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PRELIMINARY SKETCHING AND PROTOTYPING: COMPARISONS IN EXPLORATORY DESIGN-AND-BUILD ACTIVITIES

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ABSTRACT

This study explores the role of sketching when designers are creating fast, preliminary prototypes during hands on design-and-build activities. Many studies have noted the value of both sketching and the building of preliminary prototypes in the early stages of the design process. In a typical design scenario, exploratory sketches are made before prototypes are fabricated. However, in certain cases, the differences in the design exploration value of a sketch and a simple, preliminary prototype may not always be clear. In this study, three conditions for a design-and-build activity were compared: a control group (allowed to freely sketch throughout), a limited sketch group (only allowed to sketch at the beginning) and a no sketch group. The study was conducted twice, using two different prototyping materials each time. One that is assembly only (an Erector set) and one that requires both part fabrication and assembly (foam core). The performance of the prototypes, the type and quality of the sketches, and the relationship between sketches and prototypes were evaluated. Results for this study suggest that fast, preliminary prototypes are equally as useful for design exploration as sketching in building simple mechanisms, though results would likely be different for more complex design tasks.

INTRODUCTION

Designers employ a range of tools and techniques while involved in key activities of early stage design such as generating, selecting, and evaluating concepts. A range of tools may be used to explore and evaluate ideas in order to drive the design process forward, including sketching of possible design

concepts [1-3] and the building of prototypes of design alternatives [4-6]. In particular, the process of constructing physical prototypes of a design idea can uncover important design issues [7] that may not be apparent from a 2D representation such as a sketch.

Sketching is a traditional tool for exploratory, early stage design because it is fast and requires few tools. It is valuable for capturing and communicating design ideas while preserving ambiguity and design freedom [8]. The importance of sketching has been linked closely with design thinking and creativity [9]. It is often thought of its own design “language” to aid in external representation of ideas [10-13]. In contrast, the building of prototypes is usually part of the iteration and decision making process because it allows evaluation of specific aspects of design [14]. Prototypes are typically, though not always, constructed after sketching. Gerber, et al. have found that “low-fidelity prototyping allows practitioners to reframe failure as an opportunity for learning, supports a sense of forward progress, and strengthens beliefs about creative ability” [15]. Like sketching, prototyping can be thought of as residing on the continuum of the visual language of design.

This paper examines a subset of prototypes, specifically fast, preliminary prototypes, which are typically constructed using materials that allow quick fabrication of parts, and/or simple assembly of parts. Industrial designers refer to such prototypes as “sketch models” in part because they grow from sketches yet they are less than a full prototype. The line demarcating a full prototype from fast, preliminary prototypes can be a blurred one.

This study considers the interplay of sketching and prototyping in the design process of a design-and-build activity,

in which the initial and final building materials are the same. The following two research questions are asked:

1. Are there differences in design outcome when designers sketch and when they explore with materials during early stage design?
2. If designers do sketch, are the types, features and timing of sketches linked to better outcome?

Much of engineering design relies on heavy sketching up front in the process, and followed by prototyping. Understanding the role of sketching and prototyping and whether both can be used interchangeably will provide insights for better design and better interpretation of design activity and cognitive processes that occur.

BACKGROUND

Sketching in the design process

A useful way to consider sketching during the design process is to understand the goal of creating a sketch. Ferguson defined three distinct types of sketches: (1) Thinking, (2) Communication and (3) Prescriptive [16]. A thinking sketch represents the thoughts that the designer generates internally. Communication sketches serve as a focal point for stakeholder discussion, while prescriptive sketches are the most detailed and can be used to give instructions to the draftsman who is in charge of making the final drawing.

Shuang and Agogino [3] found thinking sketches pervasive in the design notebooks maintained by student designers as they worked on design-and-build projects. Communication sketches can be used within the design team, and can also provide a mechanism for eliciting feedback from users on design concepts [17]. Other work has shown that prescriptive sketching is important, and a necessary step for preparing a concept for fabrication [18]. Prescriptive sketches often include pre-fabrication information such as part dimensions and descriptive annotations about how parts fit together.

Prototyping in design process

In early stage design, design concepts are often still ambiguous and evolving, and prototypes serve as a valuable way to iteratively approximate a concept over time. Prototypes are generally provisional, and can be constructed in a way to evaluate specific aspects of a concept, such as a design's function or technical performance, its usability or role, and its appearance or styling [14]. Ulrich and Eppinger also consider prototypes beyond the early stage, and categorize prototypes as learning, or exploratory, communication prototypes that are a focal point for stakeholders, integration prototypes to assess how a design performs as an overall system, and milestones to evaluate how a design performs over time [19]. The value of communication prototypes of any fidelity is noted by Schrage [20] as a way to catalyze stakeholders.

The form and material used for these iterative, preliminary prototypes can influence design exploration by virtue of the time and effort spent creating them [21]. In particular, the

simplicity of functional prototypes has been shown to correlate with measures of design outcome [22]. Other work has shown that teams who create prototypes of any type earlier in the design cycle have more successful outcomes [23, 24]. Hannah, et al [25] compare the value of prototypes of varying fidelities, from low resolution to high fidelity.

Schon describes the creation of prototypes as a part of the process of learning that is driven in part by a "conversation with materials" [26]. One learns about a design by physically working with materials, rather than thinking about them only in the abstract. Schutze, et al [27] examined how design outcome would differ based on the amount of time design teams were permitted to sketch out ideas for a barbecue system concept on paper, though this concept was constructed as a physical prototype, and found that teams that were not permitted to sketch or sketch for only part of the time did not perform as well as those who were permitted to sketch. In contrast, Bilda, et al. [28] found that individual designers were capable of generating design concepts without sketching by using only mental imagery.

This paper builds upon this work in order to understand the comparative value of both sketching and fast, low fidelity prototyping in early stage design and build activity. Furthermore, this paper asks the following question: how does a reflective conversation with materials compare with exploratory sketching?

METHODS

1. Design Task

The design challenge for the participants was to build a mechanism to displace a Ping-Pong ball vertically as high as possible with given tools and materials. The displacement of the Ping-Pong ball that the design could achieve was measured at the end of the activity, while participants were allowed to test their design throughout the building time. 30 min were given for the design task. Participants could stop at any time. A timer was visible to the participants. In addition, the facilitator of the experiment reminded the participants of the time when there was 15 min left, 10 min left, 5 min left, 2 min left, 1 min left and when time was over.

2. Participants

The study involved 66 participants in total. The participants came from different engineering departments of a US university, consisting of undergraduate and graduate students, and research affiliates. The sample population was composed of 33 females and 33 males with ages ranging from 18 to 34 years (mean of 23 years).

No compensation was provided to the participants. The participants were recruited through email and posters. During the experiment, they were working individually in an isolated room. Each participant was not given any information about the others' design idea or design outcome (for example, the largest Ping-Pong ball displacement that had been achieved by other participants), in case of potential bias on their own design decision.

3. Experimental Treatment

To study the role sketching plays in the early phase of design, three different settings considering time of sketching were defined:

- No sketching. Participants in this group were not allowed to sketch during the experiment.
- Sketching for the first 5 min. Participants in this group were instructed to spend 5 min at the beginning of the design task to sketch their ideas. They were not allowed to sketch after the 5 min. Nor were they allowed to start building within this 5 min. This 5 min interval was chosen based on pilot experiments that showed participants spent around 5 min sketching.
- Free sketching. Participants in this group were allowed to sketch as little or as much as they desired through out the experiment.

The three conditions were run with two different building materials. In total, there were 6 experimental settings: 2 [material] x 3 [sketching] different experimental settings. Table 1 shows the number of participants within each group of the experiment.

Table 1: Condition of the experiment and number of participants within each group (F – female, M – male)

	Erector set	Foam core
No Sketching	30(F:14 M:16)	9(F:6 M:3)
Sketching for the first 5 min	5(F:2 M:3)	9(F:3 M:6)
Free sketching	5(F:3 M:2)	8(F:5 M:3)

4. Materials

Two kinds of basic building materials were used in the experiment: an erector set and foam core. These materials were chosen such that participants could gain familiarity with them quickly, and could easily be handled throughout the exercise. The erector set was a kit of pre-fabricated aluminum components with various shapes and sizes (Figure 1).

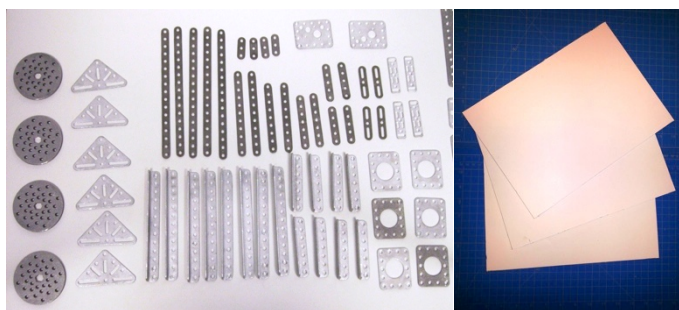


Figure 1: Sample of parts and materials available to participants for design and assembly (Left: the erector set groups; Right: the foam core groups).

The set was purchased from Gear Educational Systems, LLC in Hanover, MA (www.geareds.com). Foam core was provided in square pieces (3 sheets of 8.5 in x 11 in). The erector set components had pre-defined shapes that did not

require participants to fabricate parts, while foam core allowed participants to define the shape of parts, but also required the participants to use basic skills of cutting foam core.

Extra materials were provided such as string, rubber band, and fasteners. Tools for the respective prototyping materials were provided to the participants: pliers, wrenches and screw drivers for the erector metal pieces, while cutting mats, Exacto knives, metal rulers and glue guns were provided to the foam core group.

A 500-gram weight was used as the energy source. During testing and measurement of the design, the mechanism should be activated manually with the weight attached to the device, as specified in the design prompt. This was done to ensure that all designs would have certain rigidity as a design specification. Additionally, this prevented any difference in strength of the participants would lead to vastly different design outcomes.

5. Procedure

5.1 Pre-Survey

After signing the informed consent form, participants were asked to complete a pre-survey asking demographic questions and past design experiences.

5.2 Design Task

The participants were introduced to the design task and were given a short training session about how to cut and build with the foam core safely and effectively. They were encouraged to ask questions to clarify the design requirements and limitations. The participants then started the design task. They sketched or not depending on which group they were in.

5.3 Measurement

After the 30 min were over, final measurements were taken of the height that the mechanisms could raise the Ping-Pong ball. Participants were allowed to measure the displacement at any time during their building time.

5.4 Debriefing Survey

At the end of the experiment, participants were asked to complete a short debriefing questionnaire about their opinions for the design task such as how difficult they find the task is, and how confident they feel when complete the task.

6. Design Outcome Measures

Five measures of design outcome were observed:

- Maximum vertical displacement of ball: the vertical displacement was determined by the initial and final position of the ball. A one-time measurement was made for each design at the end of the time limit.
- For sketch conditions: type of sketches created during the exercise (Thinking, Communication and Prescriptive). The sketch types were independently analyzed after the experiment by the three raters. Thinking sketches were classified as Type I and communication and prescriptive sketches as Type II.
- For sketch conditions: sketch completeness and level of detail. Does the sketch present the whole structure of the

mechanism? Or does it only present part of the mechanism, such as several components?

4) For sketch conditions: sketch proficiency. This criterion measured the technical ability of the sketcher at representing his/her ideas.

5) For sketch conditions: sketch-prototype match. How closely did the prototype match the sketches? This gives a sense of whether prototypes were more a direct implementation of a sketch, or if prototypes were more explorations of design space on their own.

RESULTS

Both foam core and erector set designs were examined and sorted into three categories: pulleys, fulcrums and catapults. Designs were identified as pulleys if the mechanism used string to enable ball displacement. Designs that relied on a pivot point were categorized as fulcrums. Lastly, a design was designated as a catapult if the ball required exiting the mechanism at any point.

Ball attachment to the mechanism could also be placed into two categories. One was a loose connection (no physical connection between the ball and the support structure). A typical example of a loose connection was that ball was placed in a basket. Another typical connection was made either with string or with rubber bands or a combination of rubber bands, string and metal pieces. This was typically seen in fulcrums and pulley designs. Figure 2 shows sample designs of these three mechanisms.

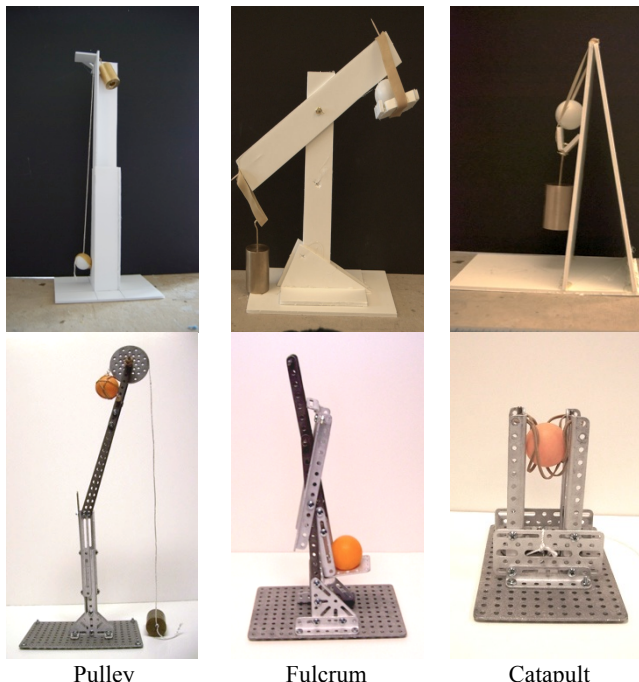


Figure 2: Representative drawings for the three types of design. Top foam core, bottom erector set.

All sketches were categorized as “thinking sketch” by at least two raters out of three. Some sketches (9 sketches out of

23) were categorized as “communication sketches” at the same time. Only a few (4 sketches) were regarded as “Thinking”, “Communication” and “Prescriptive” sketch at the same time. Examples can be found in sketches of **Figure 3**.

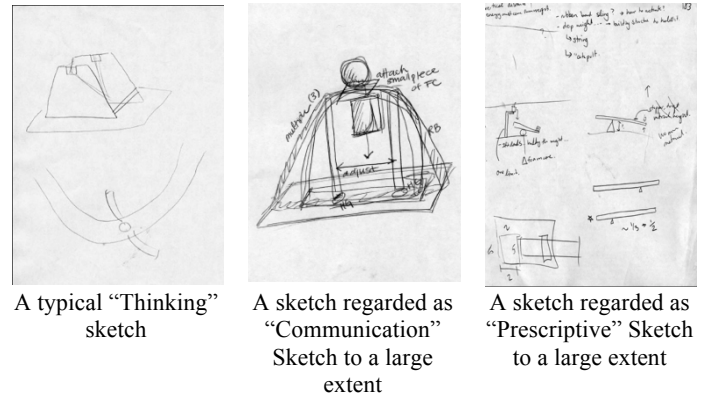


Figure 3: Examples of different types of sketching. Thinking (Type I) sketches showed the least details, whereas communication and prescriptive (Type II) sketches showed notes.

As for the completeness level of detail of sketches, and the sketch proficiency, Likert scales from 1 to 5 are used, where 1 indicates low completeness and 5 indicates high completeness. Average sum of all raters’ score of sketch completeness and level of detail was 8.14. Average sum of all raters’ score of sketch proficiency is 8.7.

When checking the inter-rater reliability, the Krippendorff’s $\alpha = 0.6323$ for Sketch completeness and level of detail; and Krippendorff’s $\alpha = 0.5836$ for Sketching proficiency, which means the evaluation between different raters matches well.

Figure 4 shows examples of low and high sketch completeness and level of detail. A high level of detail sketch may show attachment points, annotations, whereas a low completion level leaves may give a general shape, but does not have any annotations or other guidance. Figure 5 shows examples of sketches indicating low or high proficiency of the sketchers.

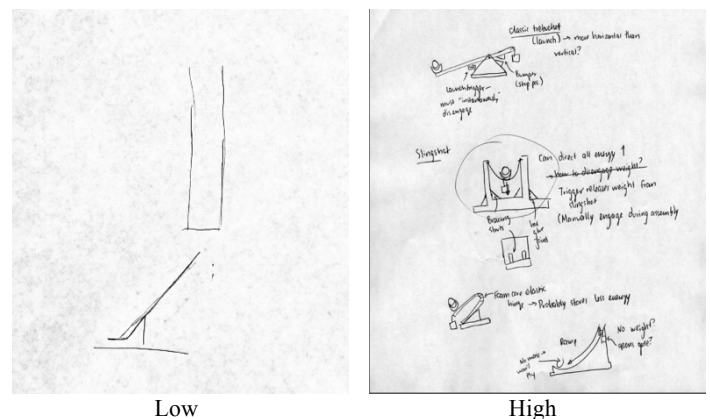


Figure 4: Representative drawings for the sketch classifications (Sketch completeness and level of detail)

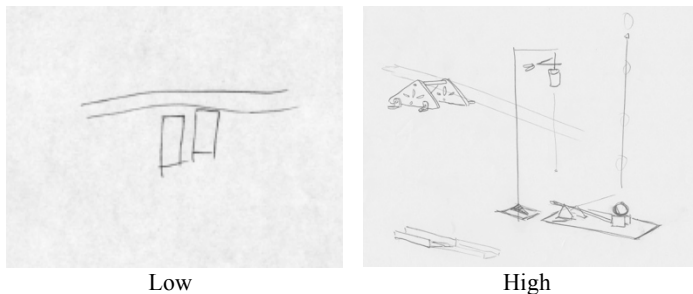


Figure 5: Representative drawings for the sketch classifications (sketch proficiency).

Furthermore, the matching-rate between sketch and prototype was evaluated, also on the 1-5 Likert scale. A high matching-rate indicated that the sketch and the prototype were very similar (see Figure 5). Summation of three authors' rating was calculated. The average score was 10.2.

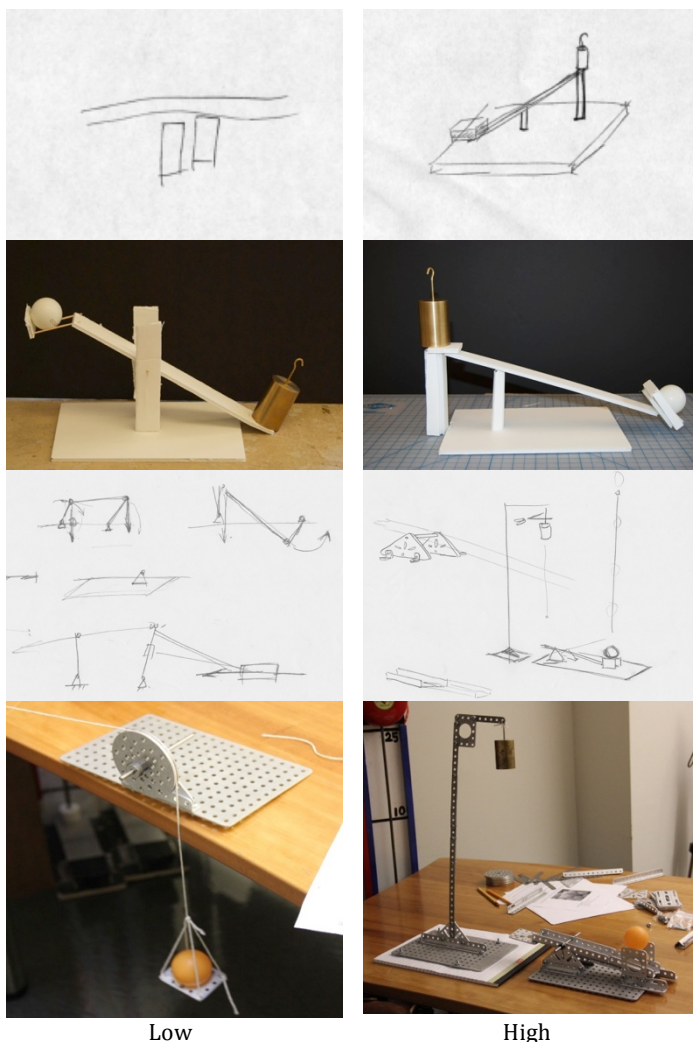


Figure 6: Representative prototypes (foam core and erector set). Low demonstrates a low matching-rate between sketch and prototype, while high shows highest matching.

During both the foam core and erector set activities, all participants experimented with the materials, trying out how parts would fit together. They modified their ideas as they went along in their design.

With foam core, participants sometimes changed the shapes of pieces after they had cut them out. For example, if one piece was too big or didn't fit, they would cut it a slightly shorter. If significant changes were required, the participants would generally make a new piece.

With the erector set, participants usually went through all the parts they could use before they started building. They tried parts together to see whether they would fit each other if attached together, a sort of "conversation with materials." After the participants started building, iterations and modifications usually happened when the participants finished their proof-of-concept building and then decided to improve the mechanism's performance. For example, after one participant finished building a pulley mechanism, he removed the pulley from the top of the support tower and added another piece to the tower to make it taller. Once satisfied, the participant added the pulley to the now taller structure.

However, most participants went through very little iteration during the task. In other words, participants rarely completely abandon one design to start a new one. Because a lot of people felt like they were on a time crunch, they seemed to spend some time figuring out what they're doing in the beginning and then building it.

OUTCOME MEASURES AND DISCUSSION

1. Vertical displacement of Ping-Pong ball

The maximum vertical displacements of ball were measured for every design. The statistical data are given in the following format: mean \pm standard deviation. Table 2 summarizes the vertical displacement measurements and the treatment.

Table 2: Summary of Ping-Pong ball vertical displacement (in)

	Erector set	Foam core
No Sketching	20.67 \pm 15.96	27.87 \pm 12.98
Sketching for the first 5 min	27.40 \pm 23.33	23.91 \pm 14.05
Free sketching	30.80 \pm 18.51	26.45 \pm 33.41
All	25.71 \pm 20.38	26.14 \pm 20.33

ANOVA result (F-Ratio = 0.4458, p-value = 0.8146) shows that there is no significant difference of the maximum vertical displacement between different groups (Figure 7).

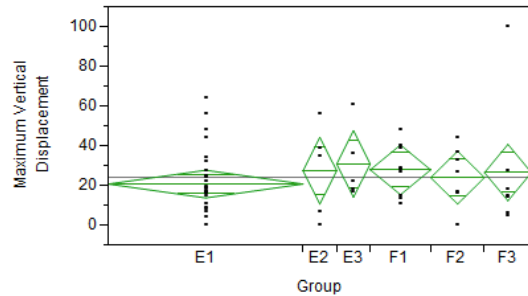


Figure 7: ANOVA of Ping-Pong ball vertical displacement between groups (E represents Erector set, F represents Foam core. And Group 1,2,3 are No sketching, Sketching for first 5 min and Free sketching group respectively).

Further, we regroup the data according to mechanism of the prototypes and compare the maximum vertical displacements (See Table 3):

Table 3: Summary of Ping-Pong ball vertical displacement (in) according to prototype mechanisms

	Erector set	Foam core
Catapult	28.20 ± 8.33	35.77 ± 8.33
Fulcrum	24.03 ± 4.39	21.98 ± 5.89
Pulley	19.81 ± 4.66	25.41 ± 6.21

The catapult mechanisms appeared to be more effective than fulcrum or pulley for both the materials. However ANOVA result (F-Ratio = 0.6448, p-value = 0.6665) shows that there is no significant difference between different mechanisms (Figure 8).

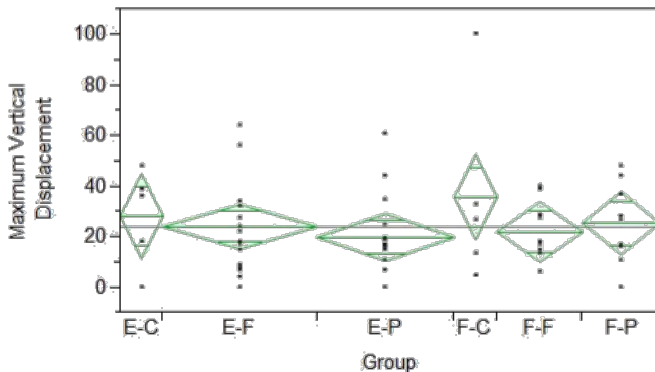


Figure 8: ANOVA of Ping-Pong ball vertical displacement between mechanisms (First letter: E is Erector set, F is Foam core. Second letter: C is Catapult, F is Fulcrum, P is Pulley)

2. Sketching and prototyping

According to the observation of sketching types in the previous session, thinking sketches are highly distinguishable from communicative sketches and prescriptive sketches, while the latter two shares more common features such as includes more detail of the design. Thus we further put the sketches into two categories:

Type I - sketches categorized only as thinking sketch

Type II - sketches categorized with multiple types (being thinking, communicative or prescriptive at the same time)

Participants with type II sketching have a higher matching rate between prototyping and sketching. One-way ANOVA shows a significant difference of matching rate between designs with these two types of sketching with F-Ratio = 8.8906 and p-value = 0.0071 (see Figure 9).

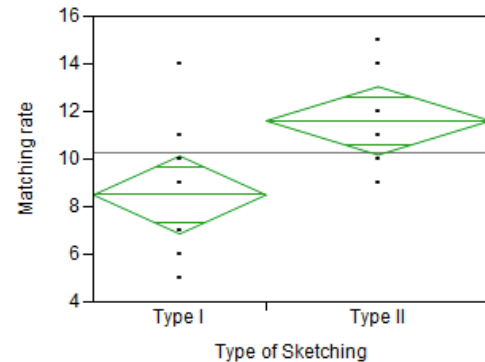


Figure 9: ANOVA of matching rate between groups with different types of sketching.

However the vertical displacement of the Ping-Pong ball has no significant difference between these two groups with ANOVA outcome of F-Ratio = 0.1541 and p-value = 0.6986. In addition, the R^2 of correlation between the maximum vertical displacement of Ping-Pong ball and the matching rate of sketches and prototypes was 0.0433, implying that there is hardly any correlation between these two.

A high matching rate suggests that the design idea formulation process occurred during the sketching period. Prototyping becomes the process of realizing the design physically. A low matching rate can indicate that the design idea was not finalized until the mechanism was actually built. Thus prototyping here is not only the method of presenting the design idea, but also the way of thinking itself.

The significant difference in matching rate between the two types of sketching mentioned above indicates that, when participants using sketching as a thinking tool, they tended to create more detailed sketching. However, a high matching rate didn't guarantee a good performance of the final design, implying that sketching as a design thinking tool is not necessarily better than prototyping as a thinking tool, and vice versa. The sketch completeness and level of detail and the sketch proficiency are well correlated (Figure 10).

However, these didn't correlate with the performance of the design (vertical displacement of Ping-Pong ball) with $R^2 = 0.0022$ and $R^2 = 0.0102$ respectively.

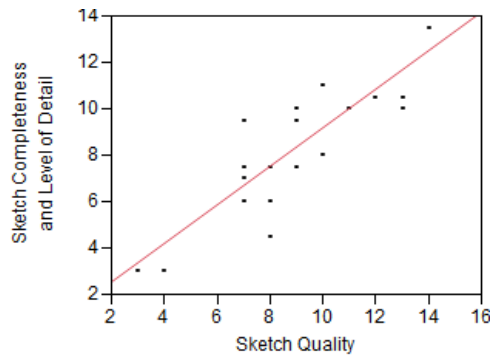


Figure 10: Correlation between sketch completeness and level of detail and Sketch proficiency (RSquare = 0.7629).

3. Influence of sketching time on design outcome

In the free sketching group, the time participants spent on sketching varied a great deal. Some participants didn't sketch at all. Some participants used up to 12 min on sketching. However, the time and effort used on sketching did not necessarily result in a better or worse design.

There were three participants who sketched for more than five minutes in the "any sketch" condition (either building with erector set or with foam core). However one of them performed better than average with the ball displacement of 36 inches, one of them performed worse than average with 5 inches, and one of them performed similar to average with 25.3 inches.

4. Building materials

There is no significant difference in Ping-Pong ball maximum vertical displacement between groups using foam core and groups using erector set. The ANOVA result is not significant (F-Ratio = 0.4774, p-value = 0.4922) (Figure 11).

This justifies the previous comparison between different sketching styles and comparison between sketching time and design outcome regardless the building materials used.

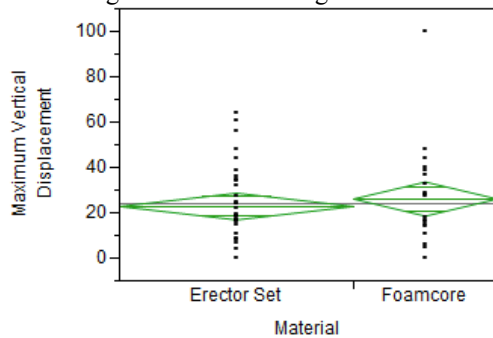


Figure 11: ANOVA of Ping-Pong ball vertical displacement between groups using different building materials.

Interestingly, there were differences in the level of sketching detail between groups with different building materials. There was a significant difference between participants in the foam core group and the erector set group. Participants in foam core groups were more likely to add dimensions during their sketching, presumably to help them while cutting out parts. Nobody in the erector set groups noted

dimensions in their sketching. In addition, 40% participants in foam core group made annotation in their sketch. Only 20% people in erector set groups did so (see Table 4).

Table 4: Sketching between groups using different materials

	Erector set groups	Foam core groups
Draw dimension in sketching	0%	20%
Make annotation in sketching	20%	40%

These observations imply that people have different sketching strategies when working with different building materials. With materials whose shapes have been pre-defined, they tend to sketch less about the details of each piece, and focus on how different pieces should be connected together. With materials whose shape hasn't been pre-defined, such as foam core, people have to plan out the shape and size of each individual piece.

CONCLUSION

This preliminary study explored three aspects of sketching skills in engineering design, and the link between various sketch classifications, prototyping, and design outcome. This experiment focuses on a specific design activity – fast, provisional design-and-building.

The results suggest the following answers to the research questions proposed:

1. *Are there differences in design outcome when designers sketch and when they explore with materials during early stage design?* The results of this study show that the height that a ball was raised did not differ significantly whether or not the individual sketched or spent that same time working directly the building materials. Presumably individuals were able to learn and explore roughly an equal amount from both types of representations.

It should be noted that this exercise was intentionally designed to be simple enough to be completed in a half an hour by novice designers. It is conjectured that sketching and building were similar enough activities for the participants that allowed them to equally explore design space. For more complex design tasks that involved more sophisticated fabrication or design insight, this interchangeability may not hold true. It is difficult to imagine designing a part to be mass-produced without having some sort of initial sketch first.

Furthermore, the initial materials used in this the design task were identical to the materials for the final design, which means there was no need to translate between types of materials through the design cycle. For example, design prototypes often start from modest materials like foam core or cardboard, but the final prototype may be 3d printed polymer or machined metal, necessitating multiple translations of design representations throughout.

2. *If designers do sketch, are the types, characters and timing of sketches linked to better outcome?* No correlation between the completeness and level of detail of sketches, the

sketch proficiency, the timing of sketching and the design outcome were found. It seems that these sketches were used as “internal” thinking and the lack of details and low level of completion did not impact the designer because the mental picture of the design could have been more complete.

One key component that was not addressed in this study was iteration. During a typical design activity, iteration of sketches and prototypes are frequent as they indicate the occurrence of new design knowledge [29-31]. In design practice, design concepts are necessarily sketched and modeled (CAD, for example) first before prototyping or manufacture.

FUTURE WORK

Sketching is a key activity in design and many designers start with sketching before they iterate on their designs. This study suggests that fast, preliminary prototypes created without sketching are equally as successful as those that are created with sketching. We would expect different results with more complex design tasks or different materials or more experienced designers. However, design (and sketching) rarely occurs in a vacuum. This study addressed how designers sketched and prototyped individually. Because sketching and prototyping also serve as a communication tool between designers, the evaluation of the sketch types is somewhat limited. When working in teams, sketches may be more communicative or prescriptive. A follow-up study on team sketching may reveal how details and completeness changes when individual and team members sketch and prototype.

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