# Considering people: An exploratory investigation of engineering student ideation

**Ms. Laura R Murphy, University of Michigan**

Laura is a PhD pre-candidate in Design Science at the University of Michigan, Ann Arbor. Her work explores ways to make design processes more empathetic and inclusive so that design outcomes across industries are more inclusive. Her background is in disability design, manufacturing and supply chain, and front-end design research.

**Dr. Shanna R. Daly, University of Michigan**

Shanna Daly is an Assistant Professor in Mechanical Engineering at the University of Michigan. She has a B.E. in Chemical Engineering from the University of Dayton (2003) and a Ph.D. in Engineering Education from Purdue University (2008). Her research focuses on strategies for design innovations through divergent and convergent thinking as well as through deep needs and community assessments using design ethnography, and translating those strategies to design tools and education. She teaches design and entrepreneurship courses at the undergraduate and graduate levels, focusing on front-end design processes.

**Dr. Colleen M. Seifert, University of Michigan**

Colleen M. Seifert is an Arthur F. Thurnau Professor in the Department of Psychology at the University of Michigan. She received her Ph.D. in Cognitive Science and psychology at Yale University. She was an ASEE postdoctoral fellow at the University of California – San Diego and the Navy Personnel Research Development Center. Her research interests center on learning, memory, and creativity.

**Eytan Adar, University of Michigan**

Eytan Adar is an Associate Professor in the School of Information and in Computer Science & Engineering. His research is at the intersection of human computer interaction (HCI), visualization, and large-scale data mining of human behavior. Professor Adar received his PhD in Computer Science from the University of Washington. He worked at Xerox PARC and HP Labs as well as helping launch a startup on personalized search.

**Sophia Brueckner, University of Michigan**

Sophia Brueckner is a futurist artist/designer/engineer. Inseparable from computers since the age of two, she believes she is a cyborg. As an engineer at Google, she designed and built products used by millions. At RISD and the MIT Media Lab, she researched the simultaneously empowering and controlling nature of technology with a focus on haptics and social interfaces. Her work has been featured internationally by Artforum, SIGGRAPH, The Atlantic, Wired, the Peabody Essex Museum, Portugal's National Museum of Contemporary Art, and more. Brueckner is the founder and creative director of Tomorrownaut, a creative studio focusing on speculative futures and sci-fi-inspired prototypes. She is currently an artist-in-residence at Nokia Bell Labs and an assistant professor at the University of Michigan teaching Sci-Fi Prototyping, a course combining sci-fi, prototyping, and ethics. Her ongoing objective is to combine her background in art, design, and engineering to inspire a more positive future.

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University of Michigan, Ann Arbor, MI, USA

## Abstract

Human-centered design is a prominent approach to engineering design. However, research has documented multiple engineering student challenges in considering the people who will use their designs. To investigate ways to support the consideration of users during early ideation, we conducted an intervention study that specifically asked engineering students to represent people in their concept sketches. This exploratory study asked engineering students to follow a "think aloud" protocol during early idea generation. First, students generated ideas in the form of labelled concept sketches. Then, we intervened by asking students to generate more ideas that include representations of people in their concept sketches. Finally, we interviewed students about each of their concepts to see how they had considered people in their designs. Through a single case analysis, we present the study methodology and intervention, and illustrate potential findings. For this case, the intervention led to a change in the sketches as well as in how the student was talking about people who would use the designs. This case study suggests that a change to instructions during conceptual sketching—requiring representations of people—may foster engineering students' engagement in human-centered design practices.

## Introduction

Human-centered design (HCD) requires a deep understanding of people in the design context [1]–[3]; however, research documents that engineering students have struggled to consider the people who will use their designs [4]–[9]. Empathy is a key mindset in human-centered design in order to effectively understand people's experiences and incorporate them into design decisions [10]–[12]. Empathy requires more than knowing about the user; further, the designer has to relate to the user and understand their feelings, experiences, and perspectives [13]. While studies have demonstrated that engagement with users can help engineering students to incorporate user context into their designs (e.g., [14], [15]), and co-creation approaches engage users during ideation ([16], [17]), limited research has explored strategies to support keeping the user in mind during ideation that happens independently.

The freehand sketch has traditionally been seen as the primary conceptual tool during early concept generation [18]. Sketching is important because it allows the visual expression of imaginative ideas, iterations through trial and error, and a playful, "what if?" consideration of alternative designs [19]. Hand sketching skills remain an important part of design practice, and are "an essential asset for brainstorming and other ideation activities" [20]. While sketching can support successful ideation ([21], [22]), sketching with regard to the principles of HCD has

received little attention in the literature. Designs are formed—and informed—by sketching, yet there is little support available to encourage engineering designers to maintain a focus on people within those sketches.

In this paper, we describe in depth one case of an engineering student who participated in a design protocol aimed at exploring relationships between sketching in idea generation and the consideration of potential human users. We asked the engineering student to sketch design ideas, without and then with the prompt to include people in the created design concepts. Our goal is to develop ways of scaffolding engineers' consideration of human users during conceptual design. We hope this will support more varied perspectives on human variability and diversity.

**Background**

There are multiple design philosophies focusing on people, such as human-centered design (HCD) [11], user-centered design (UCD) [23], and inclusive design [24]. How engineers consider people while designing is relevant to all people-focused design philosophies. User-centered design focuses on how people engage in direct interaction with physical objects including computer systems [23]. Human-centered design incorporates a larger contextual understanding beyond an individual user to the sociocultural context of use [3], [11]. Inclusive design supports considering human diversity and designing for the largest range of people [24]. However, a recent review of user-centered design strategies does not report sketches or other visual representations of the human user [25]. For example, in two studies of engineering students creating inclusive designs, visual representations and sketching were not described as part of their design process [26], [27]. While these design philosophies emphasize thinking about humans as the focus of design [12], there is little guidance available about *how* to consider humans in concepts during early idea generation.

In engineering and product design, sketching serves as a conceptual tool in forming early ideas [18]. Previous studies show design thinking is heavily dependent upon visual representations of physical objects [28]. Furthermore, designers' interpretations and uses of objects depend heavily on this representation activity [29], [30]. In fact, studies show that engineers depend on physical objects as a means of communicating and thinking through designs [29]. Do (2002) suggested sketches and the reactions to them are potentially important to the reasoning process in design [31].

Additionally, engineering designers have been shown to discover new properties and relations emerging from their own sketches (e.g., [32]–[36]). Actively reconfiguring sketches and finding new meanings in them promotes forming new design ideas [37]. Goldschmidt (2003) identified this function as the "backtalk" [36] of interpretations formed through sketches in progress, helping engineers in generating and strengthening their ideas [38]. As Barbara Tversky (2002) noted, "Sketches are a useful tool for checking and conveying ideas, for self and others. They also serve as an external display to facilitate inference and discovery, to go from the intended to the unintended, to go from the seen to the unseen [39]."

In practice, hand sketching skills are an important part of engineering and product design, aiding discussions in meetings and in idea generation [20], [40]. Studies show that the frequency and activity in sketching supports successful design outcomes [41] and guidebooks for sketching

skills ([40], [42]) are available; in fact, the quality of the sketches was not found to be a factor. Further, a series of studies have shown that sketching frequency can be improved through interventions affecting motivation, learning, and use of technology [43]. In one of their studies, students were required to produce sketches, and this increased students' reporting of sketching as important in design [43]. In a study of training and art interventions, engineering students given practical training on basic sketching showed improvement in the short term, but needed reinforcement for longer-term improvement [44]. These studies suggest engineering students can benefit from training on sketching, and it need not be an impediment during the design process.

In psychology, sketching and drawing has long been thought to reflect how individuals think. Children's sketches of human figures (the Draw-A-Person Test) have been considered to reflect their developing intelligence [45], [46]. Cognitive milestones have been tied to features reflecting the complexity of spontaneous drawings, with older children including articulated parts such as fingers [47]. Research has also identified drawing as a cognitive aid, showing it is helpful in organizing and remembering information [48]. Because sketches reveal designers' thinking [49], we reason that designers' mindset about HCD may be similarly evident in their sketches.

## Method

*Research Goal*

The goal of our research was to explore the relationship between sketching in idea generation and the consideration of potential human users. Specifically, we asked:

- How, if at all, are human users represented in engineering students' concepts, and how does that representation reveal and influence students' envisioning of potential concepts?
- What happens to concepts -- and engineering students' perceptions of their concepts -- when students are asked to represent the users of their ideas within their sketches?

We hypothesized that conceptual sketches that include representations of people would prompt engineering students to more fully consider users of their ideas during idea generation. Through a case example of one engineering student participant, we investigated the impact of an intervention requiring the participant to represent people in their generated concepts.

*Participant*

Volunteers for the study were recruited through an email list of mechanical engineering students at a large midwestern university, and were given a $25 gift card to compensate for their time. For this works-in-progress report, we examine the design study with one senior-level student majoring in Mechanical Engineering. The participant reported he identified as male with Indian ethnicity.

*Procedure*

We conducted the study over one hour following the procedure outlined in Figure 1.

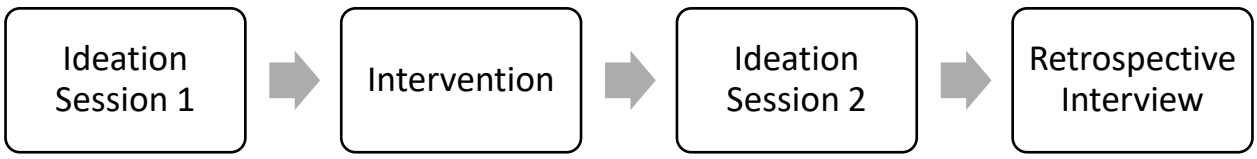


Figure 1: Flow chart of experimental procedure.

We asked the participant to generate design solutions through sketches and thinking aloud. As training, we started the participant with a practice problem ("How many windows are there in your home?"). Once the participant understood the process, we presented the main design problem: the moving scenario (Figure 2).

**Design Problem: Helping people move**

Moving is considered one of the top stressors in life. When people move, they experience multiple challenges. For example:

- lifting heavy furniture
- navigating through small spaces (door frames, corners, narrow hallways, stairs)
- keeping belongings organized
- finding other people to help them move
- continuing living (and even working) while belongings are in transit
- moving in extreme weather (snow, heat, rain)
- and many others…

Imagine you are asked to design for this problem. Considering one or more challenges on moving day, design a way to *help people move households.* Make sure to consider the physical setting in your solution.

Figure 2: Design problem provided to participants.

Then, we instructed the participant to generate as many ideas as possible during two 15-minute sessions. In Ideation Session 1, we collected data about the participant's natural design process. Before Ideation Session 2, we introduced our intervention. We explicitly prompted the participant to represent "people, a person, or parts of a person" in their sketches. We provided several simple example sketches representing people as illustrations. After the participant completed the design tasks, we interviewed the participant to reflect on any changes perceived between the Ideation Sessions 1 and 2 (Figure 3).

Spread out all of your ideas on the table.

1. What was your experience like in the first ideation session vs the second?
2. Can you talk about your approach to generating ideas in the first session vs. the second?
3. How do you think your ideas changed from the first ideation session to the second?

Figure 3: Retrospective interview protocol and questions. We asked additional questions of the participants but these data are not included in the analysis.

A complete description of the Study Protocol, including prompts and questions, is presented in Table 1.

Table 1: Study protocol including script for facilitator.

| ***Step*** | ***Time allocation*** | ***Activity*** | ***Description*** | ***Outputs*** |
|---|---|---|---|---|
| 1 | 3 minutes | Welcome, consent, overview of session | Start audio recording. "Thank you for coming. We really appreciate your participation. In this session, you'll be doing a series of tasks which will take about an hour. To start, I'd like you to read this consent form and sign it at the bottom. If you have any questions, let me know." | Signed consent |

| | | | | |
|---|---|---|---|---|
| 2 | 2 minutes | Review protocol for think-aloud process | "In this study, we are interested in what you think about when you design. So I want you to THINK ALOUD as you work on the design problem. That is, I want you to TELL ME EVERYTHING you are thinking from the time I present the problem until you have finished your answers. Just act as if you are alone in the room speaking to yourself. Most important, keep talking – if you are silent, I will remind you to keep talking. It might feel weird, but we'll practice to get you comfortable with it. Do you understand? Let's try a practice question: How many windows are there in your home? < "please keep talking" > Great job. Let's start!" | Verbal confirmation of understanding |
| 3 | 2 minutes | Read problem aloud | "Read the given problem statement and ensure your understanding of the task." | Brief explanation in their own words |
| 4 | 15 minutes | Talk-aloud design task (1) | "On these sheets of paper, sketch, label, and describe solutions to the problem during the allotted time [15 minutes]. Be sure to draw your ideas, label them, and create a written description. Place each design concept on a new concept sheet. I printed more sheets than you'll likely need, but feel free to use as many as you want. Each concept should be able to stand alone just by looking at it, so include details and text as needed. Please keep working for the whole 15 minutes. Remember to think aloud as you work on this task." | Multiple concepts; audio, and writing recordings |
| 5 | 2 minutes | Introduce intervention | "Now, we would like you to focus on including depictions of people, a person, or parts of a person in your sketches. Here are some examples." | Confirmed understanding of intervention |
| 6 | 15 minutes | Talk-aloud design task (2) with intervention | Direct participants: "On these sheets of paper, sketch, label, and describe solutions to the problem during the allotted time [15 minutes]. Be sure to draw your ideas, label them, and create a written description. Place each design concept on a new concept sheet. I printed more sheets than you'll likely need, but feel free to use as many as you want. Each concept should be able to stand alone just by looking at it, so include details and text as needed. Please keep working for the whole 15 minutes. Remember to think aloud as you work on this task. Remember to include representations of people, person, or parts of a person in your sketches." | Multiple concepts; audio, and writing recordings |

| | | | | |
|---|---|---|---|---|
| 7 | 20 minutes | Retrospective Interview | "We're now finished with the design task and think aloud. Now, I want to ask you some questions about your designs" Discuss answers to questions. Prompt if needed: "in the interest of time we have to move on." | Recording |
| 8 | 1 minute | Thanks and debrief | Stop audio recording. | None |
| Total | 60 minutes | | | |

We used a think-aloud protocol to collect information on the participant's thought process while working on generating ideas. We instructed the participant to say everything he was thinking throughout the study, and if he stopped talking, the researcher prompted to "please keep talking." We used a Livescribe Echo pen to record the participant's writing and drawing on the concepts sheets and to capture audio during the study.

We expected that the intervention—the requirement to "depict people, a person, or parts of a person within conceptual sketches"—would impact both the types of ideas generated by the participant and his perspective of the user of his design ideas.

*Data Analysis*

The researcher took notes during the session documenting observations based on what the participant said in his think-aloud processing. These notes guided analysis of the concept drawings by bringing attention to main differences perceived between the first and second ideation sessions. When evaluating concept drawings, we isolated portions of the think-aloud transcript which corresponded to each drawing. This separation of portions allowed us to compare what the participant documented in the concept drawing and description with how they talked about their design during the session. We evaluated the written and transcribed concept descriptions by identifying references to concept aspects and potential users. We evaluated concept drawings by identifying and comparing main aspects of each idea, similar to Murphy, et al. 2017 [50]. These two analyses allowed us to identify how the participant described users in both their drawings and descriptions for each concept. We also isolated key insights from the participant reflections during the post-task interview capturing the participant's overall perceptions on the differences prompted by the intervention.

**Results**

The participant generated six ideas during the first session. The ideas the participant generated are shown in Figure 3. Concept numbers indicate the ideation session (first or second) and the order in which concepts were generated, i.e. Concept 2-3 is the second ideation session and the third idea within that session.

| Concept Drawing | Written Concept Description |
|---|---|

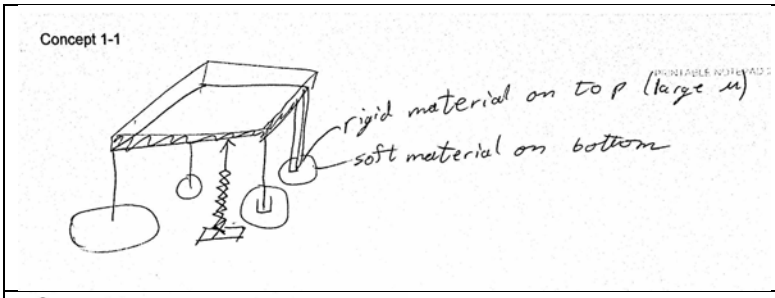
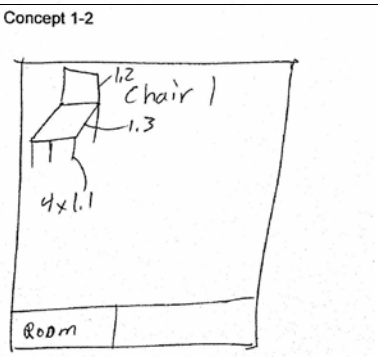
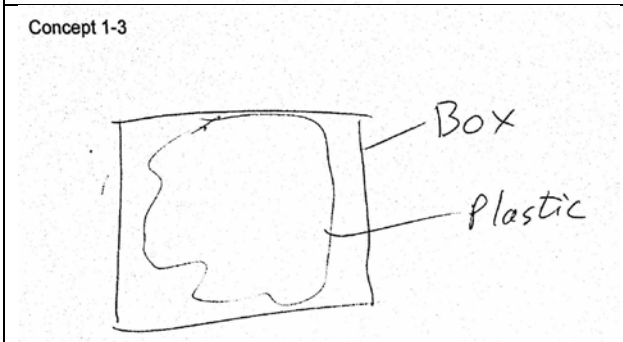
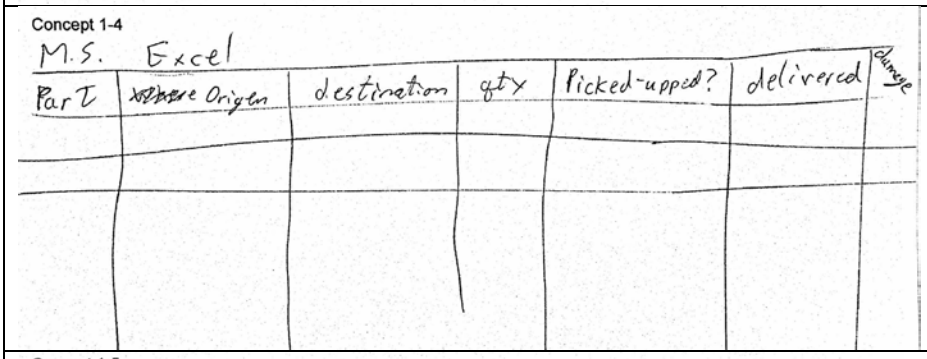
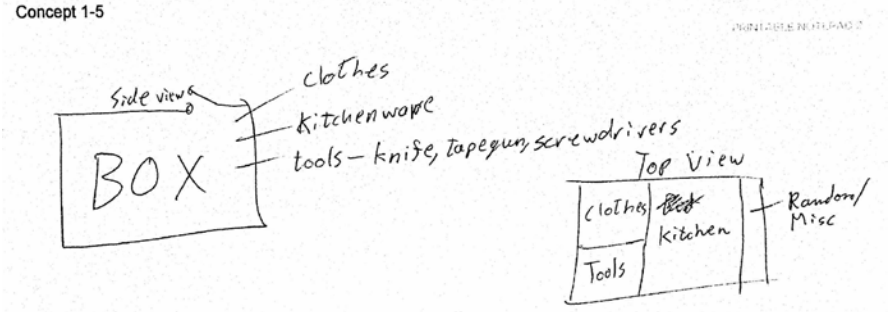
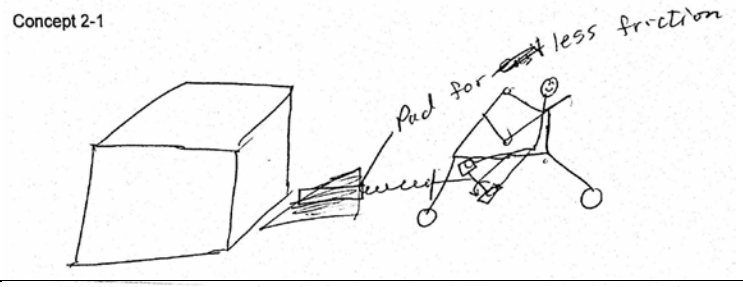
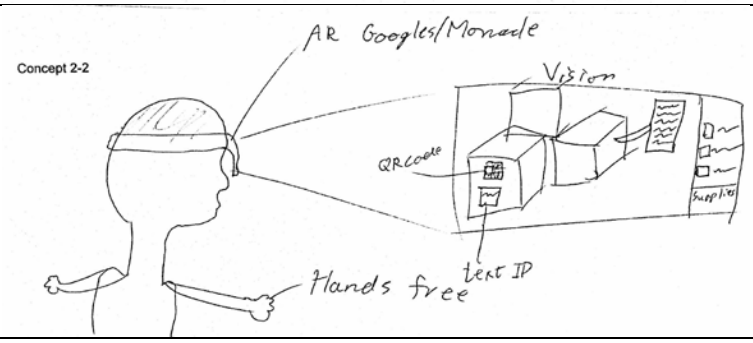
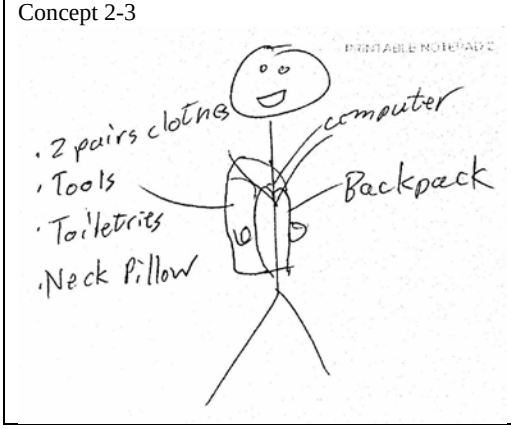
| | |
|---|---|
| Concept 1-1<br>  | Jack to lift furniture off the ground. Pads to slide under table to prevent scratching floors. |
| Concept 1-2<br>  | Furniture parts list to keep parts together. |
| Concept 1-3<br>  | Plastic bag inside box – weather proofing. Pre-manufactured plastic lining – biodegradable. |
| Concept 1-4<br>  | Excel sheet to manage all of the different aspects of moving. |
| Concept 1-5<br>  | An essentials box that you can use to pack all of the last minute items – the last items to be packed but the first to be unpacked. |
| Concept 1-6: [No drawing] | Keeping assembly documents on hand. |

Figure 3: Participant's drawings and descriptions during the first ideation session (before intervention).

In the first ideation session, the participant began by reviewing the design problem prompt and focused primarily on the functional considerations of moving. The participant noted, *"going down on the list, the first big issue is moving stuff that maybe you're not used to moving."* All but one of the ideas were in a similar vein: moving furniture, assembling furniture, packing furniture.

The participant cited materials to use in the concepts like cardboard, plastic, soft sliding fabrics, and biodegradables throughout the session. Citing materials led to a tangent on manufacturing the box (Concept 1-3)*: "Boxes are made from big pieces of cardboard, so it's easy to have maybe coat the entire side of the box and then cut it out rather than put a plastic bag in after making the box."*

Post-intervention, the participant generated four ideas in the second ideation session (Figure 4).

| Concept Drawing | Written Concept Description |
|---|---|
|  | Bike style pedals to push slider under heavy objects and move objects around. |
|  | AR goggles to create a live feed of info to aid in communication of what needs to be done and what has been done. Allows users to see what's inside a box without opening it. |
| Concept 2-3<br>  | Backpack w[ith] labels for everything so user does not have to worry about remember[ing] anything. |

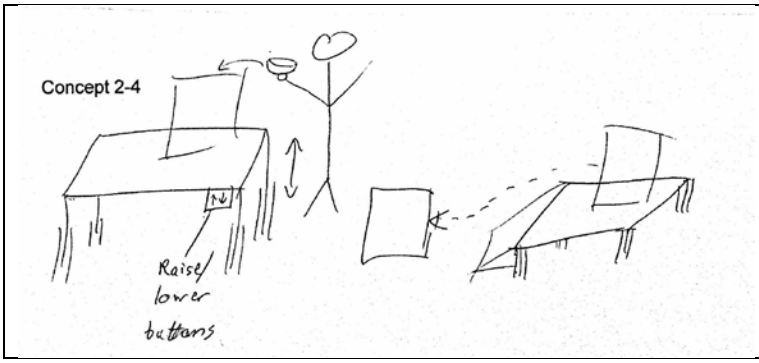
| | |
|---|---|
|  | Table with adjustable height that facilitates packing to alleviate back pack. |

Figure 4: Participant's drawings and descriptions during the second ideation session (with the intervention with an instruction to depict "people, a person, or parts of a person" in each concept).

Post-intervention, there was a noticeable shift in focus towards human needs. Each idea began with the human's physicality, and developed from there. While the participant went back to the initial design problem prompt for inspiration, every idea was related to human capability. Two of the ideas (Concepts 2-2 and 2-3) were wearables, and Concept 2-4 began from mitigating back pain: *"I guess loading stuff into boxes can be a pain because you're doing lot of the same motion and you always want to try and prevent that. So, a lot of bending and at the back."*

The ideas in the second session involved more unique or unusual technology. Concept 2-1 leveraged a bicycle mechanism in a new context of moving heavy objects; Concept 2-2 brought in developing augmented reality (AR) technology: *"And you put a holo lens on that head or some sort of just awesome Tony Stark style AR…"* The "Ironman" movie reference further indicates that these concepts are less obviously realistic.

The ideas specified the user input required for the concept to function, in contrast to the first session. When thinking through Concept 2-2, the participant said: *"You could also make this a tablet, but I think it'd be easier to just have goggles because now you have your hands free when you're packing stuff or moving stuff, it makes that a lot easier."* This reference to the impact of the user's hands being free indicates that the participant was considering the larger context in which this product would be used, rather than developing it as a singular technology.

Concept 2-3 is the first time that the participant discussed the emotional considerations of moving rather than purely the physical demands: *"So, comes in a backpack, with labels for everything so that if you're in a rush, you don't have to worry about forgetting anything. So user does not have to worry about... buying or remembering because high-stress situations, my experience with that, you always forget stuff."* The participant described the purpose of the concept was to help mitigate the emotional toll of moving, an aspect of the design problem not addressed in the first session.

**Discussion**

The intervention for the second session was intended to draw attention to including depictions of people, a person, or parts of a person in design sketches; otherwise, the task of generating ideas for the presented design problem remained the same. The intervention appeared to change the way the participant thought about people when generating ideas. For example, in the second (prompted) session, the participant considered the emotional stress of moving and incorporated

that into his ideas. This observation suggests the intervention may have potential to increase attention to empathy. Because empathy is a key principle in human centered design [3], this greater reference to emotion and context in designs may indicate a desirable outcome. In the second session, the participant appeared to understand their user's feelings, demonstrating they are building empathy for their context and user [13].

These preliminary findings indicate that a simple intervention—adding an instruction to depict people in concept sketches—may prompt engineering students to design outcomes with more user-centered and contextual concerns. Without the requirement to represent people, in this case example, the participant's designs appeared to reflect typical concepts by engineering students in focusing on material selection and manufacturing processes. In contrast, the second session prompted more examination of emotional stresses and the experiential circumstances that might motivate new and different designs. In the second ideation session, the participant considered human traits like emotional stress and back pain that were absent in the first session. The participant did not name a specific demographic or persona for these designs, but they incorporated references to human users in a new way after the intervention.

The think-aloud protocol was helpful in understanding the participant's mindset as he was generating specific ideas, and allowing the pairing of thinking to the sketch. It led to insights on why the participant thought of specific concepts and what he was considering (or not considering) about people as he was generating ideas. The retrospective interview question, "Did this change from design task (1) to design task (2)?" was answered, *"I would pursue an idea in the second half more because I think that they're... it's easier to see how people would use them, which is why you design a product at the end of the day."* This comment suggests value in adding person-representations to sketching. Ideas generated in this context may more easily answer questions like, "Who might use this?" and, "How does it work?" Representations of people may make it easier for an engineer to visualize how those ideas will become a reality for users.

The intent behind the intervention is to encourage student engineers to think more deeply about the people that will ultimately use their ideas. A simple instruction during sketching may not affect engineers' empathetic understanding of users, but may prompt an initial set of questions: "Who is my user? Who is *not* my user? What do I need to know about the user to work on this design?" To answer these questions, the engineer has to further investigate users and their contexts of use, potentially leading to more empathic designs. Other research argues that sketches are essential in brainstorming and ideation [20]; if so, it appears important that key design concerns -- such as centering design on the human – are also thoughtfully embedded in sketching.

As a case study with a single participant, the observations are limited in scope and generalizability. In creating this study protocol, we hope to expand the works-in-progress to consider multiple studies with student engineers. We hope to work with advanced (senior-level) engineering students in order to capture their current thinking about sketching as a design activity and the representation of people in ideas generated. If consistent findings are uncovered across students, this study plan may provide compelling evidence towards curricular needs in both sketching skills and in human-centered design. If changes in considering humans in design

can be motivated by a simple instruction, further studies will be required to examine how to promote such thinking over time during engineering education.

## Conclusion

This works-in-progress study protocol presents a plan for the exploration of considering people in early idea generation for engineering design. Our overarching goal is to develop scaffolding that supports engineering students' human-centered design practices. We are investigating whether a simple intervention to represent people during conceptual sketching will prompt students to consider human users and all their potential variability. To date, we examined a single case to observe whether this intervention changed how the engineering student thought about people during idea generation. Analysis of this first participant demonstrated that the intervention prompted a change, and we need to analyze further participants to further understand the quality of that change and if other participants will experience a cognitive shift. The study protocol provided the observations necessary to understand how students think about people during their design process. Over future sessions, we hope to explore how simple changes in the way students sketch concepts can help them think more deeply about the people who may ultimately use their designs.

## References


[1] E. Sanders, "Design Research in 2006," *Des. Res. Q.*, Sep. 2006.

[2] E. Sanders, "An Evolving Map of Design Practice and Design Research," *Interactions*, pp. 13–17, Dec. 2008.

[3] IDEO, *The Field Guide to Human-Centered Design*. 2015.

[4] C. B. Zoltowski, W. C. Oakes, and M. E. Cardella, "Students' ways of experiencing human-centered design," *J. Eng. Educ.*, vol. 101, no. 1, pp. 28–59, 2012.

[5] I. Mohedas, S. Daly, and K. Sienko, "Design Ethnography in Capstone Design: Investigating Student Use and Perceptions," *Int. J. Eng. Educ.*, vol. 30, no. 4, pp. 888–900, 2014.

[6] R. P. Loweth, S. R. Daly, J. Liu, and K. H. Sienko, "Assessing Needs in a Cross-Cultural Design Project: Student Perspectives and Challenges," *Int. J. Eng. Educ.*, vol. 36, no. 2, pp. 712–731, 2020.

[7] R. P. Loweth, S. R. Daly, K. H. Sienko, A. Hortop, and E. A. Strehl, "Student Designers' Interactions with Users in Capstone Design Projects: A Comparison Across Teams," in *ASEE Annual Conference & Exposition*, 2019.

[8] W. A. Sugar, "What is so good about user-centered design? Documenting the effect of usability sessions on novice software designers," *J. Res. Comput. Educ.*, vol. 33, no. 3, pp. 235–250, 2001.

[9] J. B. Scott, "The practice of usability: Teaching user engagement through service-learning," *Tech. Commun. Q.*, vol. 17, no. 4, pp. 381–412, 2008.

[10] J. L. Hess and N. D. Fila, "The manifestation of empathy within design: findings from a service-learning course," *CoDesign*, vol. 12, no. 1–2, pp. 93–111, 2016.

[11] IDEO, *The Human-Centered Design Toolkit*. 2019.

[12] J. Kramer, A. M. Agogino, and C. Roschuni, "Characterizing Competencies for Human-Centered Design," in *ASME 2016 International Design Engineering Technical Conferences*, 2016.

[13] M. Kouprie and F. Visser, “A framework for empathy in design: stepping into and out of the user’s life,” *J. Eng. Des.*, vol. 20, no. 5, pp. 437–448, Oct. 2009.
[14] H. van Rijn, F. Sleeswijk Visser, P. J. Stappers, and A. D. Ozakar, “Achieving empathy with users: the effects of different sources of information,” *CoDesign*, vol. 7, no. 2, pp. 65–77, Jun. 2011.
[15] J. Lai, T. Honda, and M. C. Yang, “A study of the role of user-centered design methods in design team projects,” *AI EDAM*, vol. 24, no. 3, pp. 303–316, 2010.
[16] E. B.-N. Sanders and P. J. Stappers, “Co-creation and the new landscapes of design,” *CoDesign*, vol. 4, no. 1, pp. 5–18, Mar. 2008, doi: 10.1080/15710880701875068.
[17] F. T. Piller, C. Ihl, and A. Vossen, “A typology of customer co-creation in the innovation process,” *Available SSRN 1732127*, 2010.
[18] D. G. Ullman, S. Wood, and D. Craig, “The importance of drawing in the mechanical design process,” *Comput. Graph.*, vol. 14, pp. 263–274, 1990.
[19] A. T. Purcell and J. S. Gero, “Drawings and the design process: A review of protocol studies in design and other disiplines and related research in cognitive psychology.,” *Des. Stud.*, vol. 19, no. 4, pp. 389–430, 1998.
[20] D. A. Robb, P. R. N. Childs, and H. Flora, “Sketching to solid modelling skills for mechanical engineers,” presented at the International Conference on Engineering and Product Design Education, Brighton, U.K., 2009, vol. 234.
[21] R. Van der Lugt, “How sketching can affect the idea generation process in design group meetings,” *Des. Stud.*, vol. 26, no. 2, pp. 101–122, 2005.
[22] G. Goldschmidt, “Modeling the role of sketching in design idea generation,” in *An anthology of theories and models of design*, Springer London, 2014, pp. 433–450.
[23] D. A. Norman and S. W. Draper, *User centered system design: New perspectives on human-computer interaction.* CRC Press, 1986.
[24] A. Shum *et al.*, “Inclusive Design Toolkit,” Microsoft Design, 2016.
[25] A. R. Dopp, K. E. Parisi, S. A. Munson, and A. R. Lyon, “A glossary of user-centered design strategies for implementation experts.,” *Transl. Behav. Med.*, vol. 9, no. 6, pp. 1057–1064, 2019.
[26] I. C. Landa-Avila and C. Aceves-Gonzalez, “Inclusive Human-Centered Design: Experiences and Challenges to Teaching Design Engineering Students.,” in *Advances in Intelligent Systems and Computing*, 2019, vol. 824.
[27] H. Dong, “Strategies for teaching inclusive design,” *J. Eng. Des.*, vol. 21, no. 2–3, pp. 237–251, 2010, doi: 10.1080/09544820903262330.
[28] J. S. Linsey, E. F. Clauss, T. Kurtoglu, J. T. Murphy, K. L. Wood, and A. B. Markman, “An Experimental Study of Group Idea Generation Techniques: Understanding the Roles of Idea Representation and Viewing Methods,” *J. Mech. Des.*, vol. 133, no. 3, pp. 031008-031008–15, Mar. 2011, doi: 10.1115/1.4003498.
[29] M. Brereton and B. McGarry, “An observational study of how objects support engineering design thinking and communication: implications for the design of tangible media.,” in *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, ACM, 2000, pp. 217–224.
[30] M. Chamorro-Koc, V. Popovic, and M. Emmison, “Human experience and product usability: Principles to assist the design of user–product interactions.,” *Appl. Ergon.*, vol. 40, no. 4, pp. 648–656, 2009.

[31] E. Y.-L. Do, “Drawing marks, acts, and reacts, toward a computational sketching interface for architectural design.,” *Artif. Intell. Eng. Des. Anal. Manuf.*, vol. 16, no. 3, pp. 149–171, 2002.
[32] V. Goel, *Sketches of Thought*. Cambridge, MA: MIT Press, 1995.
[33] G. Goldschmidt, “On visual design thinking: The vis kids of architecture,” *Des. Stud.*, no. 15, pp. 158–174, 1994.
[34] D. A. Schon and G. Wiggins, “Kinds of seeing and their function in designing,” *Des. Stud.*, vol. 13, no. 2, pp. 135–56, 1992.
[35] M. Suwa, B. Tversky, J. Gero, and T. Purcell, “Seeing into sketches: Regrouping parts encourages new interpretations,” in *J.S. Gero, B. Tversky, and T. Purcell (eds), Visual and Spatial Reasoning in Design II*, University of Sydney, Australia: Key Centre of Design Computing and Cognition, 2001, pp. 207–219.
[36] D. A. Schön, *The reflective practitioner: How professionals think in action*. Washington, D.C: Basic Books, 1983.
[37] B. L. Tversky and M. Suwa, “Thinking with sketches,” in *A.B. Markman and K.L. Wood (eds). Tools for Innovation: The Science Behind the Practical Methods That Drive New Ideas*, Oxford: Oxford University Press, 2009.
[38] G. Goldschmidt, “The Backtalk of Self-Generated Sketches,” *Des. Stud.*, vol. 19, no. 1, pp. 72–88, 2003.
[39] B. Tversky, “What do sketches say about thinking,” in *2002 AAAI Spring Symposium*, Stanford University, AAAI Technical Report SS-02-08, Mar. 2002, pp. 148–151.
[40] B. Buxton, *Sketching User Experiences: Getting the Design Right and the Right Design*. New York: Morgan Kaufman, 2007.
[41] M. C. Yang, “Observations on concept generation and sketching in engineering design.,” *Res. Eng. Des.*, vol. 20, no. 1, pp. 1–11, 2009.
[42] S. Greenberg, S. Carpendale, and N. Marquardt, *Sketching User Experiences: The Workbook*. New York: Elsevier, 2011.
[43] L. C. Schmidt, N. V. Hernandez, and A. L. Ruocco, “Research on encouraging sketching in engineering design,” *AI EDAM*, vol. 26, no. 3, pp. 303–315, 2012.
[44] J. W. Booth, E. A. Taborda, K. Ramani, and T. Reid, “Interventions for teaching sketching skills and reducing inhibition for novice engineering designers,” *Des. Stud.*, no. 43, pp. 1–23, 2016.
[45] F. Goodenough, *Measurement of intelligence by drawings*. New York, NY: World Book, 1926.
[46] J. J. Goodnow, *Children drawing*. Cambridge, MA: Harvard University Press, 1977.
[47] E. Strommen, “The Goodenough-Harris Draw-A-Person Test and drawing development,” *Vis. Arts Res.*, vol. 13, no. 2, pp. 22–28, Fall 1987.
[48] M. A. Fernandes, J. D. Wammes, and M. E. Meade, “The surprisingly powerful influence of drawing on memory,” *Curr. Dir. Psychol. Sci.*, vol. 27, no. 5, pp. 302–308, 2018, doi: 10.1177/0963721418755385.
[49] Tversky, B., “What does drawing reveal about thinking?,” in *J.S. Gero and B. Tversky (eds) Visual and spatial reasoning in design*, Sydney, Australia: Key Centre of Design Computing and Cognition, 1999, pp. 93–101.
[50] L. R. Murphy, S. R. Daly, S. Yilmaz, and C. M. Seifert, “Supporting Novice Engineers in Idea Generation using Design Heuristics,” in *ASEE Annual Conference & Exposition*, Jun. 2017.