Examining the Influence of an Ill- and Well-defined Problems in a First-Year Engineering Design Course

Ms. Jessica E S Swenson, Tufts Center for Engineering Education and Outreach

Jessica Swenson is a graduate student at Tufts University. She is currently pursuing a Ph.D. in mechanical engineering with a research focus on engineering education. She received a M.S. from Tufts University in science, technology, engineering and math education and a B.S. from Northwestern University in mechanical engineering. Her current research involves examining different types of homework problems in mechanical engineering coursework and the design process of undergraduate students in project-based courses.

Marya H Schnedeker, Center for Engineering Education and Outreach, Tufts University

Marya Schnedeker is a M.S. student at Tufts University in Human Factors Engineering. Her research focus is instructional design. She is currently researching methods of training novice users on CAD software and 3D printers.

Sarah Marie Coppola, Tufts Center for Engineering Education and Outreach

Sarah Coppola is a graduate student in Human Factors Engineering at Tufts University. Prior to attending Tufts, Sarah worked as a reliability engineer and completed an AmeriCorps service year teaching in an engineering magnet high school in Paterson, NJ. She draws upon her diverse interests in design, teaching, and social justice in her research work in physical ergonomics and engineering education at the Center for Engineering Education and Outreach (CEEO). Sarah earned a Bachelor's Degree in Mechanical Engineering and Engineering Design from Northwestern University.

Mr. Leonardo Andres Madariaga, Tufts Center for Engineering Education and Outreach / Tufts University Center for Engineering Education and Outreach / Federico Santa Maria Technical University

Leonardo Madariaga is a graduate student in the Center for Engineering Education and Outreach (CEEO) at Tufts University in Medford, MA. He graduated as a Product Design Engineer in 2006 from Federico Santa Maria Technical University (UTFSM) in Chile. Currently he is a M.S. student in Human Factors Engineering at Tufts. His primary interest is the generation of physical and digital environments that can foster design and creativity in engineering education. He has seven years of experience in teaching engineering undergraduates design methods and guiding them in project based courses at UTFSM in Chile, where he also worked as a product innovation consultant for several small companies.

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Many first-year programs begin with a course that includes one or a few projects to excite and engage students in engineering. These projects vary from real world clients based[1] to socially relevant discipline based[2] to design-build-test-compete[3] to robotics based challenges[4]. Each of these courses contain various learning goals including the engineering design process, communication skills, teamwork, use of analytical tools, learning programming languages, and introducing students to different engineering topics.

In many engineering courses, there has been a move to give students open-ended, undefined problems. Some argue more open-ended problems are needed in the undergraduate curriculum to prepare students for the types of problems they will encounter in the workplace[5]. However, literature on design has found beginning designers treat these problems as well-defined, straight forward problems and rarely come up with multiple solutions before deciding and building[6]. From our own work, we have seen students struggle with open ended problems, spending hours on a design idea they were not required to produce and do not have enough resources to complete[7]. Noticing this conflict, we decided to further examine the effect of definedness of problem had on student work. This paper examines the differences in students' user needs and product specifications as part of their design solution when given different levels of problem definition.

Literature Review

We have been exploring and analyzing first-year students' design processes as they work on different open-ended, ill-defined design challenges[7,8,9]. A previous study[8] examining students completing short in-class design competition found students' design practices are contextually dependent. The work also suggests it may be beneficial for students to tackle problems that vary in "style, scope and size" and each focus on building different design skills. Another study[7] examined students completing a week long design challenge and found students were prone to idea fixation and spending a significant portion of time on design ideas they did not have the "skills, resources or tools to efficiently implement." This work suggests that instead of assigning students a completely open-ended and ill-defined challenge, creating authentic design activities requiring students to balance sets of criteria provide a better context for engineering design learning. These studies have led us to question the affordances that different levels of criteria have on student design work.

A number of studies have examined beginning, novice and expert design practices. Crismond & Adams[6] provide a comprehensive overview of the literature on design behaviors of beginners and experts. They conclude beginning engineers typically "treat a design task as a well-defined, straightforward problem" (p.748) and rarely conduct research before deciding on and building a solution. Additionally, beginners rarely weigh options when making design decisions and spend little time evaluating their concepts.

Atman and colleagues completed a series of studies with freshmen and senior students as well as expert engineers where all three groups were asked to solve open-ended, ill-defined conceptual problems. In the first study with only freshmen and seniors[10], Atman et. al. found seniors spent a greater portion of time on problem scoping compared to freshmen. This more thorough approach led to better quality solutions. Freshmen who paid more attention to the design realization steps had better quality designs. In a follow up study, Atman et. al.[11] observed students solve two shorter design problems. Similar to previous studies, this study concluded student design practices are contextually dependent. Specifically, "some freshmen 'get stuck' defining the problem rather than moving on to the developing alternative solutions and project realization stages" (p. 351). The last study[12] compared these same students' design practices to those of expert engineers. The study found the experts spent more time problem solving than the students, and with the greatest difference in time was during the problem scoping phase.

Freshman students, as beginning designers, spend little time on problem scoping and treat open-ended design problems as straight forward, well-defined problems. As such, they spend less time problem solving than novice or expert designers. Yet, students' design practices are contextually dependent. From Atman et.al.'s previous research and our own experience studying students at Tufts, we wonder whether giving beginning designers ill-defined, open-ended problems is the best practice. The following data is the first small investigation into understanding this question.

Methods

"Designing Stuff People Can Use" is one of nine first-year introductory courses offered at Tufts University. While first-year courses with a focus on creativity and excitement of engineering have been offered at Tufts University for the past ten years, Fall 2014 was the first semester this course was offered. This course was designed to introduce students to a number of human factors engineering topics and taught by a faculty member from the Human Factors Department.

Human factors is defined at "the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and other methods to design in order to optimize human well-being and overall system performance”[13] The advancement of technology in terms of functionality and interconnectivity has a profound effect on human-technology interaction. The effect is a broad and concerns operators, maintainers or users. Human factors engineering seeks to achieve improved levels of effectiveness, safety and ease of performance. The design of such complex system interaction requires human factors professionals operate across disciplinary boundaries to collaborate with other engineers at many levels, including understanding user needs in early product development stages and developing test settings to study user performance.

The major topics covered in the course are the design process, prototyping, engineering ethics, human computer interaction, usability, and ergonomics. For each major topic, the students were asked to write a paper, complete a project, or take a quiz. Students were also given brief introductions to a number of tools such as TinkerCAD, SOLIDWORKS, anthropometry tables, LEGO MINDSTORMS NXT, and Axure which they used to complete different aspects of their projects. Projects were always completed in groups of two and three. Students were given class time to work on their projects and had the option of working on them outside of class.

The participants in the class were all first-year engineering students. Students enrolled in the course with a variety of intended majors. The gender demographic was relatively evenly split with 19 males and 17 females.

The project examined in the following data is the “Designing Wearable Gadgets” assignment. This was the second in-class project completed, and the first design project. Students worked in groups of two or three over two class periods to complete a conceptual design. Each group was assigned one of four different prompts, and were unaware that other groups were assigned different design challenge prompts. At the end of the project, each group presented their device to the class.

The first level prompt (prompt level 1) contained the least restrictive criteria. This prompt gave the students the following design objective: “Design a wearable device for helping older adults track their personal physical activity during the day, including fitness-related movement.” Each of the following three prompts added more details further restricting the problem. The complete breakdown of the information in each level is given in Table [1] below.

Table [1]: Prompt levels

Prompt Level	
1, 2, 3, 4	Helping older adults
1, 2	Track their personal physical activity during the day, including fitness-related movement
2, 3, 4	Between the ages of 70 and 75
3, 4	Track their personal physical activity during the day, including aerobic exercise
3, 4	The device should be very lightweight
3, 4	[the device should be] unobtrusive
3, 4	[the device should be] interact with social media
4	Older women
4	Wearable around their ankles

In their conceptual design, students were asked to develop five specific deliverables:

1) An overall product description including functionality
2) List of user needs
3) List of product specifications (including materials)
4) 3-D solid model drawing(s) of the product and documentation of dimensions
5) A user evaluation plan
    a) Test for effectiveness
    b) Test for efficiency
    c) Test for satisfaction

Data Collection

Six groups of students consented to participate in this study. Students were required to post all deliverables on Interactive Learning and Collaboration Environment (InterLACE).[14] For the purposes of this study, only two deliverables were examined: list of user needs and list of product specifications (including materials).

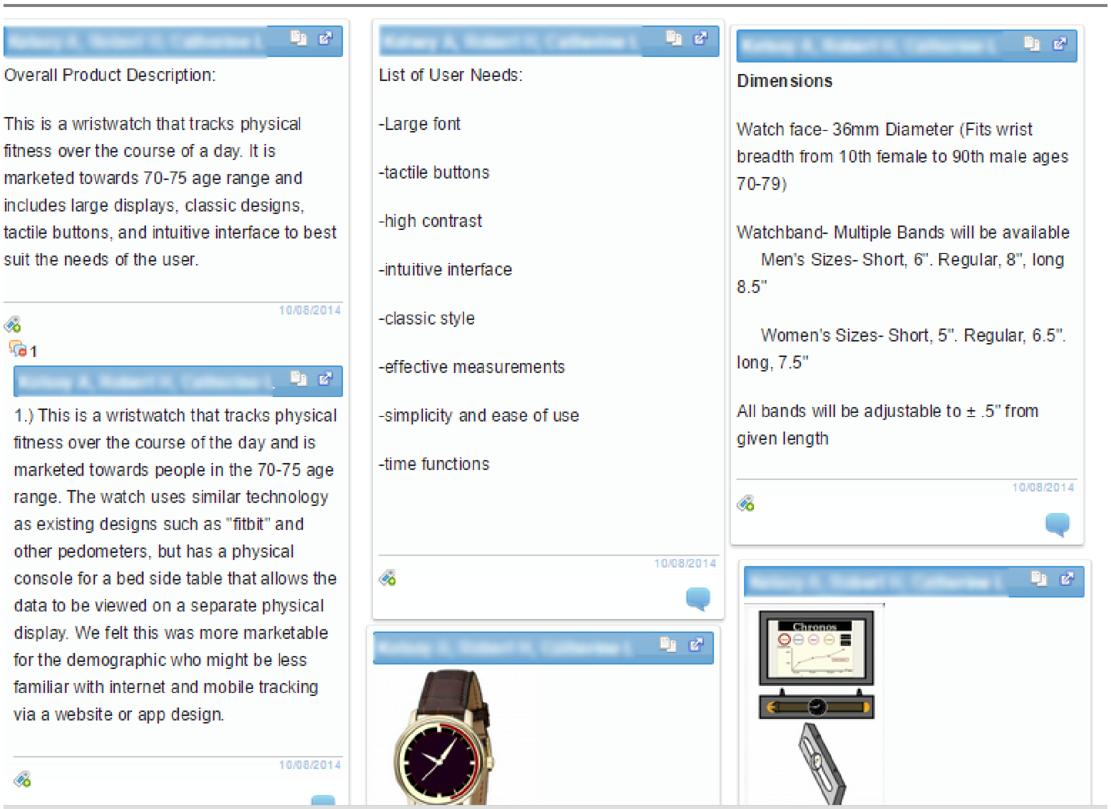

Figure [1]: Example of InterLACE post

Coding Scheme

The goal of this study is to investigate the effects of different prompt levels (design restrictions or requirements) on the students' work. Specifically, did the students implement a design idea to fulfill each given criteria within the prompt? For each criteria, how specific were the students' design ideas?

To answer these questions we developed two coding schemes to categorize and rate each user need and specification. The criteria within the prompt was assigned a letter which was used to categorize the data. The breakdown can be found in Table [2] below.

Table [2]: Coding scheme related to categorization of student work

Category		Prompt level
A	Helping older adults	1, 2, 3, 4
B	Track their personal physical activity during the day, including fitness-related movement	1, 2
C	Between the ages of 70 and 75	2, 3, 4
D	Track their personal physical activity during the day, including aerobic exercise	3, 4
E	The device should be very lightweight	3, 4
F	[The device should be] unobtrusive	3, 4
G	[The device should] interact with social media	3, 4
H	Older women	4
I	Wearable around their ankles	4
X	User need and specification is not a part of assignment criteria	No prompt level

The rating scheme was developed to measure the depth of each user need or specification. An important skill of a human factors engineer is to effectively communicate ideas to a client. Each user need or specification should be clear to the client and justified with supporting data. For example, a commonly used specification in human factors and design is 'easy to use.' Yet, designing something easy to use for a three year old compared to an eighty five year old entails very different design specifications. Devices designed for three year olds might involve very little text and no small pieces that could become choking hazards. Devices designed for eighty-five year olds might need to involve low dexterity and large text. The table below describes the different rating levels with rating 1 - general (non-specific); rating 2 - specific; and rating 3 - specific and with justification.

Table [3]: Coding scheme related to rating of students´ work

Rating	Description	Example
1	A general user need or specification	“Ease of use”
2	A user need or specification for a specific purpose (e.g. measurement, material type, angle)	"User requires the ability to view and navigate information on a separate, larger screen"
3	A user need or specification for a specific purpose with justification	"Watch face - 36mm diameter (fits wrist breadth from 10th female to 90th male age 70-79)"

Data Analysis

Together the researchers coded every user need and specification with a criteria category (A-X) and depth rating (1 - 3) for group 1. The other groups were coded individually by each researcher and then all ratings were reviewed. Any rating disagreements were discussed by the researchers until consensus was reached. The results from the coding scheme are in the following sections. Two of the six groups that consented had been assigned prompt level 2. This prompt level provided students with criteria A - C in Table [2]. The other four groups had been assigned to prompt level 3 and given criteria A and C - G in Table [2] . The data from these groups was analyzed to discover the effect of different criteria of an ill-defined (prompt level 2) and well-defined (prompt level 3) problem on student work.

Results

The number of user needs and specifications for each criteria category was tallied by group. Figures [2] and [3] separate the data by prompt level. The number of criteria met by each group varied. The prompt level 2 groups had user needs and specifications that met one or two criteria categories out of three possible. The prompt level 3 groups varied from one to four criteria categories out of six.

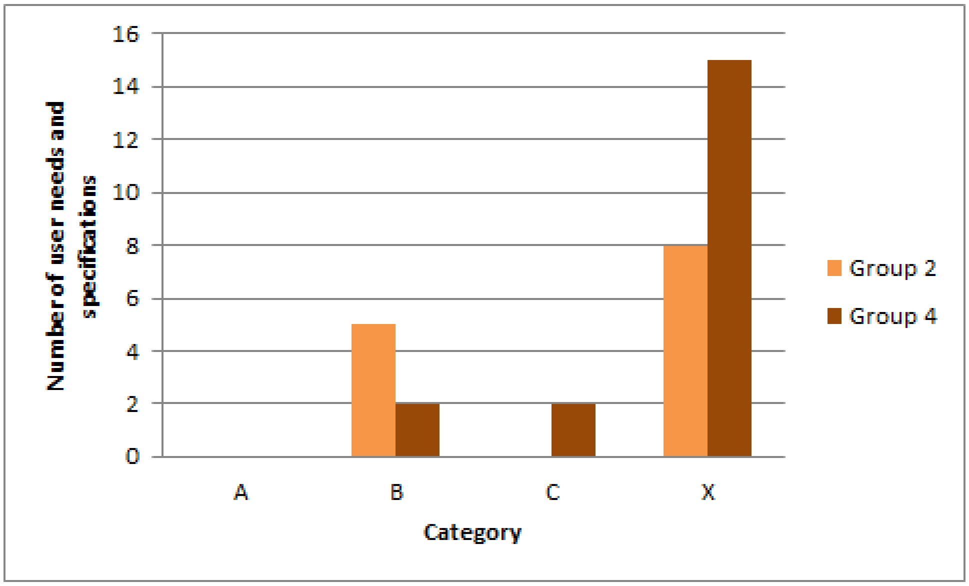

Figure [2]: Prompt level 2 groups' number of user needs and specifications per category

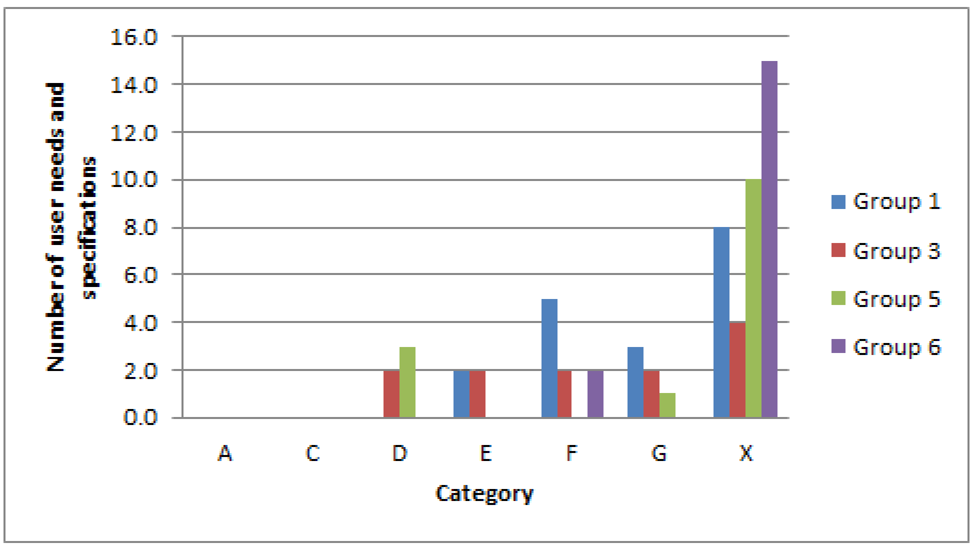

Figure [3]: Prompt level 3 groups' number of user needs and specifications per category

The two figures show that almost none of the groups (in either prompt level) listed user needs and specifications that were coded for category A or category C. These categories are related to the age of the 'clients.' Category A is defined as "helping older adults" and category C is defined as "[adults] between the ages of 70 and 75." Only group 4 had user needs and specifications coded as category C.

User needs and specifications that did not fit into one of the criteria categories for a given prompt level were coded as category X. Category X contained the greatest number of user needs and specifications for each group. The researchers reviewed this category and created subcategories to further analyze this data. The subcategories were created by grouping similar user needs and specifications together through consensus then labeling those groups. Tables [4] and [5] show the number of user needs and specifications for each subcategory separated by group.

Table [4]: Category X prompt level 2 subcategories

Prompt level 2	Group 2	Group 4
Usability	1	5
Health	5	0
Misc. Product Requirement	0	7
Category F	2	3

Table [5]: Category X prompt level 3 subcategories

Prompt level 3	Group 1	Group 3	Group 5	Group 6
Usability	6	4	4	1
Misc. Product Requirement	2	0	6	14

All of the groups listed user needs and specifications relating to usability. The next most common subcategory (for either prompt level) was miscellaneous product requirement. Category F was not given to the ill-defined prompt level 2 groups as criteria but both groups listed user needs and specifications that were coded for that subcategory. Prompt level 3 groups had category F as assignment criteria and 3 of the 4 groups listed user needs and specifications that were coded for that category as previously shown in Figure [3].

The two figures below, Figures [4] and [5] show the average levels of depth for all user needs and specifications within a category by group. Figure [4] shows prompt level 2 groups while Figure [5] shows prompt level 3 groups.

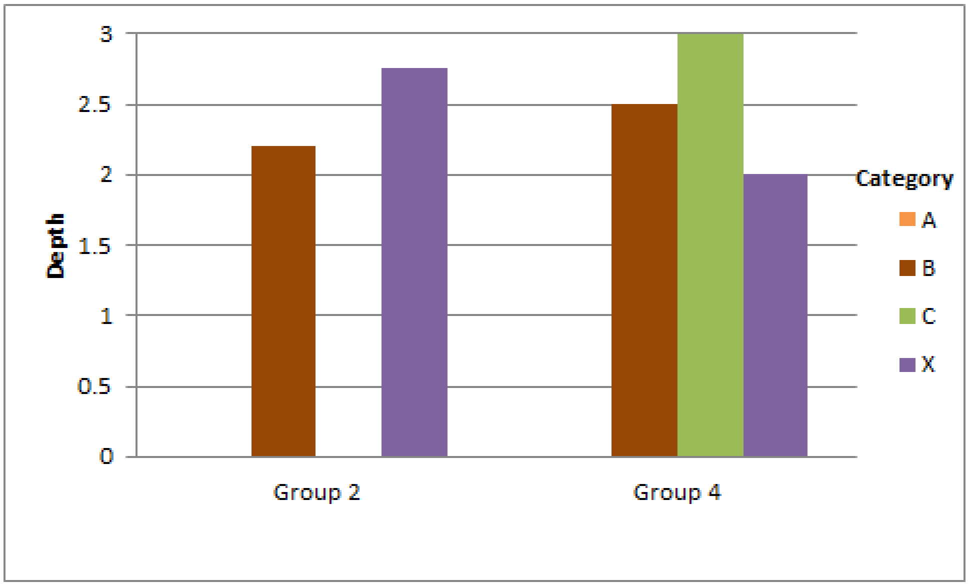

Figure [4]: Prompt level 2 average depth per category

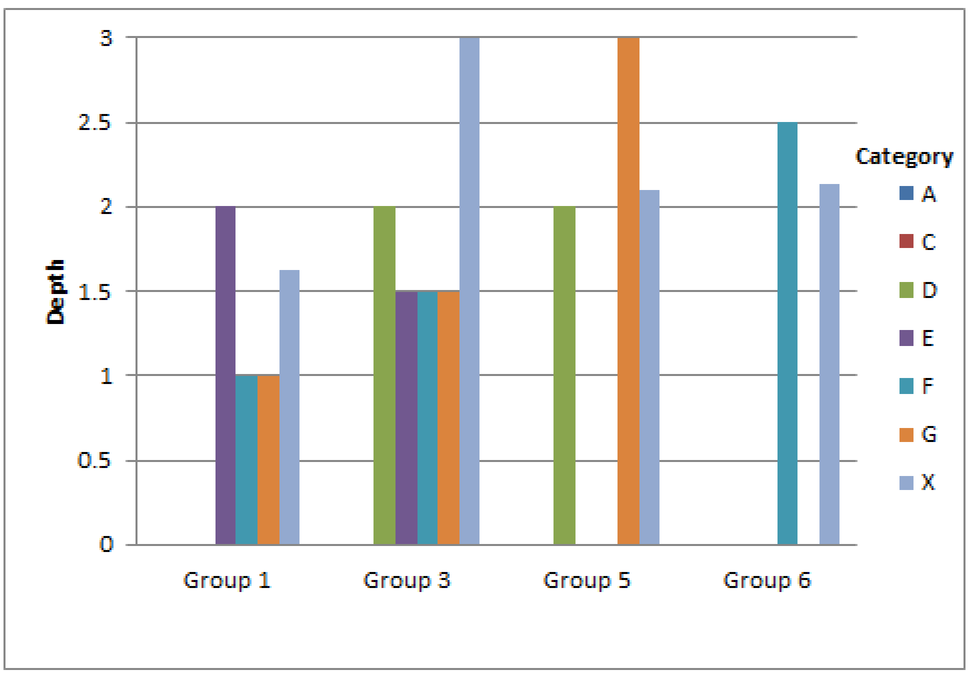

Figure [5]: Prompt level 3 average depth per category

The average depth ranges from 2 to 3 in prompt level 2 (ill-defined problem). Prompt level 3 (well-defined problem) contains a larger number of groups as well as a larger range of average depth from 1 to 3. However, most groups in this prompt level have an average depth rating for each criteria category of 2 or less.

Tables [6] and [7] below illustrate the mean depth rating for each Group. This mean was calculated by averaging the depth rating of all the user needs and specifications for each group. The means are separated by prompt level. Prompt level 2 contains means of 2.06 and 2.53. In prompt level 3, the mean depth rating ranges from 1.38 to 2.17.

Table [6]: Mean depth rating

Prompt level 2	Group 2	Group 4
Mean	2.53	2.06

Table [7]: Mean depth rating

Prompt level 3	Group 1	Group 3	Group 5	Group 6
Mean	1.38	2.09	2.14	2.17

Discussion

The main finding for first-year engineers given ill-defined compared to well-defined problems is the depth within each category: the groups given the ill-defined problem (prompt level 2) developed user needs and specifications that were more specific than those given the well-defined problem (prompt level 3). Groups whose criteria fell within fewer categories tended to have higher depth rating. Four groups had user needs and specifications that fell within 2 or 3 criteria categories, and those groups had depth scores of 2 or more in all categories. However, Group 1 and Group 3 had user needs and specifications in 4 to 5 criteria categories. These groups had depth ratings below 2 except for Group 3 in category X. This correlation seems to indicate a trend of breadth versus depth. Groups that met fewer categories had more depth, regardless of prompt level, as indicated by a higher depth score. Whereas the groups that showed breadth by meeting more criteria categories had a lower depth rating. This trend might have been influenced by the time constraint the groups were under. The groups were given two class periods, a total of 150 minutes, to work on the project. Additional time outside class was optional.

These results also yielded findings about the type of user needs and specifications first-year students develop when given a design problem. The user needs and specifications tended to not include information relating directly to the user demographics. Group 2 seemed to indirectly address demographics by listing user needs and specifications that fell into category X's subcategory of health. The user needs and specifications listed health concerns generally associated with older adults such as arthritis. Group 4 was the only group to directly address demographics by listing category C user needs and specifications. Category C relates to the age of the ‘clients’. In all other groups, there was no user need and specification relating to the demographics of their ‘clients’. The user needs and specifications instead focused on product features such as materials without a connection to user information. Product specifications including materials were listed as a deliverable in the assignment which might have accounted for the students’ focus. This also maybe is evidence of the students’ lack of knowledge in the field of human factors. The time constraint could have also influenced this result by limiting the user research in order to enable students to focus on developing a final product.

The average depth rating of 4 of the 6 groups ranged from 2.06 to 2.14. A depth rating of 2 indicated that the user need or specification was for a specific purpose (e.g. measurement, material type, angle) but lacked justification. It is expected that as students gain user centered design expertise the depth rating of their user needs and specifications would increase. For example, it is expected that human factors engineers (HFEs) would have an average near 3 when given the same problem. This is because HFEs are trained to rely on justification and supportive evidence for their design decisions.

Limitations

This study was limited by its sample size. This small sample size constrains the contribution of this work. However, the study can still provide helpful insights into the design of instruction for ill and well-defined problems.

This study relies on students’ written work. This written work might not show the complete picture in understanding student cognition and decision making. The data from their written work does not include decisions and thinking that were not written down. Therefore, individual and collective/group cognition and decision making might not be completely represented in the written data.

Conclusion - Implications

The study provides information on the user needs and specifications developed by first year engineers within the context of a design engineering problem. The data and analysis from the study suggest that giving students fewer criteria leads to more written justification of their user needs and specifications.

When developing user needs and specifications first-year students seem to focus on the product and not the user. They tend to leave out justification and not include information that has a direct relation to their user group. This might have been influenced by the time constraint, students’ lack of knowledge about the users and/or the students' focus on a final product (as opposed to the process).

These findings have implications when designing an engineering problem. Often it is believed that fewer criteria leads students into feeling lost, or the development of work that is not relevant nor focused. However, from this study we find that students can be given fewer criteria and still develop thoughtful projects. In fact, giving students fewer criteria could support the creation of user needs and specifications that are more specific than groups who are given more criteria. This information, combined with our previous work[7], indicates that students can be more successful with ill-defined problems than well-defined ones when given deliverables that support utilization of the engineering design process. For example, in this study students were required to list user needs and specifications which might have helped them through the problem scoping process. The support the deliverables added and fewer criteria might have enabled students to focus their design process and made it easier to have more project depth.

Few user needs and specifications addressed demographic user information. As mentioned above, this focus might have been caused by the first-year engineers' lack of knowledge of human factors, the instructions of the assignment, or time. Proper instructional design could mitigate this issue. For example, by providing further instruction to students or including assignment criteria around requiring user research.

Another possible cause of the user needs and specifications lacking user information could be related to the students' intended audience. Students might have assumed that the reader and evaluator of their design decisions (i.e. the professor of the course) was aware of the project criteria. Therefore, they may have thought it unnecessary to include justification of their user needs and specifications because the reader could extrapolate justification from the project criteria. For example, a user need listed by one group stated: "user requires an automated system to call for help if sudden or extreme changes are noticed in health." This design idea might have been due to the age of the client (criteria category A or C) but the origin was not specified in the group's work. Therefore, this user need was coded as category X - subcategory health. The groups might have provided more depth if they were required to write their design decisions for a broader audience that has no previous experience on the project criteria.

A goal of training future human factors engineers is to enable them to effectively communicate to a client. Therefore, students need to have a clear understanding of who their written audience is, or else they may make unfounded assumptions about their readers. By clearly stating the reading audience students might understand the importance of justifying their design decisions.

Overall, groups given the ill-defined problem (prompt level 2) performed just as well in listing user needs and requirements that related to their criteria categories as those groups given the well-defined (prompt level 3) problem. The ill-defined problem groups also listed user needs and specifications that contained more depth than those given the well-defined problem. These results have implications past a first year course. The ill-defined problem seemed to support students development of depth in their user needs and requirements. This skill will aid them in advanced design courses and future industry jobs that require the need to justify and understand their chosen design decisions. Ill-defined problems provide students with more opportunity to learn how to problem scope than well-defined ones. It is expected that students who gain more practice in problem scoping will perform better in advanced design courses where problems are typically less structured.

Future Work

We plan to examine future manipulations of problems by withholding or providing information to the students in order to understand the relationship between criteria and student work. This research will help us predict the work students will likely produce. This information will provide helpful insights in how to present problems to best educate future engineers.

Acknowledgements

The authors would like to acknowledge funding and support from Tufts University Center for Engineering Education and Outreach, Tufts University Department of Mechanical Engineering, the Center of Science and Mathematics in Context at the University of Massachusetts Boston, USAID and The Sampoerna University. This work was also supported by the National Science Foundation DRK-12 program, grant # DRL-1020243, and grant # DRL-1253344. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We would also like to thank Professor Dan Hannon for his support of the project and the student participants.

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