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EVALUATING THE IMPACT OF IDEA DISSEMINATION METHODS ON INFORMATION LOSS

Zixuan Victoria Zhao
Mechanical Engineering
Purdue University
610 Purdue Mall, West Lafayette, IN 47907
zhao831@purdue.edu

Christian E. Lopez
Industrial and Manufacturing Engineering
The Pennsylvania State University
State College, PA 16802
cql5441@psu.edu
Mem. ASME

Conrad S. Tucker[1]
Engineering Design,
Industrial and Manufacturing Engineering
The Pennsylvania State University,
State College, PA 16802
ctucker4@psu.edu
Mem. ASME

ABSTRACT

Information is transferred through a process consisting of an information source, a transmitter, a channel, a receiver, and its destination. Unfortunately, during the engineering design process, there is a risk of a design idea or solution being incorrectly transferred and interpreted due to the nonlinearity of the process, and the many ways to communicate and disseminate ideas or solutions. The objective of this work is to explore the amount of relevant design information transmitted by different idea dissemination methods and how the receiver's familiarity with the idea impacts the effectiveness of the methods. First, this work explores the advantages and disadvantages of different dissemination methods in engineering design. Next, an experiment is conducted with engineering and non-engineering participants in order to

[1] Corresponding author. 213 N Hammond Building, University Park, PA 16802, USA

quantify the information transmitted by different idea dissemination methods. This work also quantifies the effect that receivers' familiarity with a design artifact has on the amount of information transmitted by the different dissemination methods. Lastly, the results obtained from the experiments are compared with a previous theoretical model for validation. The results indicate that while certain methods are perceived as more informative and are able to convey more information than others (e.g., Linguistic textual description vs. Virtual 3D models), the effectiveness of the methods depends on a receiver's familiarity with the ideas being transmitted. Knowledge gained from this work can aid designers in selecting a suitable dissemination method needed to effectively communicate ideas and achieve a design solution.

1. INTRODUCTION

The engineering design process is nonlinear in nature and involves the passage of information across designers, disciplines, and processes. Researchers and enterprise decision makers understand the importance of properly managing the communication between team members during the course of a project [1]. The risks associated with incorrectly interpreting an idea or a message can lead to the propagation of errors, including those associated with safety. One such engineering example is the tragedy of the N.A.S.A. Space Shuttle Challenger, where misinterpretation and misunderstanding among team members contributed to the propagation of errors [2].

The information dissemination process in engineering design is analogous to Shannon's Information Theory [3], as a design idea needs to be communicated from one entity (e.g., designer A, Fig. 1) to another entity (e.g., designer B, Fig. 1). Figure 1 shows a side by side representation of how information is depicted by Shannon's Information Theory, and how information is transmitted between designers during the engineering

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design process. When an idea is first envisioned by designer A and then visualized through the aid of a design tool, the process is categorized as idea dissemination. In order to ensure the accuracy of the idea, an idea augmentation process is introduced by providing feedback from designer B to designer A.

In the field of information theory, *Entropy* (H) is associated with "*the amount of freedom of choice we have in constructing messages*" [4]. The higher the freedom of choice a receiver has (e.g., designer B, Fig.1), the higher the entropy, meaning that there are more ways to construct and interpret a message in a given context. Therefore, a wise selection of channels (i.e., idea dissemination methods from a design perspective) has the potential to help designers understand the tradeoffs that exist between information loss and dissemination methods. However, the amount of information transmitted between designers relies heavily on the idea dissemination methods implemented [5]. Furthermore, communicating ideas with verbal languages or visual aids might be perceived differently, depending on many factors such as the stage of the design, the quality of the message, and the receiver's background or prior knowledge [6]. While certain communication methods are more frequently used in certain stages of the design process (e.g., Virtual 3D CAD models are frequently used in the latter stages of the design process), there is still a lack of understanding of how different idea dissemination methods influence the effectiveness of information transfer during the design process.

In order to bridge the gap between the idea dissemination methods and the entropy variation (i.e., how effective the product information is communicated through

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those channels), this work presents an experiment with engineering and non-engineering participants serving as receivers in which the amount of information transmitted by different communication methods is quantified. The experiment is conducted with participants from multiple disciplines with the objective of simulating the diversity of the stakeholders involved in the design process. The knowledge gained from this work can help designers make better decisions as to which methods to use in order to transmit their ideas effectively. Specifically, this work seeks to (1) quantify the information transmitted by different idea dissemination methods that are relevant to a design (e.g., product), and (2) quantify the effect that receivers' familiarity with a product has on the amount of information transmitted by different idea dissemination methods.

2. LITERATURE REVIEW

Communication is a key element for a successful design process, as it enhances the collaboration among individuals [7], the effectiveness of a design [8], and the performance of a design team [9]. Studies indicate that proper feedback and communication between designers can improve the quality of their ideas [10], [11]. From a designer's perspective, there are multiple dissemination methods available to communicate ideas. For example, Owen and Horvath [12] classified the different methods designers can use to transfer knowledge as *Linguistic, Pictorial*, *Virtual, Symbolic*, and *Algorithmic*. The literature review presented in this work classifies research contributions using this taxonomy.

2.1 Linguistic Representation

According to Owen and Horváth [12], *Linguistic* representations are mainly in the form of verbal and textual communications. Linguistic written communication, compared to verbal communication, lacks information cues, feedback, and personal focus [13]. In addition, with this type of communication method, it is challenging to illustrate emotions and affective states of the information source [14]. For example, in a written document, body language and gestures are missing, thus potentially causing an increase in information loss. Given that multiple cues are added during verbal communication, information loss may be reduced [15]. Therefore, verbal communication is useful in the initial and final stages of group work [16] because the instant feedback helps designers clearly frame design problems [17]. However, it is more effective to use asynchronous communication during the execution phase of group work [16]. According to Melnik and Maurer [18], the higher the level of complexity of an idea, the greater the need for verbal communication to interactively share knowledge. However, depending on the speaker's personal background, experience, and time of presence, the choices of words are subject to vary [19]. Another disadvantage of verbal expression was discussed in Brandinnote et al.'s book [20], where it was found that verbal messages tend to hinder the effectiveness of visual-based representations.

2.2 Pictorial Representation

Being quick and inexpensive to create [21], free-hand sketches play an important role during the conceptual design phase [22]–[25]. Designers use sketches to have reflective conversations [26] with their ideas when inspecting and refining their drawings [27]. This cyclic behavior allows a design to grow from a draft to a finished product [25]. Chandrasegaran et al. [28] present an observational study to identify designers' intent through sketching and non-sketching methods. In addition, studies show that impromptu sketches allow designers to obtain a clearer idea during the conceptual design phase [29]. Due to these characteristics, sketches are typically the primary source of idea dissemination during the early stages of the design process [30]. Sometimes, sketches can also be used as a mean for designers to receive constructive feedback from stakeholders and end-users [6]. However, sketches may include internal information that cannot be perceived by others [31] due to the ambiguity and misconception of the information source [26], [31], [32]. This disadvantage results in confusion, as sketches communicate only basic features of an idea, such as its shape and size [21]. To address some of these limitations, designers can integrate annotations and improve the fidelity of their sketches. Based on their intended purpose, design progression, or physical elements, sketches can be categorized into different groups [33], [34]. McGown et al. [35] and Rodgers et al. [36] present a classification based on the physical elements of the sketches. Their taxonomy classifies sketches into five levels:

- Level 1: Monochrome line drawing without shading, text, or annotations.

- Level 2: Detailed monochrome line drawing without shading, but with different thickness of lines and brief annotations of no more than 6 or 7 words.
- Level 3: Detailed monochrome line drawing with rough shading, with possible annotations.
- Level 4: Detailed monochrome line drawing with subtle shading to emphasize 3D form, and possible annotations and colors.
- Level 5: Detailed monochrome line drawing with extensive use of shading to emphasize 3D form, annotations, and colors.

It is noted that 2D sketches may not be suitable for communicating engineering concepts such as stress, heat, or other properties [37]. In addition, compared to prototypes, sketches convey less information in a design context [38]. Performing 2D sketches in a group (i.e., the dissemination of an idea), tends to speed up reasoning [35], [39]–[41], extend memory [42], [43], help understand/feedback [35], [41], [43], and consistently represent ideas [44], [45]. For example, 2D Multiview drawings, being the most commonly used in the industry, are easy to construct and are accurate and descriptive engineering visual representations [46].

There are also several popular 2D sketching techniques that have been studied in engineering design settings. *Talking sketches* is associated with designers utilizing a shared drawing surface in support of the group discussion, making it easier to communicate within a group [47]. In addition to these benefits, graphical idea representations were shown to be better-suited than text information in a design context [29]. As discussed by Vogel et al. [48], electronic individual poolwriting has the

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disadvantage of missing the capability to review in real-time. However, this issue has been mitigated with the wide use of collaborative suites [49].

One of the challenges of communicating through 2D high fidelity illustrations is that individuals need to be equipped with many years of professional training [46]. Recently, deep learning generative models and crowdsourcing methods were implemented to generate new 2D sketched ideas with the objective of exploring the design space [30], [50], [51]. However, most of these tools are only capable of generating low fidelity, rough 2D sketches [52], [53]. Moreover, while researchers argue that these tools will foster designers' creativity [54], studies indicate that human biases might impact their effectiveness in the design process [55].

From the discussion above, no matter which technique the designer chooses, the main characteristic that sets 2D sketches (i.e., Pictorial methods) apart from written documentation and verbal expression (i.e., Linguistic methods) is the informative, yet simple idea construction process, providing richer information than Linguistic methods. However, depending on how complex and how familiar the receiver is with the artifact, the communication results may vary [6].

2.3 3D Digital and Physical Representations

While 2D sketches are widely implemented in the early stages of the design process, 3D models are often used in the latter stages [30]. Nonetheless, there has been an increased use of 3D Computer Aided Design (CAD) tools throughout early conceptual design stages [56]. 3D representation is a major tool for engineering design communication [57]. In our society, a wide range of industries utilize CAD, including engineering, entertainment, business [58]. This is mainly because CAD software enables individuals to interact with, and augment a design artifact. Examples of CAD software include SolidWorks, Blender, OpenSCAD, and Meshlab [59]. Some scholars have also provided evidence of the helpfulness of computer-supported design tools [60], [61], even in the early concept development phases [62], [63]. Using CAD tools, designers are not only able to observe the full visualization of a product, but also experience digital assembly [64]. In addition, in 2D sketches, designers only have a fixed number of perspectives to observe. However, a 3D CAD model enables designers to access the entire design from any perspective [64]. More importantly, 3D CAD models enable designers to quickly modify product ideas during the design process, reducing misunderstanding [65][66].

Unfortunately, 3D modeling software has extremely long learning curves [67], [68]. This is because the more complex the task gets, the harder the production process is [46]. For example, designing an aircraft engine requires the application of CAD software due to the complexity of different components [29]. Therefore, a longer learning curve is needed, compared to 2D sketches. In addition to the long learning curve, researchers have discovered that the application of CAD support during the early design phases, tends to reduce creative visual thinking [69]. Also, while 3D assisted visualizations enhance details and reduce rework [46], it lacks physical interactions [70]. In general, 3D CAD systems can significantly improve coordination and communication among designers and engineers due to their standardized knowledge and language

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representations [64]. As a result of this standardization, machine learning approaches have been proposed to automate the classification of 3D models based on their geometric form and functionality [71].

Different from individually generating ideas in CAD, collaborative CAD is important for dealing with complex projects that include designers from different disciplines [72]. One of the biggest advantages of a collaborative CAD system as suggested by Chen et al. [73], [74], is that it allows itself to resolve conflicts during the early stages of team design, with the help of frequent user interactions and visualization benefits from 3D CAD models. Currently, CAD conference systems like Cspray [75], Webscope [76] and Autodesk Collaboration for Revit [58], offer collaborative viewing and measuring [77]. Li et al. [78] proposed a collaborative CAD system that enables designers to effectively transmit visualizations and information across networks. Researchers have established a synchronized collaborative design platform for CAD systems, allowing designers to conduct a real-time exchange of representation and modifications [79]. In addition, Ramani et al. [80] presented a web-based collaborative environment called Computer Aided Distributed Design and Collaboration. This system enables individuals with limited hardware and software resources to install and utilize this collaborative system. However, security must be considered carefully for future development [78]. Fortunately, this security concern can be resolved through a hierarchical role-based viewing method that has been developed to reduce costs and risks during design collaboration [81].

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Different from 2D sketches and 3D CAD models, physical models and prototypes are built through the representation of a product approximation using different materials [29]. This allows designers to visualize, evaluate, learn, and improve the design specifications [82]. Foam prototyping creates design ideas faster than high fidelity 2D sketching or 3D CAD [83]. Foam prototyping also leads to memory relief [84]. Moreover, physical models contain more information than 2D sketches or 3D CAD models because physical models represent not only geometry, but in some cases the functionality and manufacturability of the design [38]. Tom Kelly [85], the CEO of the IDEO design company, encourages the use of physical models during different stages of a design process. However, it is also noteworthy that developing physical prototypes is not only time and cost consuming [86], but also might lead to design fixation [87], [88]. Moreover, Houde and Hill [89] state that this type of prototyping solution is based on the audience's need and requires a thoughtful process.

It is important that when delivering an idea with various dissemination methods available, appropriateness plays an important role in determining the final selection, as appropriateness is often associated with the output of the idea, especially under a scientific context [90]. For example, communicating an idea to an experienced designer might require little verbal explanation, while delivering a concept to someone that is not in the same field as the information sender would require additional support from other idea dissemination methods (e.g., 2D sketches, 3D prototypes) [19]. In addition, depending on the sender's personal background, prior knowledge, experience, and time of presence, the choices of words are subject to vary as well [19],[61]. Moreover, if a design goal is to only demonstrate an idea in the conceptual design phase, the method chosen could be different if the design objective is to convey a design that is going to be used for final production, as it contains more requirements and constraints [91]. When it comes to processing information, communication methods can vary, depending on what task environment the designers are interacting with [92].

From the previous literature, it is clear that many researchers have examined the advantages and disadvantages of different idea dissemination methods. They have found that multiple factors could play a role in the effectiveness of idea dissemination methods [6], [19], [32], [46]. However, there is still a lack of understanding of how different idea dissemination methods influence entropy change in the design process. In light of this, Zhao and Tucker [93] propose an information entropy approach that designers can utilize to quantify information loss at different stages of the engineering design process. This method can potentially help designers select a suitable dissemination method to effectively achieve a design solution. Based on the literature, the authors indicate that (i) entropy remains high during the early stages of design due to the creative nature of design, (ii) Virtual idea dissemination methods provide the highest amount information content, while Linguistic methods provides the least amount of information, and (iii) information content increases from early stage conceptual design to final product launch. However, their method did not take into account receivers' familiarity with an artifact, which could contribute to the effectiveness of idea dissemination [6], [19]. More importantly, their method is conceptual in nature and does not include a real-world experimental validation. To

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overcome this gap, an experiment is presented in this work to quantify the amount of relevant information transmitted by different idea dissemination methods. In addition, this work quantifies the effects that receivers' familiarity with a design artifact has on the amount of information transmitted by the different dissemination methods. Knowledge gained from this work has the potential to help designers make better decisions as to which methods to use to effectively transmit their ideas in order to fulfill their design goals.

3. RESEARCH QUESTIONS

The amount of information transmitted between designers can be impacted by the idea dissemination methods implemented [5]. However, there is still a lack of understanding of how different idea dissemination methods influence entropy change in the design process. In order to bridge the gap between the idea dissemination methods and the entropy variation (i.e., how effective the information of a design artifact is communicated through those channels), it is important to understand the pros and cons of different idea dissemination methods and their impact on the design objectives. The following research question is posed in order to understand the appropriateness of idea dissemination methods, given the design objectives and the stage of the design process:

- **RQ1:** *At a given stage of design, which idea dissemination method is more appropriate to convey information that is relevant to the design?*

Communicating ideas with verbal languages or visual aids might be perceived differently depending on many factors, such as the stage of the design process, the quality of the message, and the receiver's background or prior knowledge [6], [19], [32],

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[46]. Particularity, receivers' familiarity with an artifact could impact the effectiveness of different dissemination methods [6], [19]. Thus, in this work, the following research question is also posted:

- **RQ2:** *How does receivers' familiarity with a product affect the information transmitted by the communication method used?*

Depending on an individual's personal background, experience, time of presence, the choices of words are subject to vary [19]. Nonetheless, it is still not well understood how the different choices of words affect receivers' understanding of the information. Also, psychologists have found that textual labels that are not commonly used, are perceived as less informative, compared to a fully defined definition or more commonly used labels [94]. Hence, the effectiveness of Linguistic idea dissemination methods might be affected by the words used and the receiver's background. In light of this, the following research question is explored in this work:

- **RQ3:** *How impactful is the wording variation (i.e., whether the word is frequently used or not) on the effectiveness of the idea dissemination method?*

4. METHOD AND EXPERIMENT

To address the research questions posed in section 3, an experiment was conducted to quantify the relevant information of multiple products transmitted by different communication methods. The relevant information relates to specific features of the products (e.g., shape, material, weight). For this study, a crowdsourcing platform was implemented to recruit participants from multiple professions (i.e., engineering and non-engineering). The objective is to simulate the diversity of the stakeholders involved in the design process. In addition, a pilot study was first conducted in order to evaluate the experimental design and capture the textual descriptions commonly used for the products presented in this work. In the experiment, both engineering and non-engineering participants (i.e., receivers) were presented with information of two different products using different communication methods. The participants completed a series of questionnaires to assess the amount of information conveyed by each of the communication methods. Two different products were explored in this study since one of the objectives is to quantify the effects that the familiarity of the receiver with a product has on the amount of information transmitted by the different communication methods (**RQ2**). Moreover, in this study, it is assumed that the senders (i.e., authors as designer A in Fig.1) have a clear idea of the product that they want to transmit (i.e., are very familiar with the product). Details of the experimental design and questionnaires used are provided next.

4.1 Products and Communication Methods

Information about a (1) *coffee percolator* and a (2) *TV remote controller* was presented to participants. While each of these products is known to the average consumer, the TV remote controller is a more familiar product than the coffee percolator [83]. In both the pilot study and the experiment, participants' familiarity with the products was assessed via a set of multiple choice questions (see section 4.3). For this study, *Linguist*, *Pictorial*, and *Virtual* communication methods were evaluated. *Algorithmic* and *Symbolic* methods were not tested since the amount of information they can potentially convey relies heavily on individuals' prior knowledge of the symbols

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or functions used (e.g., the information conveyed by using Geometric Dimension and Tolerancing [GD&T] standard symbols depends on designers' understanding of these symbols [95]).

Figure 2 shows the information presented to participants, given the different communication methods evaluated (i.e., *Linguistic*, *Pictorial*, and *Virtual*). First, a between-subject design was implemented in which individuals were exposed to only one communication method in order to answer questions about the features of the products (see section 4.3, *Product Information Questionnaire*). Subsequently, to rate the amount of information that the different communication methods provide, a within-subject design was implemented in which participants were exposed to all the methods evaluated (see section 4.3, Communication Method Questionnaire). The order in which the products were presented to the participants was randomized as a mean of reducing any potential order or fatigue effects.

For the *Virtual* communication method, participants were presented with 3D CAD models of the products (TV remote controller: psu.app.box.com/v/CAD1, Coffee percolator: psu.app.box.com/v/CAD2). The models did not contain any textual data, only their texture and color were represented. The participants were able to rotate and interact with the 3D models in real-time. For the *Pictorial* communication method, the isometric view drawing of the products was presented. A single isometric view was selected as in previous studies [6] since Pictorial representation during the ideation process is typically a single view [88], [96]. These drawings were high fidelity colored sketches that emphasized the 3D form of the product but with no annotations.

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According to McGrown and Rodgers [35], [36], the Pictorial representation used in this work can be categorized as a Level 4 sketch (see section 2.2).

For the *Linguistic* method, a textual description of each product was presented to participants. The textual descriptions shown were collected from the pilot study. Participants from the pilot study were exposed to the drawings or the 3D models of the products. This was done with the objective of reducing any potential biases that the research team could have introduced by selecting the textual descriptions. From the textual descriptions shown in Fig. 2, only one from each product was randomly selected and presented to a given participant. Multiple textual descriptions were implemented to control for the potential effect that certain words might have on participants' responses (e.g., individuals' use different words to describe or relate to the same product). Moreover, these multiple descriptions allow the authors to quantify the amount of information transmitted by different textual descriptions (**RQ3**).

4.2 Participants Recruitment

For this study, participants were recruited via Amazon Mechanical Turk (AMT). Crowdsourcing platforms, such as AMT, have gained popularity as a tool to support designers during the product development process, as well as to help researchers study the design process [97], [98]. Crowdsourcing platforms are valuable tools for behavioral research since studies have found no significant differences in the response consistency between internet users and laboratory participants [99], [100]. Compared to other crowdsourcing platforms, AMT provides the benefits of (i) low cost, (ii) large rater pool access, and (iii) large rater pool diversity [100].

Participants of multiple professions (i.e., engineering and non-engineering) were recruited for the experiment. The objective is to simulate the diversity of the stakeholders involved in the design process. However, for the pilot study, a restriction that participants were identified as engineers by AMT was implemented since it was necessary for them to describe a product using short and concise descriptions. All the participants were compensated $0.20 for their time and were offered a bonus of up to $1 based on the amount of relevant information provided in the open-ended questions. Only raters with a 95% satisfaction rate or greater were allowed to participate. Similarly, participants were only allowed to be part of either the pilot or the experimental group. Other quality assurances were set in place, which are explained in the following section.

4.3 Questionnaires

Once the participants consented to be part of the experiment, they were randomly assigned to one of three communication methods implemented. Participants in the pilot study were randomly shown either the 2D drawings or the 3D models of the products and asked to provide as many names or words that describe the products. They were also presented with a (i) *Product Familiarity*, and (ii) *Demographics and Experience* questionnaires. Participants in the experimental group were first introduced to the products using only one of the communication methods shown in Fig. 2, and asked to completed a (i) *Product Information* questionnaire. Subsequently, they were introduced to the other methods and asked to compete the (ii) *Communication Method*, (iii) *Product Familiarity*, and (iv) *Demographics and Experience* questionnaires, which are explained next.

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***Product Information Questionnaire*:** For each product, participants had to complete six questions asking about specific features of the product. Figure 3 shows a representation of the *Product Information* questionnaire shown to participants for the TV remote controller using the Pictorial communication method. First, participants were asked (i) *"What form/shape does this product most closely resemble?"*, (ii) "*Provide more details about the form/shape of the product*," (ii) "*What is the function(s) of the product?*", and (iv)"*What material(s) do you feel would be good candidates to make this product out of?*" Subsequently, with a slider question, participants were asked (v) "*Given your material selection, what is the approximate weight of the product in kilograms (kg)?.*" In this question, the images of three different products and their weights were shown as a reference. Finally, via an open-ended question, participants were asked to (v) "*Describe the product in your own words*." In addition to these questions, a quality control question was implemented to ensure that participants were reading the instructions and not randomly clicking through the survey in order to receive the monetary compensation.

Communication Method Questionnaire: For this questionnaire, participants were exposed to the products using all the communication methods, one product at a time (i.e., as shown in Fig. 2). The order in which the product and communication methods were presented was randomized. While showing the different methods, participants were asked to rate them based on the amount of information the methods provided that were relevant to the product at hand using a 7-point Likert scale (i.e., 1: Not Informative-7: Very Informative).

Product Familiarity Questionnaire: This questionnaire contained three questions on a 7-point Likert scale, which asked participants (i) "*How confident are you with the answers provided in the previous pages?" (i.e., 1: Not Confident- 7: Very Confident),*(ii) *"How familiar are you with Italian style coffee makers/ Percolators?",* and (iii) *"How familiar are you with TV remote controllers?"* (i.e., 1: Not Familiar- 7: Very Familiar). All these questions were presented in a random order.

Demographics and Experience Questionnaire: Figure 4 shows the questionnaire presented to participants, in which they were asked about their (i) gender identity, (ii) age, (iii) educational level, (iv) occupation or profession, as well as (v) years of experience in their field. Participants were also asked about (vi) their experience with the Engineering Design process, (vii) experience at sketching, and (viii) with CAD software, using a 7-point Likert scale (i.e., 1: Not Experienced-7: Very Experienced). Finally, participants were asked (ix) to order the different phases of the design process in the correct sequence. In this questionnaire, a quality control question was also included to ensure that participants were reading the instructions and not simply randomly clicking through.

5. RESULTS AND DISCUSSIONS

5.1 Pilot Study

As indicated in section 4, a pilot study was first conducted in order to evaluate the experimental design and capture commonly used textual descriptions for the TV remote controller and the coffee percolator employed. These descriptions were then presented to the participants (i.e., receivers) in the experimental group. This was done to reduce any potential biases that the research team could have introduced by selecting the textual descriptions.

For the pilot study, there were a total of 19 participants (31.6% females). All participants were engineers (30% from computer or electrical engineering fields), with age ranging from 22 to 66 years old (M=37.58, SD=11.99). On average, participants reported that they are familiar with the Engineering Design Process (M=5.1, Mdn=5, SD=1.7), and have confidence in the answers provided (M=5.63, Mdn=6, SD=1.6). Furthermore, the participants spent, on average, 322.6 seconds (SD= 153.8 secs) to complete the questionnaires. Participants provided a total of 162 textual descriptions, 71 for the coffee percolator, and 91 for the TV remote controller. On average, each participant provided 4.26 textual descriptions (Mdn= 4, SD=2.91). The results of the Mann-Whitney U test reveal that participants were more familiar (p-value<0.001) with the TV remote controller (M=6.37, Mdn=7, SD=0.81) than with the coffee percolator (M=4.05, Mdn=4, SD=2.16).

The results from the Semantic Network Analysis[101] reveal that in total, 45 bigrams were presented in the textual descriptions for the coffee percolator, while 84 for the TV remote controller. Also, the results reveal that while describing the coffee percolator, participants frequently used the bigrams (i) *coffee* → *maker*, (ii) *espresso* → *maker*, (iii) *coffee* → *pot*, and (v) *coffee* → *percolator*. These bigrams were presented in 38.9% of the textual descriptions created for this product. For the TV controller, they used the bigrams (i) *remote* → *controller*, (ii) *TV* → *clicker*, (iii) *TV* → *controller*, and (iv)

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TV → *remote*. These bigrams were presented in 44.5% of the text description provided for this product. The findings from the pilot study highlight that the TV remote controller is a more familiar product than the coffee percolator. Moreover, the results reveal that participants provided more textual descriptions for the TV remote controller than for the coffee percolator. Finally, there was more agreement in the textual descriptions for the TV remote controller than for the coffee percolator since when describing the TV remote controller, participants tended to use similar bigrams more frequently than when describing the coffee percolator.

5.2 Experiment Results

After capturing the textual descriptions from the pilot study, participants (i.e., receivers) in the experimental group were shown information about the products using the different communication methods, as shown in Fig. 2. This allows the authors to quantify the amount of relevant product information transmitted by the communication methods. After filtering the participants in the experimental group based on their responses to the quality control questions and time spent reading the instructions (i.e., passed all control questions and spent more than 10 secs reading the instructions), the data of 370 participants (51.9% females) was analyzed. Participants' age ranged from 18 to 72 years old (M=36.31, SD=11.6). Participants' occupations ranged from homemaker and retirees to engineers and managers. On average, they reported having 9.3 years of experience in their field or occupation (SD=8.1). Moreover, the participants spent, on average, 876 seconds (SD= 696 secs) to complete the experiment, and reported confidence in their answers (M=5.69, Mdn=6, SD=1.3).

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Table 1 shows the summary statistics for participants' response to the *Demographics and Experience* Questionnaire. Moreover, the Kendal rank correlation test results indicate that the participants' educational level was positively correlated with their experience with the Engineering Design process (τ=0.1, p-value<0.001). Similarly, participants' self-reported experience with the Engineering Design process was positively correlated with their experience at sketching (τ=0.43, p-value<0.001), with CAD software (τ=0.65, p-value<0.001), confidence in their answers (τ=0.15, p-value<0.001), and correct ordering of the Engineering Design Phases (τ=0.09, p-value=0.009). These findings support the validity of participants' responses and questionnaires since these questions were tapping into similar constructs of experience. In addition, participants also reported to be significantly more familiar (p-value<0.001) with TV remote controllers (M=6.55, Mdn=7, SD=0.78), than with coffee percolators (M=3.87, Mdn=4, SD=2.07). These results confirm that the TV remote controller is a more familiar product than the coffee percolator.

The results from the non-parametric Kruskal-Wallis analysis of variance indicate that participants reported, on average, to perceive the Linguistic textual descriptions (M=4.87, Mdn=5, SD=1.35) as significantly less informative (p-value<0.001) than the Pictorial 2D drawings of the products (M=5.33, Mdn=6, SD=1. 25). Moreover, the difference in perception between the Linguistic and Pictorial methods was significantly different between the products (p-value=0.02). The results indicate that the difference between these two methods was greater for the coffee percolator (M=0.57, SD=1. 85) than for the TV remote controller (M=0.28, SD=1.7). The results also indicate that the

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Linguistic textual descriptions were perceived as significantly less informative (p-value<0.001) than the Virtual 3D models of the products (M=5.4, Mdn=6, SD=1. 67). However, this was not significantly different between the products (p-value=0.12). While the results also indicate that, on average, the Virtual 3D models (M=5.4, Mdn=6, SD=1. 67) were perceived as more informative than the Pictorial 2D drawings (M=5.33, Mdn=6, SD=1. 25), there was not enough evidence to indicate a statistically significant difference at an alpha level of 0.05 (p-value=0.085). These findings reveal that individuals perceived Linguist methods as less informative than Virtual and Pictorial methods. However, they also indicate that this perception depends on individuals' familiarity with the product.

Participants also perceived the multiple textual descriptions differently. Table 2 shows the summary statistics for participants' perception of the different textual descriptions, as well as the frequency that these textual descriptions were used by the participants in the pilot study. The Mann-Whitney U test results reveal that, on average, participants perceived the textual description for the TV remote controller (M=5.07, Mdn=5, SD=1.63) as more informative (p-value<0.001) than the textual description for the coffee percolator (M=4.77, Mdn=5, SD=1.73). Moreover, the results from the Kendall's rank correlation test indicate that participants' perception of the different textual descriptions used for the TV remote controller was positively correlated with the frequency at which these bigram descriptions were used by the participants in the pilot study (τ=0.12, p-value<0.001). However, there was not enough evidence to indicate a significant correlation between the textual description used for the coffee percolator and the frequency in which they were present in the pilot study responses (p-value=0.1). These results reveal that individuals' perception of a product described in Linguistic texts depends on the words used and how familiar they are with the product.

To analyze the responses regarding the materials and shapes of the products, the correct choices were selected based on the manufacturing specifications of the reference products used by the authors. When analyzing participants' responses to what form/shape the products most closely resemble, it was assumed that the shape of either "*cylinder*" or "*rectangular cuboid*" was the correct choice for both the TV remote controller and coffee percolator. Similarly, the choices of "*metal*" and "*plastic*" were considered to be the correct choices for the material of the products. The results from the χ-square test indicate that for the TV remote controller, the proportion of participants that selected the correct choices was not significantly different between the communication methods (p-value=0.267). However, for the coffee percolator, the results indicate that there was a statistically significant difference (p-value=<0.0001), showing that the majority of the participants who were exposed to the Linguistic textual descriptions tended to select the incorrect choices (proportion of incorrect responses for Linguistic: 0.32, Pictorial: 0.04, Virtual: 0.06). Moreover, the Mann-Whitney U test results reveal that participants that selected the correct choices reported, in average, to have a statistically significant greater familiarity (p-value: 0.007) with the products (M=5.26, Mdn=6, SD=2.06) than those who selected the incorrect choices (M=4.71, Mdn=5, SD=1.93).

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A similar trend was observed for the responses regarding the products' material. The results reveal that the proportion of participants that selected the correct choices was significantly different between the different communication methods (p-value=0.003). The variation in choices indicates that a greater proportion of participants that were presented with the Linguistic textual descriptions and Pictorial 2D drawing tended to select the incorrect choices (proportion of incorrect responses for Linguistic: 0.07, Pictorial: 0.03, Virtual: 0.008). Furthermore, the Mann-Whitney U test results reveal that participants that selected the correct choices reported, in average, to have a statistically significant greater familiarity (p-value: 0.042) with the products (M=5.24, Mdn=6, SD=2.04) than those who selected the incorrect choices (M=4.21, Mdn=4, SD=2.30). These findings reveal that different communication methods convey different amounts of information. This trend is more predominant when receivers are presented with products that they are not familiar with. This gives designers more opportunities to utilize appropriate idea dissemination methods to ensure the delivery of the correct information and reduce entropy accordingly.

Finally, the results reveal that participants, on average, reported the coffee percolator as heavier (M=1.49kg, SD=0.55) compared to the TV remote controller (M=0.55kg, SD=0.33kg). The independent t-test results indicate that this difference was statistically significant (p-value<0.001). These results indicate that participants responses were positively skewed considering that the coffee percolator used as reference weights 0.5kg, while the TV remote controller weights 0.05kg. Furthermore, the Analysis of Variance test results show that participants' responses to the weight of

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the coffee percolator were dependent on the communication method presented (p-value<0.001). The multiple comparisons of Tukey test results demonstrated that for the coffee percolator, there was a significant difference (p-value=0.023) between the responses of participants presented with the Linguistic method (M=1.65kg, SD=0.59kg) and the Pictorial method (M=1.47kg, SD=0.51kg). There was also a statistically significant difference (p-value<0.001) between the responses of participants presented with the Linguistic method and the Virtual method (M=1.36kg, SD=0.51kg). There was not a statistically significant difference (p-value=0.21) between the responses of participants presented with the Pictorial method (M=1.47kg, SD=0.51kg) and the Virtual method (M=1.36kg, SD=0.52kg). For the TV remote controller (Linguistic: M=0.59kg, SD=0.34kg; Pictorial: M=0.56kg, SD=0.32kg; Virtual: M=0.49kg, SD=0.32kg), this relationship was not statistically significant at an alpha level of 0.05 (p-value=0.084). These results illustrate that Linguistic communication methods are not able to convey as much information as Virtual or Pictorial methods. However, this relationship depends on how familiar an individual is with the idea being transmitted. The effect of utilizing different idea dissemination methods is not prevalent when individuals are exposed to artifacts that they are already familiar with.

6. DISCUSSION

Table 3 shows a summary of the empirical findings presented in this work, alongside the theoretical results proposed by Zhao and Tucker [93]. The results of this work support several of their theoretical propositions. The responses of participants reveal that the Virtual idea dissemination method was perceived to provide higher information content, while the Linguistic method was perceived to provide less information. The results from the multiple choice questions also provide evidence that Pictorial and Virtual idea dissemination methods are more informative than Linguistic methods. These findings help provide empirical evidence for Zhao and Tucker's theoretical framework [93]. However, the discrepancy between information content delivered through these different communication methods is affected by receivers' familiarity with the information being transmitted. According to Barrows [102], prior knowledge helps facilitate understanding. Therefore, if information about familiar products or ideas is transmitted, the difference between the information transmitted with these methods is not as significant, compared to less familiar products. When participants are familiar with an object, even if they are not given sufficient information, they might be able to fill in the information gap with their prior knowledge because participants are able to reconstruct a relationship between the outcome and given information [103][104]. In terms of entropy, the more familiar a participant is with an artifact, the lower the entropy is. However, on average, when participants are presented with textual data, the results indicate that they tent to selected incorrect choices for the shape and material of the artifacts. These results are comparable with the concept that high entropy is present in the early stages of design, which help support the conceptual model proposed by Zhao and Tucker [93].

Moreover, it is also observed in the pilot study that when a more familiar product was shown to the participants, they tended to provide more textual information. In addition, the experimental results indicate that participants perceived

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the commonly used textual descriptions as more informative than the textual descriptions that were less frequently used to describe the products. This demonstrates that the selection of words does affect the effectiveness of knowledge transfer in Linguistic methods. This observation is consistent with the conceptual example presented in Zhao and Tucker's work, where the word "*coffee grinder*" reduced entropy (compared to the world *"grinder"* alone). Furthermore, the findings are in line with the recent study presented by Hemmatian and Sloman [94], indicating that textual labels which are not extensively used by a community (i.e., unentrenched labels) are found to be less informative compared to a fully defined concepts or more commonly used labels (i.e., entrenched labels).

During the latter stages of the design process, the number of design parameters that need to be defined increases [105]. Hence, designers need to transmit more information as the design progresses. Decision-makers need to take into account not only the amount of information that needs to be transmitted when selecting their idea dissemination method, but other factors as well (e.g., the complexity of the methods, the objective of design stage). For example, while results of this study reveal that the Virtual 3D models transmit more information and are perceived as more informative, research indicates that the application of CAD support tools during the early design phases tends to reduce creative visual thinking [69]**.** As proposed by Zhao and Tucker [93], during the conceptual design phase, to facilitate idea generation and keep entropy high, verbal communication is encouraged. The embodiment design phase focuses on the specific requirements of the design. Therefore, detailed sketches should be

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promoted as they help reduce entropy, compared to verbal communication. During the detail design stage, the goal is to be able to proceed to the final production. Therefore, having a 3D/physical model enables the demonstration of functionality and cost of the product. This is observed in the responses of the participants, where they tend to provide a more accurate weight of the products when presented with the Virtual communication method.

While the results show a clear order of which communication method tends to transmit more information (i.e., (i) Virtual, (ii) Pictorial, (iii) Linguistic), the results also suggest that the differences are mediated by other factors such as receivers' familiarity with the idea being transmitted. This reveals that there is some flexibility for designers to select and tailor their idea dissemination process. For example, if a quick prototype of a familiar idea can deliver the message efficiently at the conceptual stage, designers do not necessarily have to start with verbal communication. In addition, using different media channels at the same time stimulates the understanding of the context [5]. Therefore, besides the conceptual method proposed by Zhao and Tucker [93], designers may also consider implementing familiarity into the work cycle. For example, Fig. 5 shows the method proposed by Zhao and Tucker [93] for formalizing the flow of selecting appropriate idea dissemination methods that integrate designers' familiarity with the artifact. If designer A (i.e., sender) is trying to communicate a design of an artifact to designer B (i.e., receiver) who is very familiar with the artifact, he/she may choose an available idea dissemination method, based on the given stage as discussed in Zhao and Tucker's theoretical framework [93]. However, if designer B is not familiar

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with the artifact, starting with 2D Pictorial or 3D Virtual representations might help mitigate confusion as these techniques provide more information content.

7. CONCLUSION AND FUTURE WORKS

Shannon's information theory highlights the structure of information transmission. The information dissemination process in engineering design is analogous to Shannon's Information Theory as a design idea needs to be communicated from one entity (e.g., designer A, Fig.1) to another entity (e.g., designer B, Fig.1). However, the engineering design process is nonlinear in nature and involves the passage of information across designers, disciplines, and processes. Moreover, designers have at their disposition different methods to communicate and disseminate their ideas. While certain methods are more frequently used in certain stages of the design process, there is still a lack of understanding of how different idea dissemination methods influence the effectiveness of knowledge transfer in a design process. In order to bridge this gap, this work presented an experiment in which the relevant product information transmitted by different communication methods, and the effectiveness of knowledge transfer was quantified. The results from this study help validate previous work and demonstrate that Virtual and Pictorial communication methods transmit more information than Linguistic methods. However, the results also reveal that this relation is dependent on how familiar the receiver is with the ideas being transmitted. This emphasizes that the amount of information transmitted by a communication method varies with a receiver's familiarity with the design artifact.

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While this work provides empirical evidence of the amount of information transmitted by different communication methods and supports the theoretical propositions from previous studies, several limitations exist. While a pilot study was utilized to minimize biases that the research team could have introduced by selecting the textual descriptions, the nature of textual descriptions may lack details of an object. This could potentially lead to an unequal amount of information given to the participants (i.e., receivers). Future works should improve the fairness of representation to minimize the effects of possible unfair comparisons. For example, participants' responses to the weight of the products were positively skewed, indicating that they tended to overestimate the weight of the products (see section 5.2). Hence, future studies should explore the effects that providing scale information of the products has on participants' responses. Moreover, the current experiments provide a limited range of participants. Adding diverse participant groups could enhance the research findings to include a broader range of design applications. Another potential limitation of this work is the design of the *Communication Method* questionnaire, where participants rated the different communication methods based on the perceived information transmitted. In this questionnaire, it was assumed that participants would rate the information level based on how the different methods would have helped them answer the questions regarding the product features (i.e., as shown in the Product Information questionnaire, see section 4.3). Future studies should improve the design of this questionnaire by providing more detailed descriptions or instructions.

Furthermore, the experiments were conducted via a crowdsourcing platform and not in a control laboratory environment. While studies indicate that there are no significant differences between the response of internet users and laboratory participants [100], [106], conducting the experiment in a controlled environment may improve the validity of the experiment. In addition, in this work, a limit set of communication methods was explored (i.e., Linguistic, Pictorial, and Virtual). Studies indicate that physical models contain more information than 2D sketches or 3D CAD models because they represent not only geometry, but in some cases the functionality and manufacturability of the design [38]. Hence, future work should explore other idea dissemination methods such as foam prototypes. Nevertheless, knowledge gained from this work could help designers with selecting a suitable dissemination solution to effectively deliver their ideas by considering factors including receivers' familiarity with the ideas, complexity of the ideas, and design stage.

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TABLE CAPTION LIST

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Table 1. Summary of participants' response

	Frequency	Percentage	
Educational Level			
Less than a high school degree	4	0.5	
High school graduate (high school diploma or GED)	39	5.2	
Some college but no degree	56	7.5	
Associate degree in college (2-year)	42	5.6	
Bachelor's degree in college (4-year)	153	20.5	
Master's degree	61	8.2	
Doctoral degree	9	1.2	
Professional degree (JD, MD)	6	0.8	
	M	**Mdn**	**SD**
Experience with:			
The Engineering Design Process	2.52	2	1.76
At sketching	3.39	3	1.92
With CAD software	2.4	2	1.74
Confidence in their answers	5.69	6	1.34
Order of Design Phases			
Absolute deviation from correct order	1.17	2	1.2

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Table 2. Summary of participants' perception of different textual descriptions

Textual descriptions	M	Mdn.	SD	Freq.*
TV controller	5.11	5	1.51	182
Remote controller	5.1	5	1.63	255
TV clicker	4.51	5	1.72	146
TV remote	5.56	5	1.48	219
Coffee maker	4.92	5	1.68	208
Espresso maker	4.77	5	1.8	80
Coffee pot	4.67	5	1.68	48
Coffee percolator	4.72	5	1.77	32

Notes: frequency that the word bigram was mention in the description provided by the participants from the pilot study.*

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Table 3. Summary of experimental results and theoretical propositions from Zhao and Tucker [93]

Conceptual findings from Zhao and Tucker [93]	Experimental results of this work
• Pictorial and Virtual idea dissemination methods are more informative than Linguistic methods.	• Linguistic methods are perceived as less informative than Pictorial and Virtual methods. • Participants shown Linguistic methods tended to have more incorrect answers than participants shown the Pictorial and Virtual methods.
• The Linguistic idea dissemination method introduces ambiguity and confusion in early design phases. However, adding more descriptive modifier texts helps mitigate confusion and reduce entropy.	• Participants provided more Linguistic texts to describe an artifact they were familiar with. That is, out of 162 textual descriptions provided in the pilot study, 71 were for the coffee percolator (i.e., less familiar artifact), and 91 for the TV remote controller (i.e., more familiar artifact). • The textual descriptions frequently used by participants in the pilot study to describe an artifact were perceived as more informative than the textual descriptions that were less frequently used.
• The "Feedback loop" within the formulation of selecting the appropriate idea dissemination methods takes into consideration of gaps between design A (i.e., sender) and designer B (i.e., receiver).	• There are individual factors that confound the effects of how much information a communication method transmits. Participants' perception of how informative communication methods were, and the amount of information transmitted by the methods, was dependent on their familiarity with the idea being transmitted.

FIGURE CAPTIONS LIST

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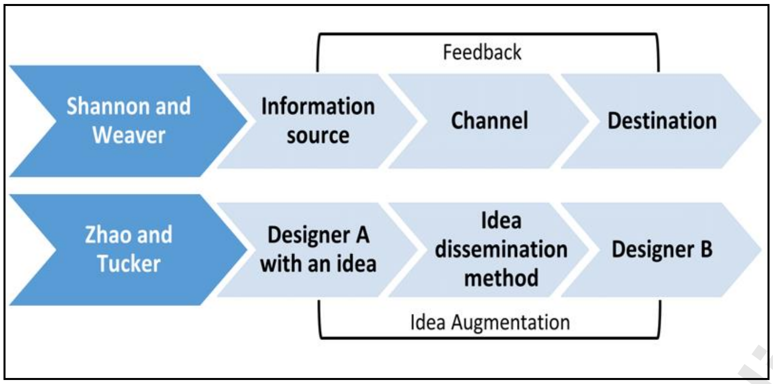

Fig. 1. A parallel drawn between Information Theory and the Engineering Design Process [93]

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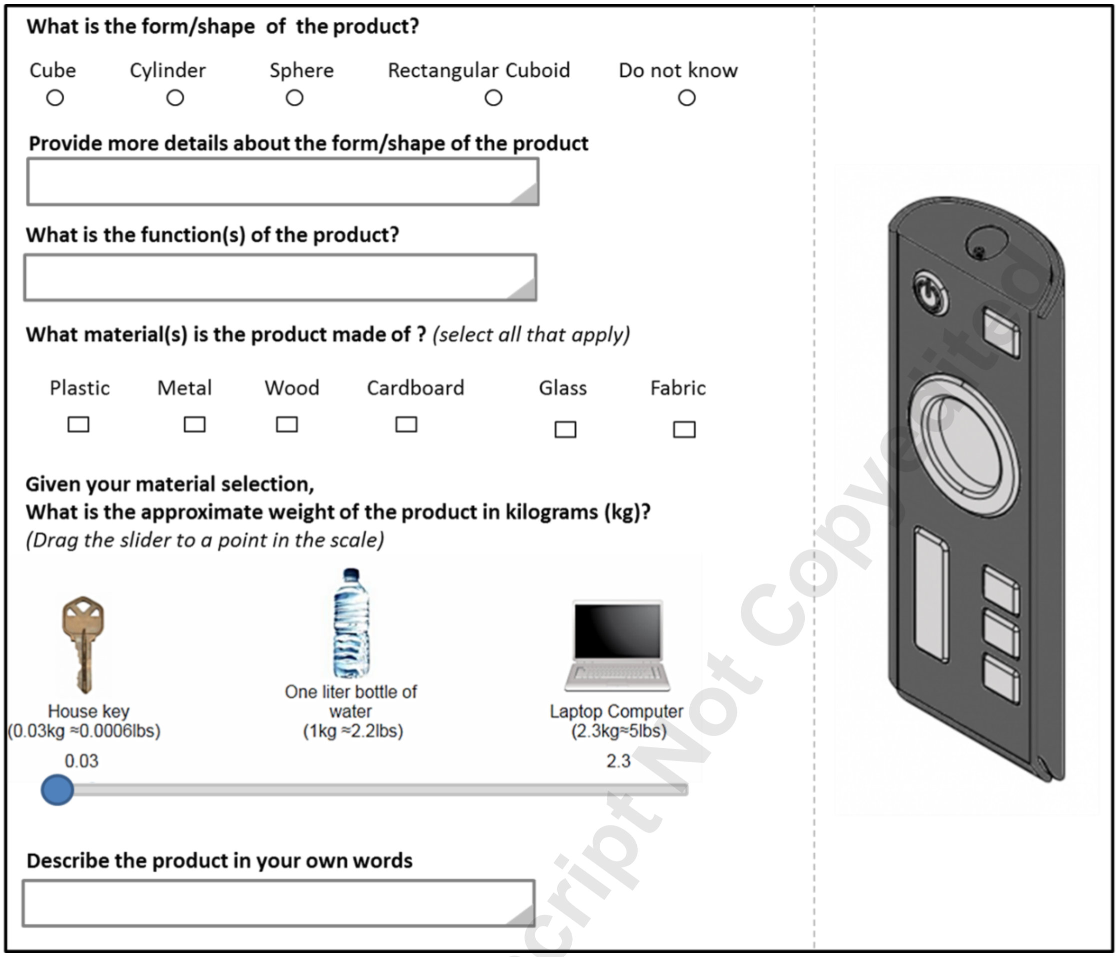
Fig. 2. Product information given the different communications methods


What is the form/shape of the product?

Cube ○ Cylinder ○ Sphere ○ Rectangular Cuboid ○ Do not know ○

Provide more details about the form/shape of the product

What is the function(s) of the product?

What material(s) is the product made of ? *(select all that apply)*

Plastic ☐ Metal ☐ Wood ☐ Cardboard ☐ Glass ☐ Fabric ☐

Given your material selection,
What is the approximate weight of the product in kilograms (kg)?
(Drag the slider to a point in the scale)

House key (0.03kg ≈0.0006lbs)
One liter bottle of water (1kg ≈2.2lbs)
Laptop Computer (2.3kg≈5lbs)
0.03
2.3

Describe the product in your own words

Fig. 3. Example of Product information Questionnaires for the TV remote controller

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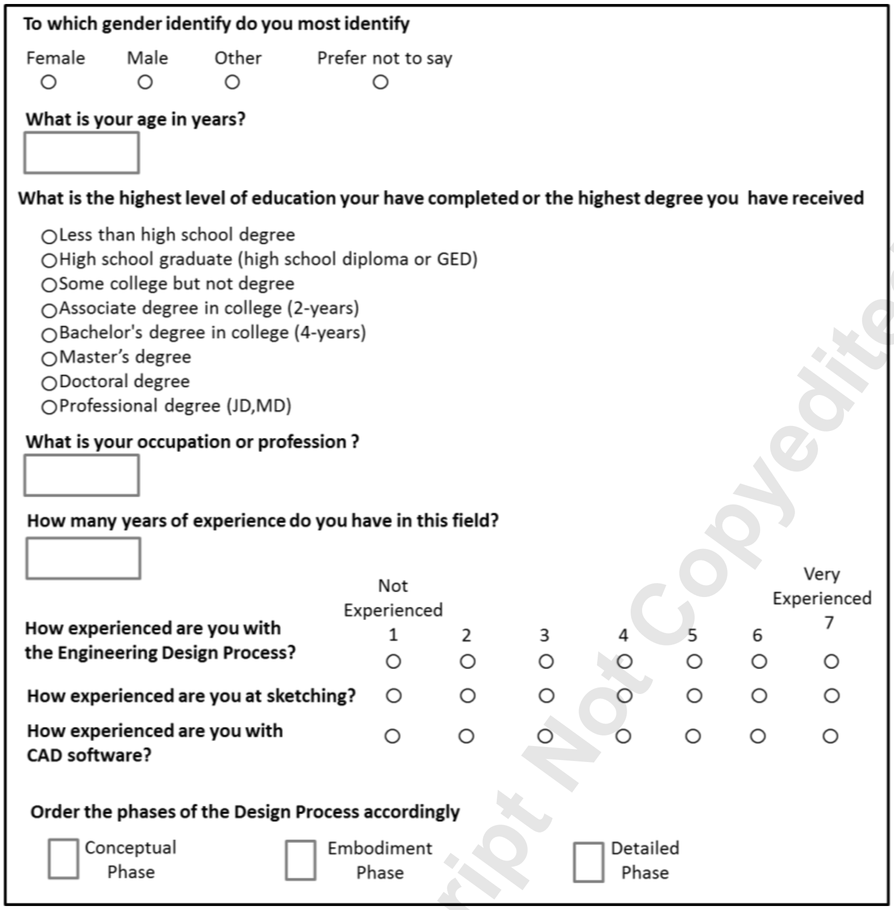
To which gender identify do you most identify

Female ○ Male ○ Other ○ Prefer not to say ○

What is your age in years?

What is the highest level of education your have completed or the highest degree you have received

- ○ Less than high school degree
- ○ High school graduate (high school diploma or GED)
- ○ Some college but not degree
- ○ Associate degree in college (2-years)
- ○ Bachelor's degree in college (4-years)
- ○ Master's degree
- ○ Doctoral degree
- ○ Professional degree (JD,MD)

What is your occupation or profession ?

How many years of experience do you have in this field?

	Not Experienced 1	2	3	4	5	6	Very Experienced 7
How experienced are you with the Engineering Design Process?	○	○	○	○	○	○	○
How experienced are you at sketching?	○	○	○	○	○	○	○
How experienced are you with CAD software?	○	○	○	○	○	○	○

Order the phases of the Design Process accordingly

☐ Conceptual Phase ☐ Embodiment Phase ☐ Detailed Phase

Fig. 4. Example of Demographics and Experience Questionnaire

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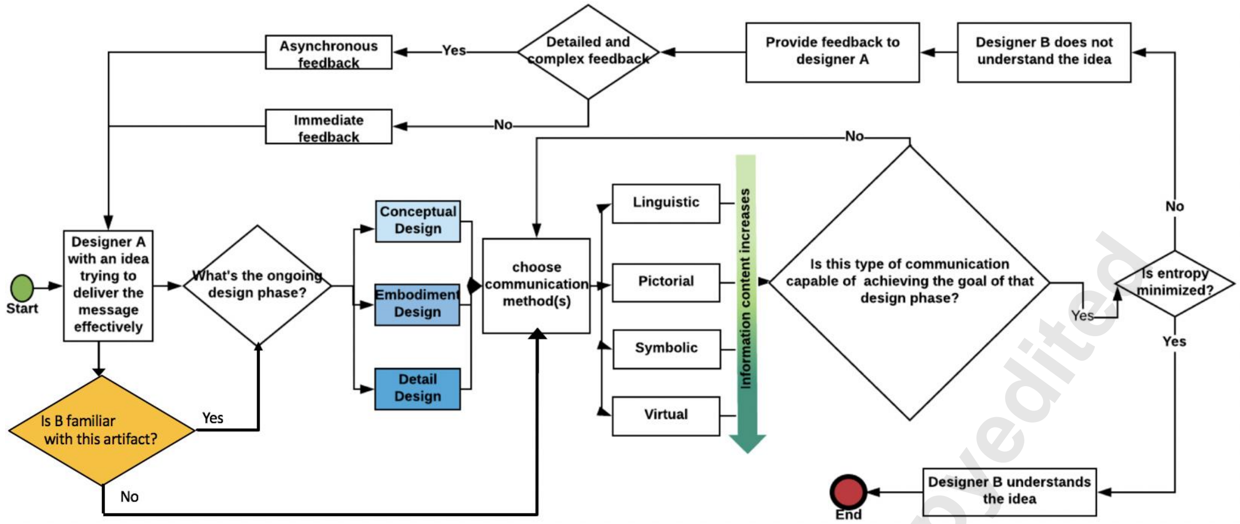

Fig. 5. Formalizing the process of selecting the appropriate idea dissemination method when familiarity is considered