INVESTIGATING THE EFFECT OF SKETCH QUALITY ON THE SHARED UNDERSTANDING OF DESIGN DYADS

Letting, Cynthia;
Krishnakumar, Sandeep;
Johnson, Erin;
Soria Zurita, Nicolas;
Menold, Jessica

The Pennsylvannia State University

ABSTRACT

While a significant amount of research has documented the importance of design artefacts in design communication, relatively little work has investigated the effect of design artefact quality on the development of a shared understanding between designers. In the current work we focus specifically on sketch quality and the effect of sketch quality on the shared understanding of design dyads. A controlled study with 22 design dyads (44 designers) was conducted to understand the relationship between sketch quality and shared understanding. Results suggest that design artefact quality, measured by sketch understandability, does not predict the shared understanding of a design concept. Our findings hold implications for the fundamental ways in which we evaluate sketch quality and the importance of artefact fidelity for communicative acts.

Keywords: Design practice, Design cognition, Early design phases, Sketching, Shared understanding

Contact:
Letting, Cynthia Jane
The Pennsylvannia State University
United States of America
cjl5836@psu.edu

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1 INTRODUCTION & BACKGROUND

Design is a team sport, and prior work has demonstrated that design outcomes are tied to the communicative abilities of team members as they work to realize a cohesive design vision (Mathieu et al., 2000). Badke-Schaub et al. (2007) define team mental models as "knowledge or belief structures that are shared by members of a team, which enable them to form accurate explanations and expectations about the task, and to coordinate their actions and adapt their behaviours to the demands of the task and other team members". We adopt this definition to describe the *shared understanding* developed by design teams. When evaluating the overlap between individual mental models amongst teams, researchers traditionally distinguish task mental models, or knowledge regarding the task or objective to be accomplished (Iluz et al., 2015), and team mental models, or knowledge and perceptions regarding the roles, responsibilities, and expertise of team members (Jeffery et al., 2005). In the current work, we focus on investigating the overlap between task mental models, as prior work has demonstrated that increased overlap between task mental models is linked with increased team performance (Mathieu et al., 2000; Smith-Jentsch et al., 2001).

Design artefacts, such as sketches, prototypes, or mind maps, act as external representations of internal designer mental models (Eris et al., 2014) and embody the technical design knowledge of the designer or the design team (Lauff et al., 2020). Design artefacts are critical to effective communication both within the design team, and between the team and external stakeholders. Design artefacts allow designers to identify and communicate similar or dissimilar elements across individual mental models (Dong et al., 2013). These communicative acts allow individual designers to adapt or change their individual mental models to represent the design solution and ensure team members are "on the same page" more accurately.

The criticality of design artefacts to the design process more broadly, and to design communication more specifically, is well documented (Krishnakumar et al., 2021). Sketches, prototypes, and digital models can help designers build a shared understanding of the design space. However, the benefits of design artefacts with regards to communication, can be tempered by the fidelity or quality of the artefact itself. For example, Macomber and Yang (Macomber and Yang, 2012) found that sketch quality affected users' perceptions of design solutions. Additionally, Starkey et al. (2019) found that communicating design ideas using high-fidelity CAD models can reduce the perceived risk associated with more innovative ideas. Much of this prior work has assessed the relationship between artefact modality (sketch, CAD model, physical model) and user or designer preferences. Very little is known about the foundational ways that the quality of design artefacts affects the development of a shared understanding of the design concept itself. Specifically, we lack a fundamental understanding of the effect design artefact quality has on the formation of a shared mental model of the design concept between individuals during communicative acts. The current work discusses the findings of a preliminary investigation into the effects artefact quality has on the development of a shared understanding between individuals during communicative design acts. We focus on the relationship between sketch quality, measured by sketch understandability, and shared understanding. We leverage sketch understandability as a measure of sketch quality in line with prior work from Das and Yang (2022). We hypothesize that sketch understandability may act as a significant barrier to the development of a shared understanding between designers. Sketch understandability could, thus, be detrimental to overall team performance and team cohesion.

2 RESEARCH APPROACH AND OBJECTIVES

This study investigates the relationship between sketch understandability—a measure of sketch quality—and shared understanding of design concepts within design dyads during an engineering design task. To study this phenomenon, we propose the following research question:

RQ: How does the understandability of sketches affect the shared understanding of design concepts within design dyads?

To answer our research question, we conducted a controlled study at the Pennsylvania State University. As part of a broader study to investigate the communication of designs, participants were studied in dyads to simulate natural communication of design solutions between partners. Each

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participant created a sketch to represent their chosen design concept and used it to supplement a verbal explanation to their partner in the dyad. Participants completed a survey in which they explained their own design concept and identified their cognitive load after each communicative act. In addition, participants completed a listener's survey in which they indicated their perceived paradigm relatedness and mental model of the presented design solution. This process is detailed in the following section.

3 METHODS

3.1 Participants

In this study, 44 participants (22 men and 22 women) were recruited from the Pennsylvania State University using email, flyers, and snowball sampling. All participants were over the age of 18 and were enrolled either as a graduate or undergraduate student from the College of Engineering. Of the 44 participants, 14 were graduate students and 30 were undergraduate juniors and seniors. 28 participants identified as White, 10 identified as Asian, 2 identified as Hispanic, Latino, or of Spanish origin, 1 identified as Black or African American, 1 identified as White and Asian, 1 identified as Middle Eastern or North African, and 1 identified as White and Hispanic, Latino, or of Spanish origin. At the beginning of the study, the study's purpose was presented, and consent was obtained from each participant, in accordance with the Pennsylvania State University's Institutional Review Board (IRB).

3.2 Procedure

Participants in our study were paired randomly. This random pairing had no effect on the analysis in this study. Figure 1 shows the experimental procedure; tasks shown inside the red box in Figure 1 were completed by participants while in the same room. The participants completed the other tasks in separate rooms. At the start of the study, a pair of participants entered the same room, were introduced to the study, and informed that their participation was voluntary in accordance with the IRB guidelines. After obtaining verbal consent, participants took a short pre-survey that generated their unique participant identification number. To ensure construct validity of the surveys and instruments used in this study, three rounds of pilot studies were conducted, and member checking was employed.

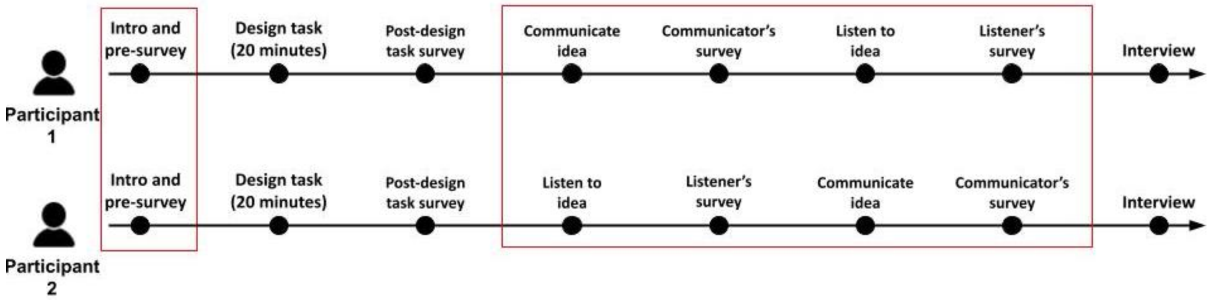

Figure 1. Experimental procedure of the study.

Participants were then briefed about their design task and were given twenty minutes to respond to the following prompt: *"You will now be given a design task to complete. You have twenty minutes to complete the task. You can feel free to sketch out as many ideas as you want, but you will only be allowed to bring your final sketch with you when explaining your design solution. Your final design can be a single idea, or a combination of your ideas generated."*

Participants were then brought to separate rooms in which they individually completed the task. This separation was made to ensure they could not view their partners' solution before their communication time. Once separated, the participants received pencils, paper, a ruler, and a design prompt that differed from their partner. They received different prompts to ensure that participants did not generate identical solutions. Prompts were chosen from prior work by Patel et al. (2019) that validated the prompts' similarity for structure, complexity, and solvability. The two design prompts were:

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"Design an automatic clothes-ironing machine for use in hotels. The purpose of the device is to press wrinkled clothes as obtained from clothes dryers and fold them suitably for the garment type. You are free to choose the degree of automation. At this stage of the project, there is no restriction on the types and quantity of resources consumed or emitted. However, an estimated five minutes per garment is desirable." Shown in Figure 2 is an example sketch for this prompt.

"Design an automatic recycling machine for household use. The device should sort plastic bottles, glass containers, aluminum cans, and tin cans. The sorted materials should be compressed and stored in separate containers. The amount of resources consumed by the device and the amount of space occupied are not limited. However, an estimated fifteen seconds of recycling time per item is desirable." Shown in Figure 2 is an example sketch for this prompt.

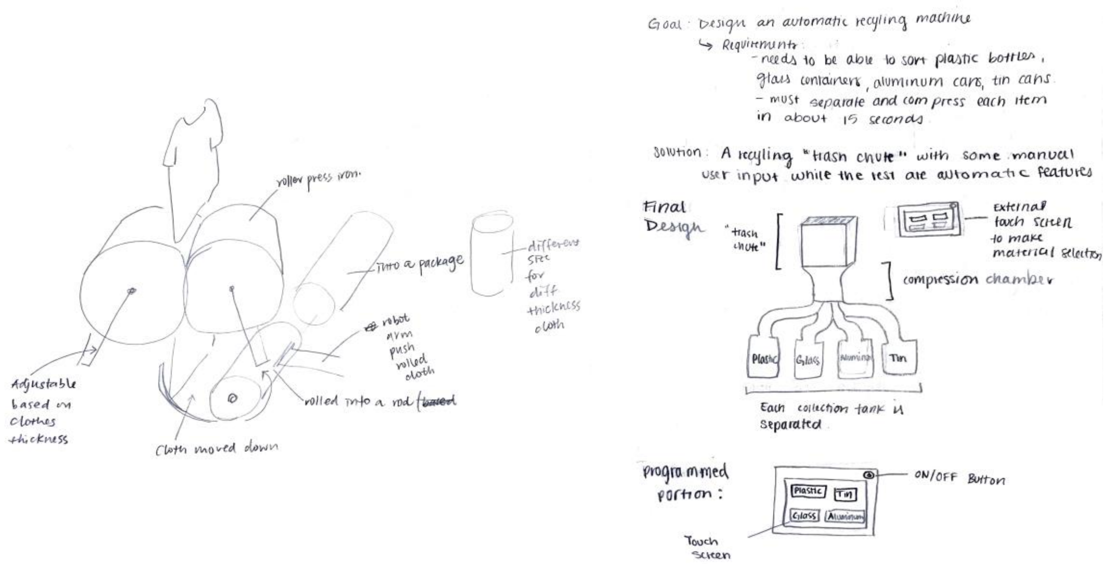

Figure 2. Example sketches from each design prompt. Shown on the left is an automatic clothes-ironing machine for use in hotels and shown on the right is an automatic recycling machine for household use.

Following the task, participants completed a Qualtrics survey in which they provided a written description of their design task, solution, and how their solution works. They also indicated the paradigm-relatedness of their solution. After each participant completed the survey, they returned to the same room and all subsequent interactions were audio and video recorded. The participants were asked to present their design solution to each other: *"You will both now present your design solution to each other, and you can use your design representation to do so. Please remember to go over your design problem, solution, how it works, and how you arrived at it, and keep the explanation of your solution consistent with your written explanation in the survey you just completed."*

To begin, participant 1 was assigned as the communicator, and participant 2 was assigned as the listener. Participant 1 was given five minutes to explain their design prompt and solution to participant 2. Next, participant 2 had three minutes to ask participant 1 any clarifying questions. Both participants were then given individual surveys through Qualtrics. Participant 2 (listener) was asked to rate the paradigm-relatedness of the solution that was just presented, as well as provide a description of the solution: *"In as much detail as possible, please recall the solution that was presented to you, and describe what the solution is, the problem it solves, and how it works in your own words."*

Participants then switched roles; participant 1 became the listener and participant 2 became the communicator. The participants then followed the procedure identical to the previous stage with five minutes for participant 2 to present their solution, and three minutes for participant 1 to ask questions. Participant 1 (listener) was then given the same survey as participant 2 previously received in which they rated the paradigm-relatedness of the solution and described it. All sketches from this study were photographed and stored.

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4 ANALYSIS

4.1 Idea complexity

Prior work has shown designers perceive a trade-off between artefact quality and design complexity (Krishnakumar et al., 2022). In this study, idea complexity was calculated using a two-step process. Using the taxonomy developed by Stone and Wood (1999), participants' explanations of their own ideas were converted into a functional structure. Following the participants' sketching time, they completed a survey in which they described the design problem they solved and detailed their design solution and how it works. Although we instructed participants to keep their verbal and written explanations similar, during verbal explanations, participants used demonstrative pronouns like "*this* goes *there*", making it challenging to extract specific functions of the design concept. Thus, the explanations participants provided in this survey were used to generate the functional structure of their design concepts rather than the verbal explanations. An expert in functional decomposition was consulted to validate the generated functional structures. First, twenty percent of the dataset was reviewed. The research team then discussed the functions and flows of the functional structures, how accurately they represented the written explanations, and the consistency between different functional structures. The expert we consulted is proficient in generating functional structures, and has published multiple works on diagnosing human error in user-product interactions using such structures (Soria Zurita et al., 2018, 2019, 2022). We then reviewed the functional structures to discuss any changes made by the expert and validate the structures. Thus, the functional structures were developed until the researchers and expert reached agreement.

Using the method developed by Ameri et al. (2008), we calculated the size complexity of each functional structure. They define size complexity as the "information content contained within a representation" (p. 165). Equation (1) uses the number of functions and flows in a given functional structure to calculate size complexity:

$$Cx_{size\_func} = (Dv + Dr) * \ln(r + n), \quad (1)$$

where Dv represents the number of instances of functions blocks and I/O types, Dr represents the number of instances of primitive relations, r represents the number of primitive modules (operands) available within the representation (35, as there are 35 possible functions in the taxonomy), and n represents the number of primitive relationships (operators) available between all available modules (3, as there are 3 I/O types, namely material, energy, and information).

4.2 Sketch understandability

Sketch understandability is a metric used to evaluate sketches in engineering design and is defined as the quantification of "how easy a sketch is to understand" (Das and Yang, 2022). This metric was developed to help determine how effective sketches are as communication tools. Recent work in the field has used this metric to study the effects of sketch understandability on modality and design outcomes (Das et al., 2022). We employ a similar approach used in these studies to determine the understandability of each participants' sketched design concept. In previous work, understandability was rated by answering the following question: "can the rater easily understand what the sketcher tried to represent without relying on words and descriptions?" (Das and Yang, 2022). However, Ullman et al. (1990) refers to sketches as "marks on a paper" and Guibert et al. (2009) argues that annotations are often used to elaborate on a solution in a sketch. Because the literature suggests that annotations are critical aspects of sketches (English et al., 2017; Ullman et al., 1990; Yang, 2009), we adapted Das & Yang's approach to include all annotations present in the sketches. Thus, we rated sketch understandability by answering the following question: "can the rater easily understand what the sketcher tried to represent?" Two independent raters rated the understandability of each sketch using the rubric shown in Table 1. Inter-rater agreement was high (99.1%), and all disagreements were resolved by discussion.

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Table 1. Rubric used to rate sketch understandability; adapted from (Das & Yang, 2022).

Rating	**Understandability** Can the rater understand what the sketcher tried to represent?
1	Cannot even begin to guess what the object is out of context
2	General shapes are understood, but it is hard to guess what the sketch is of
3	Sketch could be representing one of a few options
4	It is generally clear what the sketch is of, but some details are confusing
5	Sketch is perfectly clear; most people could guess what this sketch is of on the first try

4.3 Shared understanding

In engineering design, shared understanding represents the "similarity in the individual perceptions of actors about how the design content is conceptualized" (Kleinsmann et al., 2007). Written explanations of design concepts have been analyzed in previous work to determine shared understanding (Fu et al., 2010). In this study, we analyze the communicator's and listener's explanations of their design concept. In line with previous work (Nandy et al., 2021), we calculated the similarity between these explanations to measure the participants' shared understanding.

Nandy et al. (2021) developed a method for calculating the similarity between textual descriptions. In this method, each design is represented by a unique functional structure that is decomposed into a network. From this decomposition, the similarity is calculated using the network-based similarity approach. For shared understanding, functional structures were developed using the same method discussed in section 4.1. However, rather than creating functional structures just for the participants' explanation of their own idea, we also created functional structures for their partners' explanation of their idea. Using these functional structures, we developed their corresponding networks and calculated their similarity. As an example, consider a dyad of participants 1 and 2. To calculate the similarity between the pair for the idea developed by participant 1, participant 1 presented their concept to participant 2. We then compared participant 1's explanation of their own design concept to participant 2's explanation of the same concept.

These two explanations were used to develop their mental models of the same concept, providing the basis for the similarity calculation. As previously described, we generated functional structures that were converted to networks to quantify similarity. The chosen network-based approach is favorable over other approaches such as the vector-based approach because it allows us to not only capture the function and flows, but also capture specific components as well. In the network for each design concept, individual functions, flows, and components are represented as a single node connected by edges. To account for repeated connections between nodes, the edges were weighted accordingly.

Next, the weighted Jaccard Similarity was calculated based on equation (2) developed by Ioffe (2010):

$$J(G,H) = \frac{\Sigma_k min(G_k,H_k)}{\Sigma_k max(G_k,H_k)} \qquad (2)$$

Consider two weighted networks, G and H, that represent the mental models of the communicator and listener for a particular design concept. For an element (a connection between nodes), *k*, in the union vector, each represents the respective weight of that element in networks G and H. If an element from the union vector is not in the network, its weight is 0. Next, the minimum and maximum weights were identified for each network. The weighted Jaccard Similarity is calculated by dividing the sum of the minima and maxima. In the event that an element is present and weighted equally in both networks, the increment is equal in the numerator and denominator of equation (2). As a result, the similarity either increases or remains constant. In contrast, if the weights are unequal, or if an element is present in only one network, the increment is larger in the denominator, thus decreasing the similarity. This iterative process is used to obtain the weighted Jaccard Similarity which represents the shared understanding between two participants.

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5 RESULTS

This section presents the results of our hypothesis testing. Statistical analyses were computed using R CRAN v. 4.2.0. A hierarchical and linear regression were employed as the most appropriate method of analysis in line with previous work (Cole et al., 2020; Nolte et al., 2020). A significance level of p = 0.05 was used in this analysis. Table 2 outlines the descriptive statistics that were calculated on the participants' sketch understandability and the shared understanding of their design concepts.

Table 2. Descriptive statistics.

Sketch Understandability	*Mean*	3.59
	SD	1.22
Shared Understanding of Design Concepts	*Mean*	0.658
	SD	0.216

RQ: How does the understandability of sketches affect the shared understanding of design concepts within design dyads?

In pursuit of our research question, a hierarchical regression was conducted to determine if the covariate, design complexity, affects shared understanding of design concepts. Design complexity was accounted for as a covariate because prior work has found a relationship between this metric and designers' perceived idea quality (Krishnakumar et al., 2022) . However, the R^2 value for design complexity was small, R^2 = 0.064, and thus, we removed design complexity from the analysis. After removing the covariate, a linear regression was run to understand the effect of sketch understandability on shared understanding of design concepts within design dyads. To assess linearity, a scatterplot of sketch understandability and shared understanding of design concepts was plotted and is shown in Figure 3. Visual inspection of this plot indicated a linear relationship between the variables. There was homoscedasticity and normality of the residuals, and there were no outliers in the data. We found that sketch understandability is not a predictor of shared understanding, F(1,20) = 0.301, p = 0.589. This model only predicted 1.5% (adjusted R^2) of the variance in the shared understanding of design concepts. These results indicate that the understandability of sketches does not affect the shared understanding of design concepts within dyads. More generally, how easy or difficult it is for a listener to understand a communicator's sketch does not affect their shared understanding of the concept.

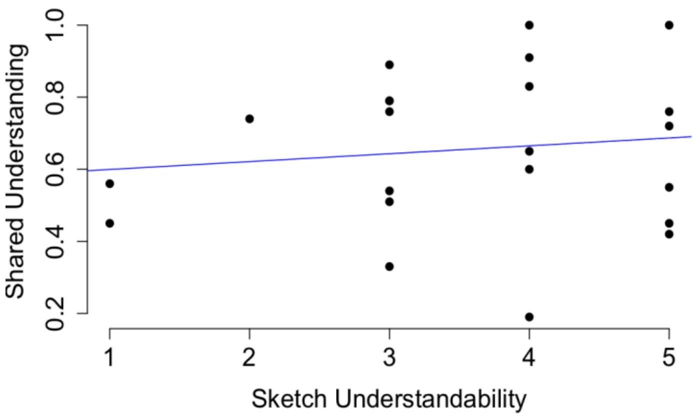

Figure 3. Scatter plot of sketch understandability and shared understanding.

6 DISCUSSION

The main goal of this study was to investigate the relationship between sketch understandability and shared understanding of design concepts within design dyads. Because sketch understandability is a

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new metric used in engineering design, we sought to understand its ability to predict shared understanding in the context of design dyads communicating design concepts. In design, artefacts such as "talking" sketches are often used to aid in communicating design concepts (Ferguson, 1994). Prior work has aimed to identify sketch characteristics that make them more effective tools for communication (Das and Yang, 2022). Specifically, they found a positive correlation between sketch understandability and sketch quality and a correlation between participants' maximum sketch quality and overall design outcomes. We hypothesized that sketches that are more easily understood would increase the shared understanding of the design concepts within design dyads. However, our findings did not support this hypothesis. Our findings first revealed that complexity is not a covariate in the relationship between sketch understandability and shared understanding. We also found that when sketches are used to aid verbal communication, the level of understandability of the sketch does not affect the shared understanding between the communicator and the listener. Results suggest that sketch understandability may not be an appropriate estimation of sketch quality and may not be directly linked to shared understanding between individuals. We highlight this as an area for future work.

7 CONCLUSION AND LIMITATIONS

The main goal of this study was to determine if sketch understandability could predict the shared understanding of design concepts within design dyads. To achieve this goal, a controlled study was conducted on 44 engineering students from the Pennsylvania State University. Our results indicate that sketch understandability does not predict shared understanding of design concepts within dyads. The current study was limited in three significant ways. First, the study was limited by a relatively small sample size that was geographically clustered at one university in the northeastern United States. Thus, the participants' educational background, knowledge, and skills are specific to this region and institution. Future work should compare findings to results across a broader representation of geographic locations. This research was also limited by the time participants were provided to develop their sketches. Participants were given only twenty minutes to develop their design concept and finalize their sketch. Thus, participants may not have had the enough time to comprehensively plan out their ideas and make their sketch presentable. Finally, the study was limited in that shared understanding was determined by the participants' descriptions of design concepts and sketch understandability was rated by the researchers. This discrepancy could contribute to our findings which contradict existing work that suggests a relationship between these two constructs. Future work should aim to understand if the results would differ from participant-rated sketch understandability.

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