Proceedings of the Design Society, Volume 5: ICED25
https://doi.org/10.1017/pds.2025.10352

Visual communication in engineering design: impact of line work in explanative sketching

Shiho Nakamura, Dingmohen Li and Julie Linsey✉

Georgia Institute of Technology, USA

✉ julie.linsey@me.gatech.edu

ABSTRACT: As conceptual design sketches are a common tool used to communicate between team members, it is important to understand the relationship between sketch characteristics and engineers' perceptions. This study evaluates 4 line styles common in many sketch techniques: the Single Line, Feathered Line, Heavily Feathered Line, and Variable Line. 40 mechanical engineers ranked preferences of complex engineering products in these line styles and provided adjectives to describe their choices. Results show that engineers preferred the Single Line, which had the common adjectives of clear and professional. The findings suggest that engineers should generally be learning and using a single, uniform and clean line style.

KEYWORDS: design cognition, human behaviour in design, conceptual design

1. Introduction

Sketching is a critical idea visualization tool used throughout the engineering design process with several practical and cognitive benefits (Goldschmidt, 1991; Suwa et al., 1998; Tversky & Suwa, 2009). Prior work has shown that sketching enables the rapid manipulation of complex ideas (Ullman et al., 1990), off-loading working memory (Goel, 1995), and can improve design outcomes like solution quality and solution time (Ahmed & Boelskifte, 2006). External representations aid in engineering solution development, testing, and communication (Römer et al., 2001). Kudrowitz et al. (2012) found that specific sketch characteristics, such as higher sketch quality were perceived to be more creative by end users while Macomber and Yang (2012) found that sketch features such as line style and render/shading finish can impact end-user preferences. The benefits of sketching are particularly relevant during the early stages of the design process when sketches are used for explorative and explanative purposes (Olofsson, 2005). The initial design phases, which include idea generation and conceptual design sketching, have the most significant effect on product cost and can reduce time to market (Römer et al., 2001). Prior studies of the early-stage design process have shown that generating solutions almost always involves the use of explorative sketches to prompt participants to reflect on their thought process (Goldschmidt, 1991). Furthermore, explanative sketches are often used to communicate ideas to important stakeholders, such as teammates, engineers, manufacturers and managers, prompting feedback and promoting collaboration in idea generation (Olofsson, 2005). This approach of collecting feedback is commonly associated with design thinking and human-centric design (Dym et al., 2005). As sketches are a common tool used to communicate within an engineering or design team, different sketching styles can reflect differences in preferences and the perceived overall value of an idea which in turn can heavily impact the decision-making process when selecting final ideas.

Therefore, as this decision-making process may have a significant influence on the trajectory and outcomes of a project, it is important to understand how engineers respond to different styles of linework when presented with sketched ideas. The 3 sketching line styles chosen for this study, *single line style, feathered line style, and variable line style,* are seen in previous studies of sketching styles on end-user/non-expert perceptions (Macomber & Yang, 2012).

This research aims to build upon the existing work with the broader goal to begin to identify the visual communication skills needed by engineers and help engineers' better present their ideas. In particular, the goal of this study is to explore engineers' preferences and perceptions of 4 different line styles (with the addition of a *heavily feathered line style*) seen in industrial design, fine art, and illustrative/cartoon sketching, for conceptual sketches that are shown to engineers within an engineering team and analyse the effects of various complexity of products.

2. Background

2.1. Sketching in idea generation

The act of sketching often initiates the generation of ideas during brainstorming processes. Studies have found that higher sketch quality is correlated with better design outcomes such as solution quality, solution time, and confidence (Ahmed & Boelskifte, 2006) and are perceived to be more creative by stakeholders (Kudrowitz et al., 2012). Sketching allows for unexpected discoveries and reinterpretations due to its nature of preserving ambiguity while allowing for the investigation of alternative design solutions (Goel, 1995). The introduction of this ambiguity can, as an advantage, create space for uncertainty, which can lead to flexible transformations, the building of ideas, and act as a safeguard against premature commitment to uncreative solutions (Tseng & Ball, 2011). However, as a disadvantage, this uncertainty can foster undesirable ambiguity with how a design is communicated (Stacey & Eckert, 2003). To diminish the negative effects of ambiguity, it is crucial to examine how visual factors in sketching communication, such as line quality and line style affects how engineers perceive and respond to ideas. As Macomber and Yang (2012) have shown that certain sketching and rendering styles (CAD vs shading) can influence end users' preferences of ideas, it is important to investigate whether this holds for engineers making decisions within the team. Thus, understanding engineers' line style preferences is integral to optimizing visual communication for engineers and can help engineers better present their ideas.

2.2. Sketch categorization in engineering design

Sketch types have been categorized in several ways. Olofsson and Sjolen (2005) outline sketch evolution through 3 stages of explorative, explanative, and persuasive sketches. Explorative sketches are seen at the inception of a product concept and promote creativity. Explanative sketches portray alternative design solutions and are shown to stakeholders for feedback before a final solution is chosen. Finally, persuasive sketches imply a final solution has been chosen with high quality sketches and renderings. Another categorization of sketches was made by McGown et al. (1998) which considers the complexity of sketches: Level 1 is a monochrome line drawing with no shading or text annotations or dimensions. Level 2 is also a monochrome line drawing with no shading but with the use of different thickness and line pressure. Brief annotations may be used. Level 3 is a monochrome drawing with some shading to suggest form. Annotations and dimensions are used here. Level 4 includes subtle shading and 3D form. Annotations and colour may be used. Finally, Level 5 is a realistic sketch where colour is used to accurately represent the end product with extensive use of shading and annotations to explain the concept. The role of sketching and rendering styles on user preferences has been investigated. Macomber and Yang (2012) examined preferences of eight sketch styles, divided into two broad categories of 4 Level 1/Level 2 early stage line drawings (Category 1) and 4 CAD rendered and shaded, more finalized Level 4 drawings (Category 2). The first category of line drawings included: (1) a *single line* industrial design sketch style with construction lines, resembling a Level 1 in-progress sketch, (2) a *single line style*, again seen in industrial design, with no construction lines resembling a more finalized Level 2 sketch. (3) a Level 2, stylized, graphical interpretation using a *variable line style*, and (4) a hashy, multi-line, *feathered line style*, described as *"rough Level 1 sketches"* (Macomber & Yang, 2012).

The second category considered more finalized CAD renderings and realistic sketches with shading and is not described here as it is outside the scope of this work. The objects chosen for investigation were a cube, a phone, and the Amoebe chair (Macomber & Yang, 2012). In all cases there was no clear preference for a particular line style, as respondents ranked the finalized Level 2 *single line style* highest for the phone, the *variable line style* highest for the chair, and 3 of the 4 line styles tied as most preferred for the cube (i.e. the *single line style*, the *single line style with construction lines*, and the *variable line styles* were all equally the most preferred for the cube drawing). Macomber and Yang (2012) suspect that this was due to the particular objects being drawn being too simple. In this study we focus on only explanative sketches with Level 2 complexity, maintaining a constant high sketch quality and complexity while only varying line work. The goal of this study is to investigate the role of linework styles for more finished Level 2 drawings of complex engineering products to simulate the engineering team feedback process. Therefore, the style with construction lines was not investigated. The effects of 3 line styles investigated in this study can be seen in Figure 1.

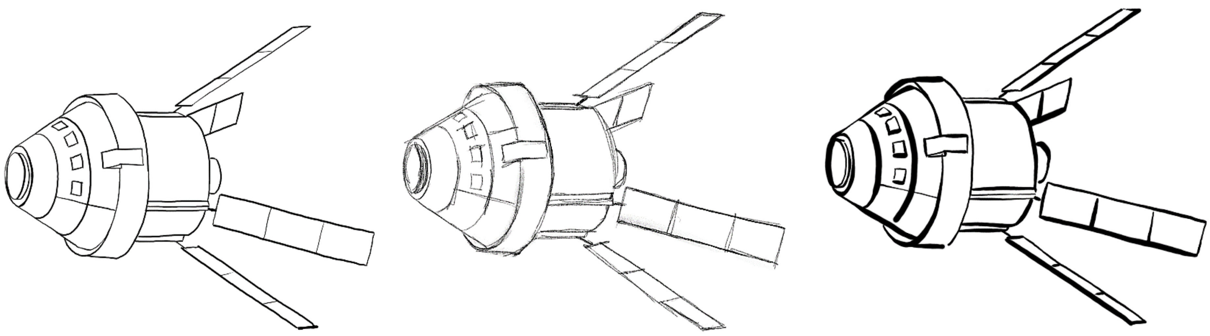

Figure 1. Orion spacecraft in 3 styles, left- Single Line (S), middle-Feathered Line (F), and right-Variable Line (V)

2.3. Types of line styles

The selection of line styles in this work was primarily informed by prior research on sketching styles (Macomber & Yang, 2012), focusing on specific line work within a sketching style. The *single line style* is commonly used in industrial design sketching and engineering drawings for its clean and precise qualities and consists of a single line of approximately uniform thickness throughout (Olofsson, 2005). A large part of the industrial design education is dedicated to learning this line style and is often seen in professional work in the field (Barnhart & Walters, 2018). Furthermore, engineers may be familiar with this style as engineering graphics courses utilize it when teaching isometric and orthographic drawings and is often used in manufacturing drawings (Bertoline et al., 1998). Orthographic drawings are a very common way for engineers to sketch with no perspective techniques and are limited in that they do not allow for spatial thinking (Ferguson, 1994). Isometric sketches allow for more spatial thinking, but lack accurate proportions and perspective (Sorby, 1999). Thus, engineers likely have exposure to the *single line style*, which the adjacent field of industrial design also utilizes. This research further seeks to add to the work by considering two more sketching styles from the fine art and illustrative fields, rather than from a more engineering and industrial design centric view. The *feathered line style* consists of using a multi-line, feathered/hashy line (Barnhart & Walters, 2018), which offers an advantage in speed over *the single style* (Macomber & Yang, 2012). This feathered technique is commonly used in observation drawings in fine art where artists will gauge a holistic understanding through roughly sketching outlines of major forms to accurately describe proportions (Gale, 2023a). Additionally, this technique can also be seen in gestalt and movement drawings in fine art where a drawing is completed quickly using fast and expressive lines (Gale, 2023b). The *variable line style* is commonly used when creating comics and cartoons and offers greater contrast and expression than a single line style (Furniss, 2011). This line style is also seen in industrial design and architecture and uses an accented outline technique (Guptill, 1997). It involves a process called inking where one uses varying line thicknesses and adding bold and valuable blacks to add depth to the image (Furniss, 2011). From an engineering design standpoint, this linework could allow for the emphasis of important parts of the product, potentially resulting in increased understandability and effective communication of product aspects.

2.4. Research questions

This study builds upon the work of many discussed above. Based on the existing literature there is a gap in investigating how line work seen in other fields can influence preference among engineers in an engineering team. To further understand the subtleties of the participants' reasoning, this study investigates adjectives to aid in understanding preferences in sketching styles. The following hypotheses were developed:
RQ1. What impact does the line style have on the preference for different complex engineering products depicted in conceptual sketches?

A clear preference of line style was not observed for non-experts for sketches of simple form objects (Macomber & Yang, 2012). We hypothesize that engineering students prefer the *single line style* over the *feathered line style*, similar to trends seen in industrial design students (Barnhart & Walters, 2018).

RQ2. What are engineers' perceptions associated with different line styles?

We predict that engineers will perceive the *single line style* as highly confident and the *feathered line style* as hesitant and unsure, as highlighted by the type of adjectives given by participants. These trends were observed in semi-structured interviews with industrial design students who perceived fine art hashy sketching styles to be unconfident and industrial design sketches as confident (Barnhart & Walters, 2018).

By using 3 product groups of high complexity, this study aims to solidify the findings of prior work and expand on conclusions in the engineering design field. The study builds on prior research in a novel way by looking at more complex engineering product groups and exploring line styles from the industrial design, fine art, and illustrative fields, compared to prior studies that have only looked at engineering and industrial design sketching styles. Finally, this study aims to explore the findings with engineers to see if a more technical audience has different preferences through looking specifically at more finalized line styles and sketches presented to individual engineers.

3. Methods

3.1. Study design

This study explores the relationship between the line style of a product concept sketch and the engineers' perception and preference for a style in a within-subjects, computer-based, repeated measures study. 50-60 different products were initially chosen and eventually narrowed down to 10 by discussion among the authors. The 10 products were selected because of their nature as high complexity, engineering products: the Orion spacecraft, the Gateway spacecraft, the Crawler, the Amoebe Chair, the Leaf Chair, the Flower chair, Doodle Toaster, Coffee-maker/Toaster, Horizontal Toaster, and Crumb Tray Toaster. The 4 line types considered were *single line, feathered line, heavily feathered line*, and *variable line.* These line types correspond to those seen in Industrial Design, Fine Art, and Illustrative sketching styles, respectively. Participants were asked to rank their preferences of line styles for each of the 10 products based on what they liked the most and provided adjectives for their choices. The preference question was intentionally left open-ended to allow participants to interpret it freely and capture the participants instinctive gut preferences (Macomber & Yang, 2011). The wording for this question was provided by Dr. Yang and not found in the original paper. An example question for the Toaster/Coffee maker is shown in Figure 2.

3 individual products were chosen within the chair and spacecraft product groups to explore the preferences of 3 line styles (not including the *heavily feathered line*) as ranked relative to each other. A fourth additional *heavily feathered line style* was added to the toaster product group because 4 toaster images were directly adapted from the high-quality toaster sketches in a previous study that evaluated the effects of sketch quality on user perception of innovative toasters (Kudrowitz et al., 2012). The fourth style was only investigated for the toasters to replicate prior work that uses 4 toasters for user perceptions. Furthermore, the fourth style allowed for the exploration of whether an extreme feathered style often seen with lower skill influences engagement, further investigating the nuances of the fine art style. The toaster images represent a highly functional consumer product that engineers may be more familiar with. In the chair product group, one of the chair images, the Amoebe chair was used from Macomber and Yang (2012) and two other unique chair designs of varying complexity were chosen to be compared against the Amoebe chair. The use of prior images provides a baseline for comparison to investigate whether similar findings emerge in technical participants compared against more complex, engineering related products. The 3 spacecrafts were chosen from the NASA "Learn how to draw Artemis" series (Webb, 2020) based on the intricate and technical design features representative of space-related devices.

All sketches were created by one of the authors, a graduate mechanical engineering student with BS and MS in mechanical engineering and a minor in industrial design with coursework in fine art, industrial design and engineering design. The students' sketching coursework includes fine art sketching, photorealism/hyperrealism, product design, industrial design methods, digital rendering and presentation, and engineering graphics. The sketch artist demonstrated the fastest execution and comfort sketching in the feathered line style. This is actually preferred for the current study as it enables a deeper exploration into the nuances of artistic sketching styles that are neither emphasized nor typically taught in engineering education, and investigate its impact on visual communication for engineers. Sketches were all made using the Procreate app using the 'Technical pen' tool at varying thickness. Procreate is widely used by artists and designers for creating digital illustrations, paintings, and artwork. The app offers a range of brushes, tools, and features to facilitate creative expression. A digital medium was used for consistency among the sketches. For each sketch an underlay image was traced over to ensure that the sketch quality (size, shape, and details of the product ideas) were consistent across all drawing styles while only varying the line work (feathered line style –hashy/sketchy multiple lines, single line style– single uniform line, and variable line style – variable thickness line). The underlay images used were provided by Dr. Kudrowitz, Dr. Yang or found online. All the sketches were then photoshopped to be a similar darkness and sized to equal height and width.

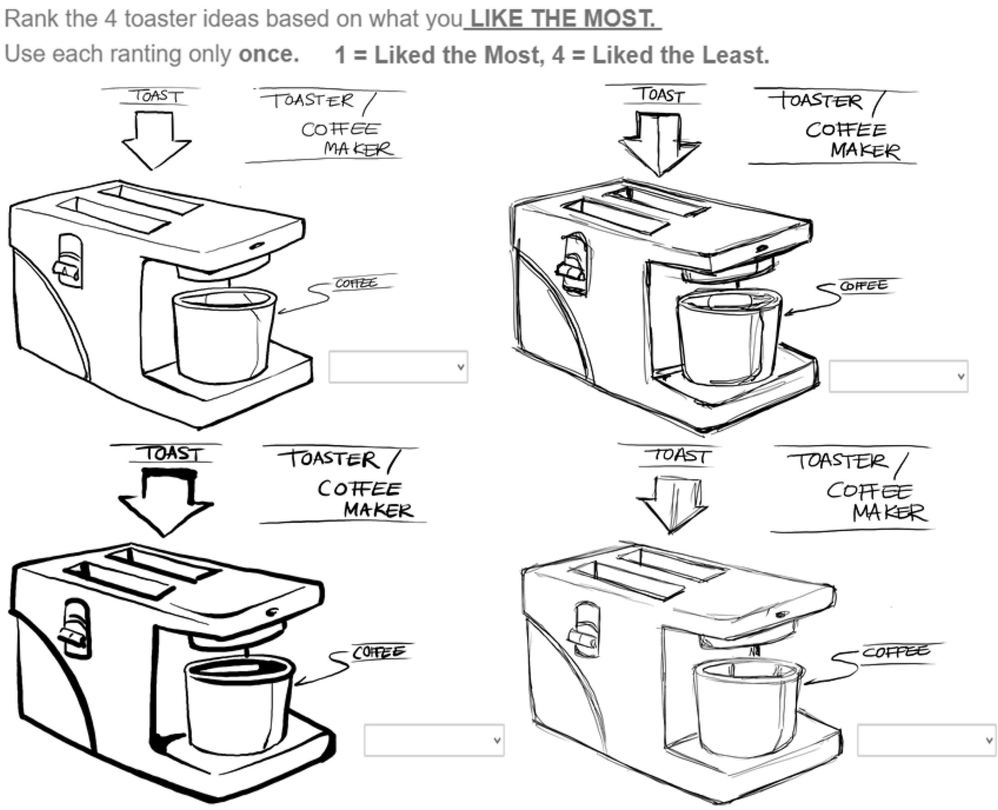

Figure 2. Qualtrics survey question for toaster/coffee maker in 4 styles. Top left -Single Line style (S), Top right- Heavily Feathered Line style (HF), Bottom left - Variable Line style (V), and bottom right - Feathered Line style (F)

3.2. Participants

40 Mechanical Engineering students from a graduate-level additive manufacturing class at a public university in Southern US participated in the study. 24 participants identified as men, 13 as women, 1 as non-binary and 2 preferred not to disclose. The study was approved by the institutions IRB, and students were recruited through an in-class announcement and were able to choose to be compensated with either extra credit for the course or with a $10 Amazon gift card. 39 participants chose the extra credit and 1 student chose the $10 Amazon gift card for compensation.

Participants completed a short Qualtrics survey online, accessed through a link that was sent to them by email. All participants ranked their line style preferences for all 10 products in the same order; first the spacecrafts (orion, gateway, crawler), then the chairs (flower, amoebe, leaf) and lastly the toasters (Doodle toaster, coffee maker/toaster, horizontal toaster, crumb tray toaster. Each question showed a product in a random order of line styles to account for order bias. For the spacecraft and chair product groups, 6 sets of sketches were arranged so each set presented a different combination of the 3 different line styles. For the toaster questions, 24 sets of 4 sketches were arranged for each toaster question so that each set presented a different combination of a toaster in 4 different line styles. Each participant answered 1 random question set for each product.

3.3. Research methods

The data was first analysed using a global Freidman ranks test to see if there were overall differences among conditions. As the data was non-normal, the Freidman test was used as a non-parametric counterpart to a one-way repeated measures ANOVA. The non-parametric Freidman test of differences among repeated measures revealed significant differences between the ranks for the different line styles (Chi-square value of = 75.261, $p<0.001$) based on different products. A Mann-Whitney U test was then conducted for each product on the raw ranking scores in a pairwise comparison to check for statistical differences between average rankings for each product to evaluate whether the raw rank scores differed by line style, adjusting for a Bonferroni correction (chairs and spacecrafts alpha = 0.05 /10 comparisons = 0.005). Macomber and Yang (2012) also used Mann-Whitney U to analyse their data but did not correct for multiple comparisons. It is a compatible non-parametric post hoc test to the Freidman test. Note that the ranking scale has been reversed, swapping a rank of 1 to least liked and a rank of 4 as most liked to enhance the clarity of the data visualization and ease of understanding for the results and discussion. In other words, a higher numerical value was swapped to represent a more favourable response with 4 or 3 indicating highest preference and 1 indicating lowest. This modification does not alter the substantive findings but only simplifies the visual representation for a clearer interpretation.

4. Results and discussion

Figure 3 shows the average rankings for all 10 products for each line style. Several key trends were observed from the preference rankings as shown in the Table 1 below. Here ">" means there were statistical differences and that the inequality statement holds true with more preferred line styles on the left of the inequality, and "≈" meaning no statistical differences with the 2 line styles having virtually the same ranking. Table 2 shows the Z-value and P-values used to derive Table 1. Across different products, there appeared to be a consistent trend in preference for the *single* (S) and *variable* (V) line styles over the *feathered* (F) and *heavily feathered* (HF) line styles in the various contexts. Overall, the *single line style* consistently emerged as a preferred choice; however, there were some differences in preference depending on the product sketched.

For the Orion and Gateway spacecrafts, the *variable line style* was ranked as highly as the *single line style*, as seen in Table 1. However, for the Crawler spacecraft, respondents preferred *single line style* significantly more than the other two styles. The *feathered line style* consistently ranked as the least preferred option among spacecrafts; although, for the Crawler, the *feathered* and *variable line styles* were both least preferred with the *single line style* as most preferred. For all chairs, the *single line style* was most preferred, and the *feathered* and *variable line style* were ranked the same. The variation in

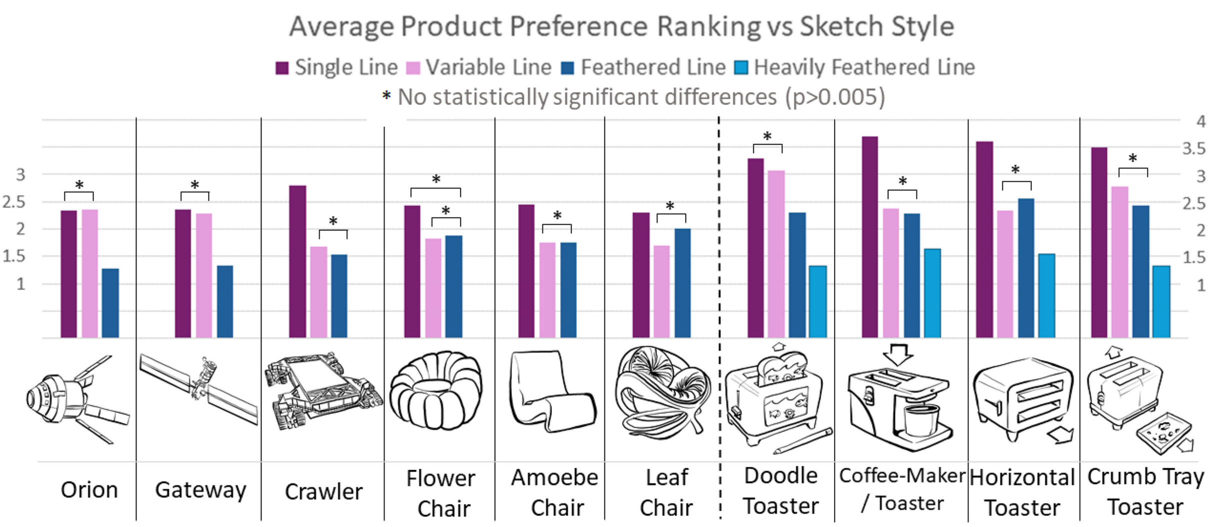

Figure 3. Average preference ranking of each product in the different sketching styles where 1 - least preferred and 3 - most preferred for products on the left and 4 is most preferred for toasters on the right. The images of the products are all in the Variable Line style with annotations removed for visual clarity

Table 1. Order of preference for line styles where > indicates a statistically significant difference and ≈ means no statistically significant differences. All $p<0.005$ with exact values shown in Table 2. Single line is always either preferred or no significant difference.

Product name	Order of Preference	
Orion Spacecraft	S ≈ V > F	**Legend**
Gateway Spacecraft	S ≈ V > F	S - Single line
Crawler Spacecraft	S > V ≈ F	V - Variable line
Leaf Chair	S >V, S ≈ F, V ≈ F	F - Feathered line
Flower Chair	S > V ≈ F	HF - Heavily feathered
Amoebe Chair	S > V ≈ F	
Doodle Toaster	S ≈ V > F > HF	≈ No statistical difference
Toaster/ Coffee Maker	S > V ≈ F > HF	> Greater, statistically significant
Horizontal Toaster	S > V ≈ F > HF	
Crumb Tray Toaster	S > V ≈ F > HF	

ranking scores was smaller than for the chairs than the spacecraft. Moreover, the average ranking for the *feathered line style* across the chairs was significantly higher than that of the spacecraft. For all toasters, the *heavily feathered line style* were ranked significantly lower than the other line styles. The sketches in the *single line style* were significantly ranked as the most preferred for 3 of the 4 toaster products except for the doodle toaster where the *single* and the *variable styles* were tied in rank as the top line style preferred. For all the other toasters, the *feathered* and the *variable line styles* were ranked equally.

The most frequently provided adjectives to describe each style are shown in Table 3 with the total words provided for each style. Interestingly, the most common positive and negative adjective for the *variable line style* was "bold" highlighting that the bold features of this line style could be a negative or positive attribute. The *feathered line style* accompanied by positive words such as "clear", "nice" and "understandable". These descriptors within the chair group suggest that products associated with softness and comfort may be represented well in *the feathered line* but further experimentation is needed to confirm this hypothesis. Finally, the *single line* had the most consistent words out of all the styles, demonstrating that there was a common consensus among participants on the positive perception of *the single line styl*e. Participants provided adjectives "clear" and "clean" most frequently, revealing that the *single line style* was simple and easy to understand. Overall, the *single line style* had the most positive adjectives out of all the styles by roughly double and the least number of negative adjectives, suggesting the single style is the top preference among participants. The *heavily feathered line* had the most negative adjectives followed by the *feathered line*, suggesting that the feathered line styles are least preferred by engineers.

Table 2. Z-values and P-values from Mann-Whitney U test for preference rank of line styles. Significant P-values are bolded* (alpha = 0.005). Table 1 shows significant trends.

Product	Line Style	*Single (S)* Z	*Single (S)* P	*Variable (V)* Z	*Variable (V)* P	*Heavily Feathered (HF)* Z	*Heavily Feathered (HF)* P
Orion	***V***	0.0675	0.95				
	F	-5.842	**5.17e-09***	5.809	**6.27e-09***		
Gateway	***V***	-0.268	0.79				
	F	-5.474	**4.41e-08***	4.809	**1.51e-06***		
Crawler	***V***	-6.545	**5.95e-11***				
	F	-6.726	**1.75e-11***	1.188	0.24		
Leaf Chair	***V***	-3.127	**0.0018***				
	F	-1.788	0.074	-1.782	0.075		
Flower Chair	***V***	-3.141	**0.0017***				
	F	-3.813	**1.37e-04***	0.684	0.49		
Amoebe Chair	***V***	-3.813	**1.38e-04***				
	F	-3.813	**1.37e-04***		1		

(*Continued*)

Table 2. Continued.

Product	Line Style	*Single (S)* Z	*Single (S)* P	*Variable (V)* Z	*Variable (V)* P	*Heavily Feathered (HF)* Z	*Heavily Feathered (HF)* P
Doodle Toaster	***V***	-1.258	0.21			6.523	**6.89e-11***
	F	-5.044	**4.55e-07***	4.140	**3.47e-05***	6.016	**1.79e-09***
	S					6.800	**1.04e-11***
Toaster/Coffee Maker	***V***	-4.942	**7.72e-07***			3.565	**3.64e-04***
	F	-6.266	**3.71e-10***	0.895	0.37	3.570	**3.57e-04***
	S					7.005	**2.46e-12***
Horizontal Toaster	***V***	-4.873	**1.10e-06***			3.480	**5.01e-11***
	F	-5.234	**1.66e-07***	-0.757	0.45	5.047	**4.50e-07***
	S					7.269	**3.63e-13***
Crumb Tray Toaster	***V***	-3.129	**0.0018***			6.096	**1.09e-09***
	F	-5.511	**3.58e-08***	1.555	0.12	6.720	**1.82e-11***
	S					7.662	**1.83e-11***

Table 3. Most commonly provided adjectives by participants to describe the most (positive) and least (negative) liked line drawings with total frequency word count for each style.

Line Style	Most Frequently used words and count				Total Words
S	Positive	Clear: 74	Clean: 69	Simple: 39	458
	Negative	Plain: 5	Flat: 4	Basic: 3	60
V	Positive	Bold: 50	Clear: 30	Refined: 10	228
	Negative	Bold: 29	Thick: 12	Defined: 8	234
F	Positive	Clear: 8	Nice: 4	Understandable: 4	100
	Negative	Rough: 30	Messy: 24	Unclear: 21	284
HF	Positive	Simple: 1	Basic: 1	Clear: 1	10
	Negative	Messy: 32	Rough: 20	Unclear: 19	226

4.1. Discussion and limitations

The overall statistically significant preference towards the single line style in this study compliments earlier findings suggesting that non-technical end-users had no clear preferences for a particular line type. These differences in sketch style preferences can likely be attributed to variations in the participant pool (technical vs. non-technical) and the types of the products analysed in this study. The findings from this study suggest that engineers should be learning and utilizing a clean, single line style for conceptual design sketches, based on engineer preferences. For simpler objects drawn with fewer line strokes such as the orion and gateway spacecrafts, and the doodle toaster, the *single* and *variable line styles* were equally preferred. The inherent simplicity of the product may make visual distinctions between the two styles harder to differentiate for the viewer. We suspect that these images in particular may have been difficult for participants to see clear visual differences between the line styles if their device type and screen size were smaller. Another exception to this trend is the leaf chair, where the *single* and *feathered line styles* were ranked equally, and the *variable* and *feathered line* were ranked equally, with differences between the *single* and *variable line styles*. This could be due to the chair's soft features (pillow and fabric) or the fact that the drawing styles for this product were harder to differentiate from the drawings shown on the screen. For more complex objects with a high number of line strokes, such as the crawler spacecraft, the flower chair, and the other 3 toasters, there is a significant preference towards the *single line* which suggest that clean line types may be better to communicate visual intricacies of more complex designs. These findings align with those from Macomber and Yang (2012) who found that simpler drawings of a cube led to equivalent rankings for 3 line styles. Similarly, this study showed equivalent rankings for simpler products. While the earlier study indicated that non-technical had no preference in line style, this investigation involving engineers showed a clear overall preference for the single line style. These differences underscore the nuanced nature of design preferences and hint at the potential influence of factors such as professional background. Further limitations of the study design include the relatively small sample size and the sample consisting of only mechanical engineering graduate students. Despite the significance of the results, future work should explore a participant pool of practitioners such as product/project managers who make important decisions based on presented work, to enhance generalizability of findings to industrial settings and engineers making decisions within team settings. Another drawback is that the test was administered online, resulting in participants viewing the sketches in varied environments and on different screen sizes, which may have introduced confounding variables. This decision was made to facilitate broader participation, hopefully allowing for a larger sample size and to capture a more naturalistic viewing experience that reflects real-world conditions where sketches are often evaluated on different devices and in diverse settings. Future work seeks to address the current works' limitations of small sample size and difficulty in viewing images on small screen sizes through conducting the study on paper and in person to ensure the representation is the same for all participants. While order bias was a concern—hence the decision to randomize the presentation order of line styles for each product—future studies could further mitigate this effect by fully randomizing the order of products as well. Furthermore, future work will analyse individual differences to better interpret patterns within the aggregate data.

5. Conclusion

The findings from this study provide valuable insights into engineers' perceptions of 3 distinct line styles- *single, variable,* and *feathered line styles* – across various high complexity product categories. These styles of lines are common in industry design, and fine art approaches to sketching. The analysis of participants' adjectives for most and least liked drawings revealed distinct perceptions associated with the styles. The overall preference rankings for spacecraft, chairs and toasters demonstrated consistent statistically significant trends with the cleaner line work from *single* and *variable line styles* being favoured over rougher line types in the *feathered* and *heavily feathered line* styles. Moreover, as the *single line style* had the highest total number of positive adjectives, lowest number of negative adjectives, and the highest number of repeated positive adjectives, the single line style is not only preferred but also the most consistently positively perceived as clear and clear and we recommend its use to engineers. This preference suggests that clarity and precision in visual communication are valued in engineering contexts, where sketches serve as tools for conveying design intent efficiently.

RQ1. What impact does the line style have on the preference of different complex engineering products depicted in conceptual sketches?

The study found that the *single line style* was clearly preferred for a vast majority of the products, indicating that engineers generally prefer ideas presented in this style. However, for the less complex sketches, the *variable line style* sometimes matched the *single line style* in ranking, suggesting that engineers may prefer the expression and dynamism offered by the *variable line style* for particular products.

RQ2. What are engineers' perceptions associated with different sketching line styles?

The most common words for the styles focused on the physical appearance of the sketch. We conclude that engineers consistently perceive the *single line style* to look professional and clear while the *feathered line* to be more rough or messy. We suggest that engineers use this style of line work when presenting ideas to team-mates and other engineers. Interestingly the *variable line style* has split opinions, with "bold" appearing as both the most common positive and negative adjective. This could imply that the variable line weight could reduce the visual clarity of the sketch or enhance the visual interest, depending on the sketch complexity and density of lines.

Acknowledgements

This work was supported by the National Science Foundation under Award 2013505. The authors would also like to thank Dr. Maria Yang and Dr. Barry Kudrowitz for their insightful thoughts and sharing supplemental materials from their studies that were not in their original paper.

References

Ahmed S., & Boelskifte P. (2006). Investigations of Product Design Engineering Students Intentions and Users Perception of Product Character. *In NordDesign.*

Barnhart B. R., & Walters K. K. (2018). The Hot Industrial Design Sketch: Perpetuating The Dominance of the Male Industrial Designer. *DS 93: E&PDE 2018*.

Bertoline G. R., Wiebe E. N., & Miller C. L. (1998). Fundamentals of Graphics Communication. *McGraw Hill*.

Das M., Huang M., & Yang M. C. (2022). Tablets, Pens, and Pencils: The Influence of Tools on Sketching in Early Stage Design. *Proceedings of the ASME Design Engineering Technical Conference*, 6. https://doi.org/10.1115/DETC2022-89154

Dym C. L., Agogino A. M., Eris O., Frey D. D., & Leifer L. J. (2005). Engineering Design Thinking, Teaching, and Learning. *Journal of Engineering Education,* 94(1), 103–120.

Ferguson E. S. (1994). Engineering and the Mind's Eye. *MIT Press*.

Furniss H. (2011). How to Draw in Pen and Ink - The Art of Illustration. *Read Books Ltd*.

Gale A. (2023a). How to Create an Excellent Observational Drawing: 11 Tips for High School Art Students. https://www.studentartguide.com/articles/realistic-observational-drawings

Gale A. (2023b). Line Drawing: Guide A. for Art Students. https://www.studentartguide.com/articles/line-drawings

Goel V. (1995). Sketches of Thought. *MIT Press*. https://doi.org/10.7551/MITPRESS/6270.001.0001

Goldschmidt G. (1991). The dialectics of sketching. *Creativity Research Journal,* 4(2), 123–143. https://doi.org/10.1080/10400419109534381

Guptill A. L. (1997). Rendering in Pen and Ink: The Classic Book on Pen and Ink Techniques for Artists, Illustrators, Architects, and Designers (Meyer S. E., Ed.). Watson-Guptill.

Kudrowitz B., Te P., & Wallace D. (2012). The influence of sketch quality on perception of product-idea creativity. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM,* 26(3), 267–279. https://doi.org/10.1017/S0890060412000145

Macomber B., & Yang M. (2012). The Role of Sketch Finish and Style in User Responses to Early Stage Design Concepts. *Proceedings of the ASME Design Engineering Technical Conference,* 9, 567–576. https://doi.org/10.1115/DETC2011-48714

McGown A., Green G., & Rodgers P. A. (1998). Visible ideas: information patterns of conceptual sketch activity. *Design Studies,* 19(4), 431–453. https://doi.org/10.1016/S0142-694X(98)00013-1

Olofsson E., Sjolen K., Design Sketching. KEEOS Design AB.

Römer,A., Pache M., Weißhahn,G., Lindemann U., & Hacker W. (2001). Effort-saving product representations in design—results of a questionnaire survey. *Design Studies,* 22(6), 473–491. https://doi.org/10.1016/S0142-694X(01)00003-5

Sorby S. A. (1999). Developing 3-Spatial D. Visualization Skills. *The Engineering Design Graphics Journal*, 63(2). http://www.edgj.org/index.php/EDGJ/article/view/126

Stacey M., & Eckert C. (2003). Against ambiguity. *Computer Supported Cooperative Work: CSCW: An International Journal,* 12(2), 153–183. https://doi.org/10.1023/A:1023924110279/METRICS

Suwa M., Purcell T., & Gero J. (1998). Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions. *Design Studies,* 19(4), 455–483. https://doi.org/10.1016/S0142-694X(98)00016-7

Tseng W. S. W., & Ball L. J. (2011). How Uncertainty Helps Sketch Interpretation in a Design Task. *Design Creativity 2010, 257-264*. _https://doi.org/10.1007/978-0-85729-224-7_33

Tversky B., & Suwa M. (2009). Thinking with Sketches. *Tools for Innovation*. https://doi.org/10.1093/ACPROF:OSO/9780195381634.003.0004

Ullman D. G., Wood S., & Craig D. (1990). The importance of drawing in the mechanical design process. *Computers & Graphics,* 14(2), 263–274. https://doi.org/10.1016/0097-8493(90)90037-X

Webb C. (2020, June 4). *NASA Learn How to Draw Artemis*.