on the orientation or the angle of the design elements in the product
Cover	Overspreading the surface of the product with another component to utilize the inner surface
Detach / Attach	Making the individual parts attachable /detachable for additional flexibility
Fold	Creating relative motion between parts by hinging, bending, or creasing to condense the size
Offer optional components	Providing additional components that can change the function or adjustability
Repeat	Dividing single continuous parts into two or more elements, or repeating the same design element multiple times, in order to generate modular units
Replace solid material with flexible	Changing a product's material into a flexible one for creating different structural and surface characteristics
Scale	Changing the size of a feature of the product

Note. This table is adapted from Table 3 in Yilmaz et al. (2011) on pp. 10–12.

The Framework

"The model for creative design, which illustrates the co-evolution of the problem and solution spaces during engineering design problem solving (see Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996)" (Dixon & Johnson, 2011, p. 49), was used for this study. According to Maher, Poon, and Boulanger (1996), "whenever engineers are solving design problems, their problem and solution spaces co-evolve with an interchange of information between the two mental spaces" (Dixon & Johnson, 2011, p. 49). Dorst and Cross (2001) confirmed the accuracy of the Maher et al. (1996) model in a protocol study of nine experienced industrial designers whose designs were evaluated on overall quality, creativity, and a variety of other aspects. For simplicity, we illustrate the coevolution of the problem and solution spaces in Figure 1. The overlapping space represents the space in which an exchange of information between the solution and problem spaces takes place; in this space, the designer is transitioning or moving back and forth, exchanging information between the two spaces.

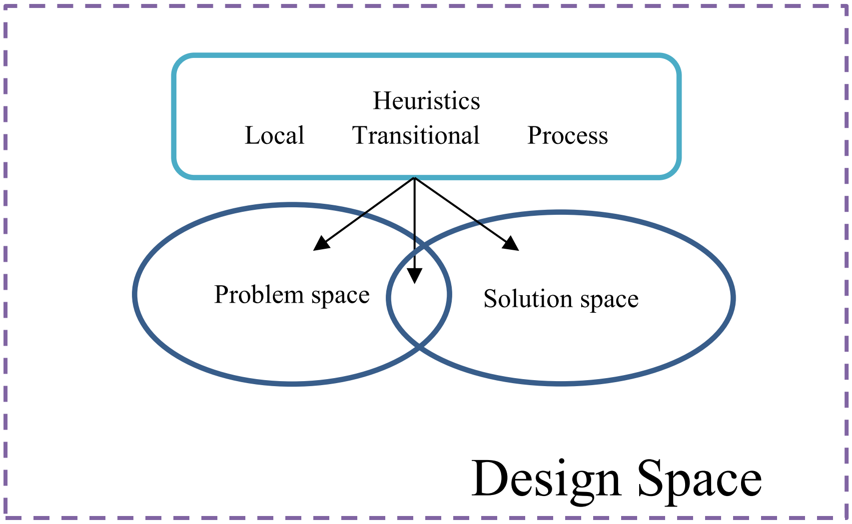

Figure 1. Conceptual model.

Idea generation, as a phase in the design process, is the stage where designers consider multiple alternatives. It is not restricted to a single phase; rather, it occurs throughout the design process as ideas are transformed and developed. For initial idea generation, the goal is to explore, in both depth and breadth, the *design solution space*, which is the theoretical space containing all possible solutions for a given design problem (Daly, Seifert, Yilmaz, & Gonzalez, 2016; Dorst & Cross, 2001; Newell & Simon, 1972). As the designer explores solutions, heuristics are used as one of the ideation techniques to generate concepts. Multiple heuristics can be employed within a single design, and each heuristic can be applied repeatedly to initiate ideas, transform existing ideas, and generate ideas for subcomponents of complex design (Yilmaz, Seifert, & Gonzalez, 2010; Kramer, Daly, Yilmaz, Seifert, & Gonzalez, 2015). Heuristics can focus on the form or function of the design idea. Function tells what the device or mechanism does, whereas form relates to any aspects of physical shape, geometry, construction, material, or size (Ullman, 2003).

Research Questions

This study explored types of heuristics (local, transitional, and process) used by experts and novices in the design space as they go through the initial ideation of a design problem. The following research questions guided this study:

1. What is the predominant type of heuristics used by novice designers in the problem, solution, and overlapping spaces during the initial ideation of a design problem?
2. What is the predominant type of heuristics used by expert designers in the problem, solution, and overlapping spaces during the initial ideation of a design problem?
3. How do experts and novices differ when using heuristics directed at function and form of design?

Method

A qualitative comparison of novice and expert engineers was conducted. A purposeful sampling procedure was used to select participants. According to Gall, Gall, and Borg (2007), "in purposive sampling the goal is to select cases that are likely to be 'information rich' with respect to the purposes of the study" (p. 218). The use of heuristics by a small group of mechanical engineering students was compared with a small group of professional mechanical engineers.

Participants

An email was sent inviting juniors and seniors enrolled in a 4-year mechanical engineering program at a Midwestern university to participate in the study. Four mechanical engineering students agreed to participate, two juniors and two seniors. The four professional engineers were recommended by a member of the American Society of Mechanical Engineers. Each professional engineer is recognized as an expert in mechanical engineering design. Each professional engineer had at least the minimum 10 years of experience that it generally takes to be considered an expert in a particular domain (Phye, 1986). The small sample size is typical of verbal protocol studies (Jiang & Yen, 2009; Trickett & Trafton, 2009).

The Design Task

Each participant was given the same design problem to generate ideas for a solution. The design task was vetted by two professionals in the field: an engineering technology professor with over 20 years of teaching experience and a mechanical engineering professor with over 10 years of experience as a manufacturing consultant and over 3 years of experience teaching manufacturing principles. This review helped ensure that the design task was sufficiently ill-structured and of an appropriate difficulty level to engage the students and professional engineers (see Figure 2).

Procedure

The design task was administered at a time and place convenient for each participant. Pencils, erasers, and sketchpads were provided, along with the instructions for the design task. Each participant was allowed approximately 1 hour to complete the design solution. Participants were required to produce only one conceptual design. Data were collected primarily using concurrent verbal protocol analysis.

Each participant had the choice of doing a verbalization practice session of about 5 minutes, thinking aloud as they solved a simple mathematical problem, to prepare them for the study. After they were comfortable with the think-aloud process, the task was administered. The participants were encouraged to speak aloud whatever they were thinking as they solved the problem. Their think-aloud verbalizations were audio recorded. If the participants stopped talking, they were prompted or reminded to continue to speak their thoughts aloud.

THE DESIGN TASK

The objective of this engineering design activity is to understand the cognitive process of engineering designers as they solve a design problem. Verbal Protocol Analysis will be used. This means that as you solve the problem, you will be required to **"think aloud"** (say aloud) what you are thinking. If you stop speaking, I will remind you to resume speaking aloud as you solve the problem. Please include all the notes and sketches of your solution on the sketch pads that are provided.

Duration: 1 hour

The Context

Fonthill is a hilly terrain in the District of Saint Mary with narrow tracks and virtually nonexistent roads. This area also experiences high amounts of rainfall yearly. There are several communities like Fonthill on this mountainous tropical island. Because of the very poor state of the roads, the most frequent mode of transportation are motorcycles. Motorcycles are used to take residents to and from work, market, and school. Although the residents see this system of transportation as essential, the government has serious concerns about the safety of the riders and their passengers. The government therefore secured a loan to purchase a fleet of motorcycles that are specially built to handle these rugged terrains. These motorcycles will be leased as taxis to specially trained riders.

The Design Problem

The Honda CRF230 shown on the next page is a cross between a dirt bike and a street bike. Modify the Honda CRF230 so that it is robust enough to handle repeated journeys through these mountainous terrains that are prone to a lot of rainfall annually. The average cost of a new car in this country is about US $25,000.00, and the government expects that the cost of this motorcycle will not exceed one third this cost. The motorcycle must also:

- Be equipped with more cargo carrying capacity and at the same time make the rear seating (pillion) more comfortable.
- Have an improved rack or a holding system for carrying packages, books, or a reasonable amount of groceries on the motorcycle. The rack must be non-metallic but of sufficient sturdiness to withstand a rugged terrain, occasional brushing against rocks, and a lot of rainfall.
- Be capable of enough horsepower to climb sections of mountains with slopes of 30 degrees, carrying the rider and the pillion passenger.
- Have a device to prevent the theft of helmets from the motorcycle.

Figure 2. The engineering design task. This task was previously presented in Figure 2 in Dixon and Johnson (2011) on p. 53.

Data Analysis

The audio recordings of the protocols were transcribed. The transcribed protocols were then segmented into think-aloud utterances, divided into sentences, and coded. The quality of the sketches was not evaluated because the objective of the study was to examine the heuristics used by the engineering students and the professional engineers. The sketches and notes, however, acted as a reference to clarify some sections in the protocols.

The purpose of segmenting is to break the transcribed verbal protocol text into units (or segments) representing discrete thoughts that can be coded with a predefined coding scheme. Each segment was coded manually using the following predefined constructs: local heuristic, transitional heuristic, process heuristic, local and transitional heuristic, problem space, solution space, and overlapping space (Daly, Yilmaz, Seifert, & Gonzalez, 2010; Dorst & Cross, 2001; Yilmaz et al., 2011). Each heuristic was further coded for function or form. Reliability coding was conducted using two coders to code seven pages of one transcript (Miles & Huberman, 1994). A reliability kappa coefficient of 0.76 was obtained. One coder then completed the coding of the remaining transcripts.

Results

Predominant Types of Heuristics Used by Novice and Expert Designers

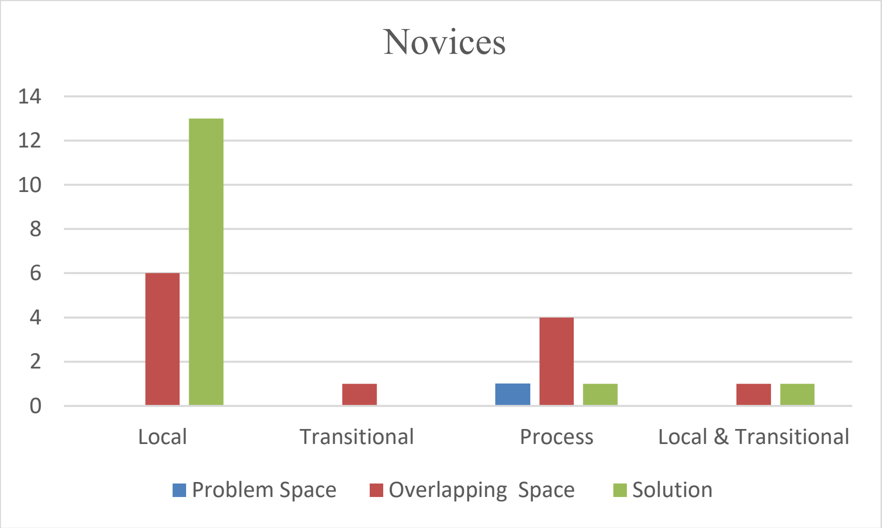

Figure 3. Heuristics used by novices.

The transcripts of the novices revealed that local heuristics were used more often (19 in total), and they were mainly concentrated in the solution space and the overlapping space. The overlapping space is the space in which an interchange of information between the two mental spaces are taking place. That is, as the designer focuses on a solution within the solution space, she or he may move back to the problem space to retrieve information about the problem. Process heuristics were used in all three spaces. Transitional heuristics were used only in the overlapping space, and local and transitional heuristics were used in the overlapping and solution spaces (see Figure 3).

Figure 4. Heuristics used by experts.

In contrast, transcripts revealed that the experts used fewer heuristics than the novices (16 compared to 28 by novices). However, like the novices, the majority of heuristics used were local. Almost equal amount of heuristics were used in the overlapping and solution spaces. No transitional heuristics were used in the problem and overlapping space, and process heuristics were used only in the overlapping and solution spaces. Local and transitional heuristics were only used in the solution space (see Figure 4).

Differences in Use of Heuristics Directed at Function and Form

Transcripts were examined to determine whether the heuristic used related to the function or the form of the design.

Novices. The majority of local heuristics used by the novices related to design form. They used heuristics to elevate parts of their design component, scale the size of components of the design, or extend the component to ensure that the design concept center of mass was properly distributed, allowing proper balance of the vehicle. These heuristics were used mainly in the solution space of the designer.

> If you are going to have an engine in this thing that's not or that's elevated off the ground by I'd say a half foot or foot. You are going to have a fairly high center of gravity.
>
> The concern about or the possible concern about tipping would require B to be some not too small fraction. I'm am not entirely sure what requirement would be that would be based on the kind of weight distribution, which of course would be depending on the size of the trunk that would be attached.
>
> The only problem with that is it might throw off the balance of the bike but you probably just have to put more of a counter weight in front. Like shift the engine more forward to allow for more weight to be in the back of the bike.
>
> Because if you use an external rack you're either going to have to put it on the sides you probably want it on both sides so it didn't throw off the weight distribution so you probably could put, like container on both sides to do things, but then that would add to the width again and you'd be likely to hit things more that you would with this.

The local heuristic, scaling, was also used to improve structural soundness at the rear of the vehicle, traction, and horsepower. These however were mainly used in the overlapping space.

> Another problem with added weight as your traction you might have to upgrade your entire selection to a little more meaty tire.
>
> Along with this improved rack comes more weight, so therefore, you could have some problems with the horse power not being sufficient enough.

Transitional heuristics were used for both function and form of the design. Ideated form included making the vehicle longer and transitioning from a vehicle without cover to one with cover. Ideated function included increasing airflow in order to increase the horsepower of the engine.

I am thinking I'm going to make the motorcycle longer than they had in the past.

> Almost thinking of putting a covering on it let's see how that works though, . . . okay I'm going to keep the original design with the dirt guards for now.
>
> I do know that the cylinder can easily be bored out so that they have more displacement with more horse power, but that would be very expensive . . .

> you might be able to do something with the intake to increase the air flow or something like that.

Process heuristics were used primarily to improve function. The novices focused on the context in which the vehicle is to operate and drew on analogies of vehicles that operate in a similar context. They redesigned the existing concept from a two-wheel to a three-wheel vehicle in order to increase carrying capacity, improve safety, and decrease cost.

> Because I'm am thinking when going to the market or grocery store around here you would need a lot more than a motorcycle to carry because I've walked home with 50 pound of food and you're not going to carry that on a motorcycle. So my first thing would be to try to get away from that and use at least like a three wheel system that would give more carrying capacity in the back.
>
> If you're are going do that you might as well just go to an ATV and those would work well enough and not cost $25,000.00 Um which would probably be safer.

Local and transitional heuristics were used in the solutions space and overlapping space and focused on both function and form of the design. They included folding components on the design for safety and lowering the frame for better balance.

> You wouldn't want the rods to hurt the operator in any way, so you'd have to look at maybe some way whenever it is in use they could fold away, you know to where it's not sticking out.
>
> Although I would still of course recommend that the frame be lower in the back for this. This would have also lowered the center of mass.

Experts. Unlike the novices, local heuristics used by experts in this study referenced both form and function of the design in most cases in which they were used. For example, experts focused on a wider array of features than the novices. They included scaling the size of the engine to increase horsepower, scaling the width of the tire to increase traction and safety, changing number of rear wheels from one to two to increase heat dissipation, and relocation of a component to improve balance. Local heuristics were used in all three spaces.

> I think the rear tire need to be wider, concern that if the tires are not wider then it will help to prevent swerving or hydroplaning.

> Yea I would probably go. I'd would start a motor at 1.5 time the size right now. So I would look at 1.5 times current size as a starting point without doing the actual analysis.
>
> And my thinking there was maybe I would go to two tires in the rear to provide additional heat dissipation capability because of the smaller diameter.
>
> Because we probably don't want to because of the need of the luggage we don't want to add too much weight to the overall size of this, but frankly what weight we do want to add we want it on the front.

Transitional heuristics were used less frequently by the experts and primarily referenced the form of the design. In addition, they were used only in the solution space and focused on lowering and extending components as they shift to new concepts in their ideation.

> So the whole thing is much lower to the ground and look at the lowest part of the seat is only just slightly above the rear wheel. Whereas this one the lowest part of the seat is significantly above the rear wheel and I would want to lower it.
>
> I like the fixed tunnel that runs through the rear of the vehicle, where the load deck is, um up to the frame recognizing that if these they will provide torsional rigidity.

Process heuristics used related to both form and function of the design. Like the novices, the experts focused heavily on the context in which the vehicle is to operate; however, unlike the novices, they focused on simplifying the design as an overall strategy in solving the problem.

> I say that because I think we are better off coming here, cantilevering back, adding more steel, and keeping my tires this span apart to allow for um movability or to handle roads.
>
> The other thing is I'm wondering for the same roughly the same price and ah durability why you're are not looking at something like one of these all-terrain vehicles…Yeah the ATV kind of thing would be more stable for the rider I mean that not the present task.

Discussion

Both experts and novices used various types of heuristics in their ideation. What was different, however, is that novices used more local heuristics than experts. These were noticeable in the solution space as they explored the problem and solution spaces, referred to in this study as the overlapping space. The novices focused on making adjustments to the existing design problem based on specifications given in the design brief, using mainly local heuristics to improve the form of certain subcomponents of the vehicle. Comparatively, the experts used more transitional heuristics as they navigated the solution space, focusing on improving both the function and form of the design through the substitution of new concepts.

Studies in design cognition show "that successful ideation involves exploring the problem and solution spaces simultaneously [(Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996)]" (Gray, Seifert, Yilmaz, Daly, & Gonzalez, 2016, p. 1350), and "design thinking often involves analogy to past solutions, or precedents, that can be usefully applied in future work [(Cross, 2004; Hofstadter & Sander, 2013; Kolodner, 1993; Lawson & Dorst, 2009)]" (Gray et al., 2016, pp. 1350–1351; see also Cross, 2007; Dorst & Cross, 2001; Maher, Poon, & Boulanger 1996). Experienced designers possess a vast knowledge of particular precedents, and they also carry with them a conceptual repertoire that they are able to apply to design problems. According to Gray, Seifert, Yilmaz, Daly, and Gonzalez (2016), "this *conceptual repertoire* represents a collection of intermediate-level knowledge [or design heuristics] that is built on experiential precedents, containing successful patterns of design reasoning that, in their formation and use, assist the designer in creating new design concepts" (p. 1351). This repertoire of experiential precedent would explain why experts would focus on function and form concurrently in their ideation as they search for a solution.

Novices' usage of heuristics, even at a greater rate than the experts, as was the case in this study, indicates that they do possess knowledge of particular precedents and have a conceptual repertoire. This, however, is limited by the extent and quality of their experience in designing, and thus may constrain their ability to use heuristics to focus on both function and form simultaneously. It is interesting that, overall, the general ideas presented by both experts and novices were not vastly different. They both focused on (a) stabilizing the vehicle by adjusting the center of mass and certain components on the vehicle, (b) increasing the load carrying capacity of the vehicle, (c) using a three wheel configuration for stability, and (d) using an ATV analogy type design. The experts, however, spent less time generating solutions than the novices. The heuristics used by both groups led to similar solutions.

Gray et al. (2016) purported that ideation quality can improve when designers are exposed to design heuristics that may have a bearing on their conceptual design. For example, using heuristic cards has been shown to scaffold the metacognitive development of both early design students and experienced designers and to facilitate the generation of novel concepts (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Yilmaz, Daly, Christian, Seifert, & Gonzalez, 2014). Therefore, using design cards as an instructional strategy in the teaching of engineering design, and more specifically for prompting and scaffolding during the idea generation phase, can help students generate creative and innovative solutions.

Gray et al. (2016) also argued that “some forms of design education are predicated on the knowledge of canon first, only allowing the implementation of variation later in the learning experience (e.g., copying successful designs before creating ones’ [*sic*] own)” (p. 1353). “Educational approaches to teaching design thinking in other design disciplines (e.g., architecture, industrial design) have focused primarily on the learner’s exposure to precedent examples—or ultimate particulars . . . [(Nelson & Stolterman, 2012)]—to build this repertoire . . . [(Lawson, 2004)]. The traditional studio educational experience pioneered in design education centuries ago follows this pattern, with an explicit focus on learning a relatively well-defined canon of examples . . . [(e.g., Pasman, 2003)]” (Gray et al., 2016, p. 1353). The searching for a solution stage of the design process used in high school curriculum also expose students, to some extent, to precedent examples. However, Gray et al. (2016) “propos[ed] that *Design Heuristics* offer a conceptual bridge between design theories and the individual design precedents often provided to learners, forming a body of intermediate-level knowledge that is valuable in engineering design education and practice” (p. 1354). Using design heuristics as an instructional technique may help “to enhance the elaboration of ideas, as well as facilitate more attention to particular components of concepts [(Christian, Daly, Yilmaz, Seifert, & Gonzalez, 2012)],” and “support the development of practical and functional ideas across diverse design problem contexts [(Kramer, Daly, Yilmaz, & Seifert, 2014; Kramer, Daly, Yilmaz, Seifert, & Gonzalez, 2015)]” (Daly et al., 2016, p. 3).

Conclusion

The teaching of design heuristics should be among the instructional strategies used in engineering and technology education. It is obvious that engineering college students will acquire a repertoire of heuristics through engineering design content, experience through the designing and the making of artifacts, and exposure to precedent examples. Students, like professional engineers, often become fixated on a single concept early in the design process, failing to consider a variety of design solutions (Cross, 2001; Jansson & Smith, 1991). The deliberate teaching of design heuristics, however, along with other strategies, will help in the development of the generative skills of students, stimulating more creative and innovative designs. Several design heuristics that have been empirically validated (see Daly, Christian, et al., 2012; Daly, Yilmaz, et al., 2012) can be used in the classroom to teach design problem solving. Gray et al. (2016) recommend that: (a) instructors develop students' knowledge of design heuristics as they work on organic idea generation, (b) instructors and students relate design heuristics to design artifacts being generated, and (c) students are allowed to transfer design heuristics to new concepts in different context.

The strategies recommended to teach design heuristics to college students can equally be applied to high school students who are doing engineering design. Selected design heuristics from the list of validated heuristics that are deemed to be grade-level appropriate can be introduced in the high school curriculum to provide the cognitive prompt and scaffold that students will need to generate creative and innovative ideas as they conceptualize design solutions.

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