Proceedings of the ASME 2021
International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2021
August 17-20, 2021, Online, Virtual

DETC2021-71750

INVESTIGATING MIND-MAPPING AS A TOOL FOR PROBLEM EXPLORATION IN EARLY DESIGN

Ting-Ju Chen*, Shantanu Vyas†, Vinayak R. Krishnamurthy‡
J.Mike Walker '66 Department of Mechanical Engineering
‡Department of Computer Science and Engineering (by Affiliation)
Texas A&M University, College Station, TX, USA.

ABSTRACT

We present an experiment to study the role of mind-mapping as a tool for design opportunity identification and problem understanding. Our goal is to investigate how the quality of design opportunity statements change with two different techniques, namely, mind-mapping and free writing. Identifying design opportunities is an important step in new product development and little is currently understood in terms of what tools can provide cognitive support for problem clarification. In this work, we focus on mind-mapping as one example of a potential tool for providing such support. Mind-maps are well-known for their ability to enable the exploration of ideas in an unconstrained and structured way. To study their role in helping problem exploration, we conducted a between-subject user study with 28 *participants to investigate how information structure and organization affect the exploration of ideas in a given design context. Further, we propose new evaluation metrics to quantitatively assess key elements presented in the design opportunity statements generated after exploring the problem domain. We report on the quantitative results, the exploration behaviors, and the general user feedback about the experience. Finally, we discuss the implications of these findings on design problem identification and future digital mind-mapping tools for exploratory tasks.*

*Email: carol0712@tamu.edu
†Email: svyas@tamu.edu
‡Email: vinayak@tamu.edu, Address all correspondence to this author.

1 Background & Motivation

Identifying product opportunity gaps and needs for a product is an essential and critical step in the product development cycle, wherein designers discover unmet needs through problem exploration, and frame the design scope to be focused yet broad enough for innovative possibilities. A well-developed understanding of the given design context is important as it allows the designer to discover new perspectives to identify the needs behind a given product opportunity gap [1]. However, identifying potent design opportunities is often difficult because the problem space is often ambiguous, open-ended, and has many degrees of freedom as is common in design [2, 3].

Given the importance assigned to problem exploration [4] and clarification (and rightfully so), it is interesting to note that much of the research in design theory and methodologies has generally focused on cognitive tasks involving the solution space. Specifically, most current efforts focus on implementing methods for ideation [5, 6], conceptualization [7, 8], and concept evaluation [9, 10]. As a result, techniques such as sketching, brain-writing, c-sketch [7], morphological matrices [11], word-trees [12, 13], design by analogy [14, 15] and many others are primarily studied as tools to develop design concepts to solve the problem. In this paper, we seek to complement existing literature with a study of problem exploration and opportunity identification. We specifically focus on mind-mapping as a tool that could be especially useful for problem understanding and clarification.

Mind-mapping is a visual tool used for externalization and organization of ideas thereby promoting critical thinking and learning skills [16, 17]. Mind-maps can be created for virtually any topic of interest. The central premise of our work is that it is this generality and simplicity of mind-mapping that potentially makes it a powerful tool for facilitating the *pre-conceptualization* stage when a crisp design problem statement is not yet available. In particular, the possibility of explore a diverse set of ideas and emphasize the relationships between ideas in a hierarchical fashion [18] is what may be useful during problem clarification and opportunity identification around a design theme. However, like most other techniques, most studies in design research have explored mind-maps as tools for conceptualization [19, 20, 21] and creative ideation [22, 23, 24]. It is important to note here that problem exploration and conceptualization are not necessarily sequential processes, i.e., it is entirely possible (and perhaps even common) for solution concepts to help clarify the problem and for the problem exploration help generate meaningful solution concepts [25]. However, for simplicity, we follow the approach typically taken in the engineering design classroom where one typically conducts problem exploration as a first step in product development cycle to identify design opportunities and needs in a solution-neutral fashion. Within this context, our objective in this paper is to study mind-mapping as a problem exploration tool. Specifically, we aim to identify the features of mind-mapping that affect ideation on the problem statement, product opportunity gap, and the needs around a given design context.

Approach & Contributions. This paper presents an experiment on the capabilities of identifying design opportunities enabled by mind-mapping. Previous study has shown that performing problem exploration increased one's perception of how much they understood about the problem [4]. Based on this, we designed a study whereas we compared mind-mapping with another technique "free writing" under the assumption that the structure of mind-maps affects one's thinking process and hence enhances the quality of the design opportunities subsequently identified. For a fair evaluation, we further propose new metrics to quantitatively assess key elements in the design statements generated through our study protocol. Finally, we map the evaluation outcomes with detailed qualitative observations and share insights on the effects of mind-maps that are often recommended but without empirical justification. Based on our investigation, we bring up a few more research questions to the community and suggest guidelines on future works for exploratory tasks and digital mind-mapping.

2 Evaluation Methodology

2.1 Rationale

Usually, an opportunity for a new product is articulated with several statements explaining the goal of the idea and the needs that it is satisfying. Proper identification of such opportunities is key to innovation, which emphasizes the importance of problem domain exploration and learning in early design phases. Usually, designers promote the use of design thinking process to establish a clear idea of the problems that they are trying to resolve for the users of the product [26]. Specifically, design thinking process emphasizes the "4 Ws" strategy to find the gap for a new product: "who is the target user", "what is the problem" and "why does the problem matter". This helps designers define the problems properly and set a foundation about how value might be created in the following design phases.

2.2 Design Problem Rubric

Evaluating design opportunity statement is challenging, and also little-investigated in design literature. Most well-established metrics in the domain cater to either ideation or conceptualization outcomes [9, 10], rather than the potential of the design opportunities identified in the first place. To fill the gap, we draw from guidelines of design thinking process [26] and principles of engineering design [3,27] to formulate a ***Design Problem Rubric*** to quantitatively assess key elements in the initial design opportunities developed. We further note that design opportunity statement is recommended to be broad in the sense that it is better to have something to sharpen later on, rather than being constrained in the first place. Therefore, the goal of this rubric was to assess the vision that the product idea creates, and the possibility of a thoughtful start. The designed rubric is elaborated in the following. Each criterion is assessed on a scale of 1 to 4:

Identification of Gap. Gap that is linked to a new product is identified and is well-described in a logical manner. The gap statement that draws a clear connection between an identified problem and the possible solution receives higher score.

Development of Needs. Key needs are identified [28]. No critical need is missed or forgotten. This is used to evaluate whether the participant gained an understanding of the context and was able to visualize the scenario that the product will be operating.

Comprehensiveness. The problem domain was explored comprehensively. Identified both hidden needs and explicit needs [28]. This is used to evaluate whether the participant made a dedicated effort towards developing deep insights.

Solution Neutral. The design problem description does not suggest an explicit solution. For example, the statement for "product that helps us drive safe on icy road" cannot be "we need spikes or chains that increase friction". Instead, it should be "need for adequate friction between a wheel and a road under variable road surface conditions" [29].

Scope for Creative Outcomes. The statement promotes innovation within the context. Here, we evaluate the effort made by the participants to think out-of-the-box while maintaining the usefulness aspect [30].

3 Study Design

3.1 Overview & Rationale

In this work, we aim to study how mind-maps can be used as a means to help designers develop their understanding of the design problem space and hence stimulate the capabilities of envisioning a new product. Such a task is generally difficult, owing to the fact that design problems are usually too abstract, too unstructured, and have too many degrees of freedom [3]. Motivated by this, we make the following observations to characterize the role of mind-maps for problem exploration and understanding:

1. Mind-map's hierarchical and network-like structure implicitly guides people to organize their thoughts and explore the central theme in a more systematic way, hence helping them in narrowing down the scope of the design problem.
2. The associative capability enabled by mind-maps stimulates people in thinking about indirect relationships between concepts. This further helps them broaden their vision and come up with ideas that have a higher scope of creativity.

To test whether our observations are true (and to what extent if they are true), we designed a study focusing on leveraging the value of mind-maps in the context of developing design problem and needs statements, which we refer to as *design problem descriptions* in the remainder of the paper. Design problem statement is a description stating a product idea by identifying a connection between the current state (i.e. the problem) and the desired state (i.e. the goal). The needs statement is a list of needs that can serve as targets for the product creation process. They are usually identified by using methods such as Market Survey or Consumer Ethnography. In this work, we constrain our study such that the participants utilize the User Scenarios method to gain empathy, a method where the participants create scenarios to show how users would act to achieve a goal. We enforce this constraint for two main reasons. First, the degree of complexity would surge (e.g. unpredictable events, inconsistent study conditions, etc.) if we allowed participants to develop needs based on Voice of the Customers (VOC). Second, we wanted to see whether the participants were able to immerse themselves in several different contexts for gaining insight. Here, it is worth noting that this strategy cannot be used to uncover insights from which generalizations can be drawn and acted upon. The participants were also told that the design problem descriptions they generated will only be used in the evaluation process of this research to minimize any inhibitions that may be caused by having genuine concern about the outcome [31]. We further control the study by asking the participants to structure each of their needs statements by starting with the following phrase: *The need exists to* ____________.

3.2 Study Setup & Preparation

Due to the global pandemic, all the studies were conducted via ZOOM to comply with COVID-19 protocols and ensure the safety of the participants and the study investigator. We created digital questionnaires using Qualtrics, which the participants used to complete each study task step-by-step, following the guidance of the study investigator. To maintain the consistency of the study setup even in remote conditions, we asked each participant to (1) use a computer (or a laptop) along with a mouse during the study, and (2) have Chrome browser installed in their device. Each participant's internet stability was also checked before the study started to minimize the risk of incomplete data. Further, the participants were also instructed to (1) not search for anything using the internet, and (2) stay in the same ZOOM meeting with the study investigator throughout the process, with their video camera on with their consent. Upon the start of each study session, the participant opened the digital questionnaire using Chrome and began screen sharing to allow the study investigator to guide and make observations on their behavior. Each study session took around one and a half hours which included open-ended interviews.

The participants who were asked to create mind-maps as a task during the study, were provided with a web-based mind-mapping application compatible with Chrome. We developed this application to allow the participants to span their ideas with any given central topic using a simple input interaction — double-clicking on any existing node to add a new node that linked to it. To represent the hierarchical aspect in the mind-map, we encoded varying font sizes and color gradients in a radially outward direction from the central topic. The visual scheme was achieved using D3JS. The application was deployed using NodeJS and Firebase Database REST API.

3.3 Study Tasks & Procedure

We recruited 28 undergraduate and graduate students within the age of 18-30 years old from the university. These participants came from engineering, architecture, liberal arts, and sciences backgrounds. Out of them, 12 had prior design experience through course projects, and another 6 had been involved in the product development cycle in the industry (eg. internship, graduate students with working experience). Apart from design background, 20 participants expressed their familiarity (used > 5 times) with brainstorming and creative tasks. In the study, each participant was asked to brainstorm about the given problem before thinking about the design problem statements and needs. We conducted a between-subjects study to minimize learning effects across the two brainstorming techniques, where 14 participants did free writing, and the remaining 14 did mind-mapping:

G1 *Free Writing Group*: The participants were asked to write down everything that is on their mind with respect to the given design theme. Here, instead of writing in prose, we asked them to write in lists to externalize the flow of ideas. While this is a little different from typical free writing, we use the term due to the lack of proper terms. The participants were also told not to worry about things like spelling or grammar when writing. This method was chosen because of its ubiquity and lack of explicit structure [32, 33].

G2 *Mind-Mapping Group*: The participants were asked to create mind-maps using the digital tool provided. Before creation, they were introduced to the general spirit and principles of mind-map. They were also allowed 2-5 minutes to get acquainted with the tool. 10 participants in this group had prior experience in creating mind-maps (2-6 in number).

3.3.1 Design Themes

Each participant was provided with two design themes (corresponding to two central problems in the mind-map) to brainstorm. Themes that were of distinct nature were selected because we wanted to study how the participants would approach problems that were of different scopes and familiarity. We borrow the design themes from prior works and describe it as follows [23]:

T1 *Pollution*: This is a theme that most people would feel familiar with, either through primary education, social events, or involvement in the process. We chose this theme to be general enough to study whether the participants were able to narrow down the scope and find the pain points for developing design opportunities.

T2 *Underwater Camping*: We chose *underwater camping* as an atypical theme that not many people would have thought of before. While peculiar, concepts for this theme are still relatable in the sense that the participants would have some knowledge about underwater activities and typical camping in general, if not experienced.

3.3.2 Study Procedures

Each participant was asked to create at least two design problem descriptions for each design theme. The total time taken during the study varied between 75 and 95 minutes, and the order of the two design themes was randomized across the participants. For each participant, the entire study was recorded, including the screen recording of the task, the completion time, and time-stamped generated ideas. Specifically, each participant performed the following tasks:

Q1 *Demographic Survey*: The participants were asked to fill out a demographic survey to help the study investigator understand their background, including general design experience and self-efficacy tests, to better analyze the data.

E *Thought Externalization*: To develop the mindset for the given design theme (**T1** or **T2**), the participants were asked to externalize their thoughts using the technique assigned (**G1** or **G2**) for 10 minutes. They were encouraged to explore the design theme in as much depth as they could.

I *Instruction*: To familiarize themselves with the general principles of developing design problem and needs statement, the participants went through guidelines on how designers usually identify problems, methods to think about the needs, and simple examples [3]. The study investigator gave the explanation and clarified any questions the participants had. The total time taken during this step varied between 5 and 20 minutes depending on the their general design experience.

DD1 *First Set of Design Problem Descriptions*: The participants were further asked to develop 2 design problem descriptions (the design problem and needs statements) for the given design theme for 20 minutes. Time notices were given at both 10 and 15 minutes mark. The participants were encouraged to not be constrained due to practicality or current technological limitations. They were also allowed to generate more descriptions if they felt like doing so within the given time.

DD2 *Second Set of Design Problem Descriptions*: The participants were asked to perform the **E** and **DD1** tasks again for another design theme. They were allowed to take a 5-10 minutes break between **DD1** and **DD2** if they wish to.

Q2 *Questionnaire*: Finally, each participant answered a series of questions regarding their exploration of design problems and needs statements. We also conducted post-study interviews to collect open-ended feedback regarding the experience.

3.4 Evaluation Metrics

Apart from our proposed ***Design Problem Rubric*** (Section 2), we also adapted Shah's novelty and variety metrics [9, 34] for a comprehensive assessment of the generated design problem descriptions. In our context, the ***Novelty*** metric measures the rareness of the product opportunity (gap). We wanted to value the type of problem that the product idea was trying to tackle more than the form of it. For example, *"Portable CO2 filter"* and *"Air refresher mask"* would belong to the same problem type *"Clean air"*. The ***Variety*** metric further addresses the dimension of the generated product needs. The calculation is described as follows:

Novelty: This can be measured as the statistical infrequency of the design problems that were identified during the study — lower the count, higher the novelty. The rater has to first build a master list and assign each design problem description to the i^{th} bin in the list. Then, count the number of descriptions in each bin (C_i), and normalize it by the total number of the descriptions (T). The score is then calculated by $1 - {}^{C_i}/_{T}$.

Variety: The rater has to build another exhaustive list of bins of explored needs. The score is then given by the percentage of bins that are presented in the given design problem description. Variety provides opportunities for the design team to challenge different assumptions, and develop a substantial foundation for the later phase of the development process, which are likely to lead to successful products [3].

Condition	Gap Identification	Needs Development	Comprehensiveness	Solution Neutral	Creative Scope	Quantity	Variety	Novelty
Pollution (Free Writing)	2.83	2.72	2.48	3.2	3.03	29	22%	0.89
Pollution (Mind-Mapping)	3.03	2.83	2.6	3.03	3.2	35	28%	0.87
Underwater Camping (Free Writing)	3.41	2.61	2.34	3.28	3.34	32	25%	0.83
Underwater Camping (Mind-Mapping)	3.43	2.79	2.56	3.36	3.34	35	29%	0.84

FIGURE 1: The scores of various metrics were averaged across themes. This table summarizes the mean scores of various metrics calculated by the inter-raters. Each criterion in the Design Problem Rubric was assessed on a scale of 1 to 4, while Variety and Novelty metrics were measured between 0 and 1. A higher score means high-quality performance on that metric.

4 Quantitative Analysis: Inter-Rater Evaluation

In total, 28 participants created 131 design problem descriptions, where 64 belong to the *pollution* theme and the remaining 67 belong to the *underwater camping* theme. We recruited two inter-raters to evaluate the design problem descriptions using the aforementioned metrics (Section 2 & 3.4). The two raters were senior doctoral students with over 4 years of design experience gained from coursework, being teaching assistants for senior capstone design projects, and their dissertation projects. Each of them first evaluated 15 common sets of design problem descriptions for both *pollution* (∼23%) and *underwater camping* (∼22%) themes using the metrics provided [35]. Then, they met virtually to discuss and come to a consensus on their ratings by sharing common sets of the lists for the ***Novelty*** and ***Variety*** metrics. After modifying the scoring scheme accordingly, they further rated the remaining data and checked for consensus again. The reliability of their ratings for the ***Design Problem Rubric*** was calculated using Cohen's Kappa. The coefficient for each criterion was found to be in the range of 0.9 and 1 showing strong agreement. Further, the Pearson's correlation between raters for the ***Variety*** and ***Novelty*** scores was found to be 1 indicating perfect agreement [36].

4.1 Rating Results

For each design theme, the raters compiled two sets of the category lists for evaluating the ***Variety*** and ***Novelty*** aspects of the generated design problem descriptions. For *pollution*, they sorted the types of problems based on the following bins: Recycling, Clean air, Waste disposal, Environmental friendly design, Clean water, Service, Awareness, Laws, and Assessment. The needs were further categorized as: Sustainability, Durability, Portability, Accessibility, User-friendly, Affordability, Environmental impact, Maintenance, Effectiveness, Value for money, and Quality control. For *underwater camping*, the bins for design problems were: Habitat, Mobility, Temperature control, Air control, Water control, Entertainment, Food, Standards, Safety, and Energy generation. Further, the design needs were grouped as: Portable, Pressure control, Air control, Temperature control, Water control, Feedback to user, Stability, User experience, Affordability, Environmental impact, Maintenance, Effectiveness, Safety, Marketing, Service, and Energy utilization.

To draw conclusions from the ratings, we performed two-way ANOVA with two independent variables: (1) type of technique, and (2) choice of design theme. Owing to the fact that the robustness of the ANOVA test can be affected by unequal sample sizes, we decided to use the average score of the generated descriptions from each participant to perform the statistical test (N=14 for each condition). We further note that ANOVA is generally less sensitive to the normality of the data distribution [37]. Across exploration techniques (**G1** and **G2**), p-values were above 0.05 for metrics discussing Identification of Gap (**T1**-0.45; **T2**-0.81), Development of Needs (**T1**-0.87; **T2**-0.69), Comprehensiveness (**T1**-0.87; **T2**-0.57), Solution Neutral (**T1**-0.72; **T2**-0.47), and Scope for Creative Outcomes (**T1**-0.39; **T2**-0.8) for both the design themes indicating no significant difference. In fact, few p-values were above 0.6 showing a higher similarity in the variable that was being compared. This provides an initial insight on how the usage of techniques is neutral to the development of the design problem descriptions for the same design theme. We further found that p-values across the themes were also above 0.05 for nearly all metrics, except for Identification of Gap whose p-value across **T1** and **T2** for free writing was 0.003. This highlights how free writing users may have topic-dependent behavior when trying to elaborate on the gaps.

In general, results show that the mean of the scores given by the inter-raters for all metrics except Solution Neutral and Novelty was greater in mind-mapping group compared to the free writing group for both the themes (Figure 1). Specifically, participants in the mind-mapping group showcase a stronger capability in generating the design needs in various aspects (Variety: **T1**-28%; **T2**-29%). This unveils the importance of the associative capability enabled by mind-maps, that helps the participants to connect things and find caveats easily. Other important metrics that showed significant improvement from free writing group to mind-mapping group are Identification of Gap, Development of Needs, and Comprehensiveness. This indicates the potential of mind-maps to allow the participants to develop a comprehensive understanding of the scope of the problem provided. As a part of the evaluation, we also recorded the number of design problem descriptions generated during the study. We observed that the participants were more engaged in thinking about different product ideas after mind-mapping (Quantity: **T1**-35; **T2**-35), as compared with free writing (Quantity: **T1**-29; **T2**-32). We believe this to be the case because mind-mapping users were able to conceptualize the problem and find the pain-points through systematic exploration. However, such differences were not observed significantly for Novelty (**G1**: **T1**-0.89; **T2**-0.83, and **G2**: **T1**-0.87; **T2**-0.84). This could mean that although mind-mapping allowed one to explore more opportunities, the uniqueness of the gap identified was similar to that of the free writing group.

5 Observational Analysis: Externalization of Ideas

Each participant was given 10 minutes to explore each design theme with either free writing or mind-mapping (depending on their group). We studied the recordings of the sessions (N=56) and found patterns in their behavior. In the following section, we share our findings and expose some interesting examples.

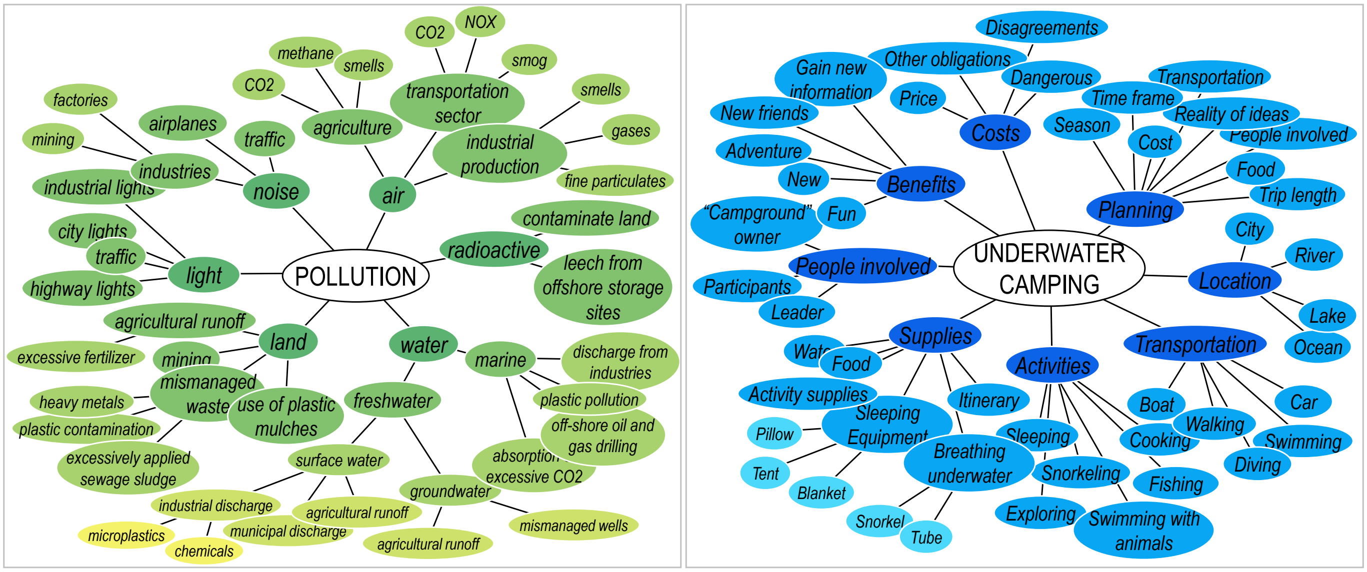
5.1 Topic-Dependent Behavior

We observed three primary exploration strategies adopted by the participants. First was the *direction-oriented approach*. Participants were inclined to explore ideas towards the direction that he/she felt more comfortable with and followed a depth-first strategy. Second was the *solution-oriented approach*. This group of participants spent most of their time thinking about ideas that may have alluded to the solution of the given problem. Third was the systematic and organized approach. Participants focused on the fundamentals of the problem, created several sub-categories to break down the problem, and explored each of them in-depth. Across the problems, the second strategy was found mostly during sessions for *underwater camping*, while the first and the third were observed more for *pollution*. This could be due to the nature of the theme, and the participants' familiarity with it. For the *underwater camping* theme, most of the participants were surprised at first and started to think about ideas that could enable such an activity, like *water-proof electronics*, *tent*, *scuba*, *submarines*, etc. While this is reasonable, we also noticed few participants began with the "Five Ws" (who what when where why) and put down ideas like *benefits, challenges, location*, etc. that could question the fundamental aspects of the central theme. This set of participants were found mostly in the mind-mapping group (**G1**-4; **G2**-6) and were able to discuss the problem in a constructive manner.

For the *pollution* theme, most of the participants expressed their extensive understanding of the topic before the session started. They wrote down a mixture of categorical (*types*, *effects*, *causes*, etc.) and solution-oriented concepts (*green energy*, *recycle*, etc.) immediately and used that as starting points to explore further within the given time. There were also several participants who spent the whole 10 minutes to discuss one or two specific aspects of pollution in-depth. For example, one participant in the free writing group put down ideas related to air pollution spanning from *CO2, UV, sandstorm* to *mask* and *face cover*. While interesting, we also observed that the participant focused only on air pollution for the remaining time, limiting their ability to expand on other ideas.

5.2 Technique-Dependent Behavior

While participants' behavior may be topic-dependent, we also noticed different thinking strategies across the given techniques. With mind-mapping, a majority of the participants (**T1**-9; **T2**-8) followed a breadth-first idea exploration strategy in the sense that they created several main branches before going into detail in each. We also noticed that these participants made efforts in balancing their two distinct modes of thinking — logical, detail-oriented, and lateral, breadth-oriented [38] — while brainstorming, and hence explored the central problem comprehensively. For example, one participant first created *Supplies* and *People involved* as two main branches for *underwater camping*. After exploring 2-3 ideas for *Supplies*, she went back to *People involved* and added *Leader* and *Participants* to it, potentially thought of the usability of the supplies. Immediately after that, she created another new main branch to the central node to list down *activities* other than camping that could be carried out underwater. She further used these as basis to discuss the benefits of such activities and corresponding planning strategies (Figure 2(b)). Another participant first categorized the theme *pollution* by adding different types of it (*water, air, land, noise, light*). He explored *water pollution* in the first 1 and a half minutes, rest for a while, then went to *light pollution* and added *city lights.* Subsequently, he made relations to *noise pollution* and added ideas that allude to the origins of these phenomena, such as *traffic*, *airplanes*, and *industries*. Further, he identified several industrial factors like *mismanaged waste* and *agricultural runoff* that result in *land pollution* (Figure 2(a)). We can see the decent flow of thought here — the participant jumped between different groups of concepts and made associations. We observed this to happen mainly because the tree-like and hierarchical structure of mind-maps stimulated the users to think about concepts of multiple levels and directions parallely and hence encouraged them



(a) *Pollution* map created by a participant (b) *Underwater camping* map created by a participant

FIGURE 2: Mind-maps created by participants in the mind-mapping group before developing design problem descriptions for (a) *pollution* and (b) *underwater camping* using the digital tool provided. The white node represents the central theme of the mind-map. The color gradient represents the hierarchy of nodes (ideas explored) in a radially outward direction.

to balance their exploration.

In contrast, 10 out of 14 participants in the free writing group tended to perform depth-first exploration throughout the process in the sense that they were spanning their ideas without jumping between written concepts or putting efforts into organization. This could be natural due to the form of the technique. For example, with the theme *pollution*, one participant spent around 6 minutes discussing water pollution by listing ideas like *coral reef*, *ocean acidification*, *hurricanes* and affected *migration patterns*. She further shifted to air pollution in the remaining time by mentioning *greenhouse gases* and *electric cars*. For *underwater camping*, popular ideas in the free writing group were solution-oriented, spanning from *waterproof technical equipment* to *breathing apparatus* and *food/sleeping supplies*, etc. In general, they performed a relatively confined and biased scope of exploration and encountered impasse more frequently potentially due to difficulties in relating new ideas. During the study, we further noticed one participant in the free writing group performed exploration in a more systematic way. For *pollution*, she wrote down topics that could break down pollution in different aspects such as *types*, *sources*, *methods to eliminate*, and *who should be responsible* in the beginning. She further explored each equally in the remaining time. Similarly for *underwater camping*, she started with topics like *who, why, how*, and *issues*, and created a hierarchical list to investigate the fundamental challenges and needs in-depth. This was particularly interesting because we interviewed the participant at the end of the study and found that, she was a fan of mind-mapping after having a lot of experience with other brainstorming techniques in her past art projects (architecture background). This shows mind-map's potential long-term effects on one's thinking process.

6 Analysis of Problem Descriptions

For each design theme, the participants were allowed 20 minutes to develop design problem descriptions, each consisting of one design problem statement and several needs statements to deliver one product idea. The participants were instructed to develop at least two problems. In this section, we study the participants' behavior during the process, and investigate its correlation with the thought externalization outcomes.

6.1 Behavior Across Participants

We observed that, overall, participants in the mind-mapping group performed consistently across the two design themes as indicated by the similar average scores (Figure 1). The performance of participants in the free writing group varied across metrics between the two themes for Identification of Gap (**T1**-2.83; **T2**-3.41), Scope for Creative Outcomes (**T1**-3.03; **T2**-3.34), Quantity (**T1**-29; **T2**-32) and Variety (**T1**-22%; **T2**-25%). We further noticed that the problem descriptions created by the free writing users received comparatively discrete scores specifically for Identification of Gap (**G1**&**T1**-mean:2.83, SD:1; **G2**&**T1**-mean:3.03, SD:0.86; **G1**&**T2**-mean:3.41, SD:0.87; **G2**&**T2**-

Design Theme: Pollution

Design Problem: An exhaust-gas dissolver machine

Needs Statement:
- The need exists to dissolve the exhaust gas
- The need exists to operate by eco-friendly energy
- The need exists to detect the exhaust gas
- The need exists to show the dissolver result
- The need exists to visualize the dissolve progress
- The need exists to operate in quiet
- The need exists to consume lower energy
- The need exists to contain user-friendly menu

Design Problem: H2O powered engine: Design an engine that is able to power a car through the use of H2O consumption.

Needs Statement:
- The need exists to give enough power (torque) to the automobile to have it function
- The need exists to include an emission portion for the engine to allow the engine to breathe
- The need exists to prevent any electrical damage (shock) from happening to the engine
- The need exists to have a lightweight design for lower exertion on the automobile and tires
- The need exists to allow the design to be maintainable for monthly or yearly maintenance
- The need exists to have a durable design
- The need exists to be heat resistant to high temperatures
- The need exists to emit the H2O into a safe mist that doesn't harm lungs nor the environment

(a) Design problem descriptions developed by the participants in the free writing group

Design Problem: Plastic waste is damaging marine ecosystems. Design a system to remove plastic waste floating on the surface of oceans.

Needs Statement:
- The need exists to float
- If the design uses nets, the need exists to avoid plastic nets if possible to avoid more pollution
- The need exists to run on plastic
- The need exists to be remote operated or human operated
- The need exists to have a way to capture plastics and store them until they can be collected
- Need exists to protect the engines/fans/rudder so wildlife cannot be hurt
- There needs to be a way to inspect collected material so that there is not a significant amount of marine life trapped

Design Problem: Reusable face masks with breathable technology

Needs Statement:
- Need exists to reuse the face masks multiple times before washing
- The need exists for a comfortable face mask that one can keep on for hours at a time without feeling uncomfortable
- The need exists to create a face mask for use at gyms that do not make you leave feeling dirty and not being able to breathe
- The need exists to be attractive to all individuals, where they can create their own look and design for individual masks
- The need exists for the masks to be machine washable for all different types of washer/dryers
- The need exists for the masks to come in multiple sizes (or one size fits all with size adjusters on the sides)

(b) Design problem descriptions developed by the participants in the mind-mapping group

FIGURE 3: The design problem descriptions developed by 4 different participants for the design theme *pollution*. 2 participants are in the (a) free writing group, and another 2 are in the (b) mind-mapping group.

mean:3.43, SD:0.83) and Development of Needs (**G1**&**T1**-mean:2.72, SD:0.94; **G2**&**T1**-mean:2.83, SD:0.81; **G1**&**T2**-mean:2.61, SD:0.88; **G2**&**T2**-mean:2.79, SD:0.81). We suspect two potential reasons for this. First, free writing may exaggerate the influence of participants' personal knowledge on their ability to identify product gaps. On the other hand, mind-maps likely help participants in discovering associations that they originally were either not aware of or did not consider relevant. These could be pronounced especially for a topic that is broad and complicated in nature, such as *pollution.*

6.2 Problem Exploration and Understanding

It is reasonable to assume that the problem descriptions would generally be a reflection of what each participant may have conceived from their experiences, regardless of the technique. For example, one participant in the free writing group limited his mind to air pollution only while brainstorming. He further came up with two product ideas that tackle air pollution in different ways — *"Exhaust-gas dissolver machine"* and *"Air pollution identifier"* (Figure 3). Another participant developed one product idea *"Ocean plastic removal"* after identifying the issues of plastics in different types of pollution during mind-mapping (Figure 4). What is important to note is that most participants heavily relied on their externalization (whether free writing or mind-mapping) when developing design problem descriptions as noted in these comments: *"Free writing/mind-mapping definitely helps"*; *"I tried to think what was there in my mind-map whenever I was out of ideas"*. That being said, one particular advantage of mind-mapping over free writing was its ability to allow participants to develop their needs statements comprehensively as suggested by the overall high scores on the Development of Needs, Comprehensiveness, and Variety (Figure 1, 3 & 4).

We further observed that mind-mapping users tended to be more engaged in coming up with various product opportunities as indicated by the quantity score (Figure 1). Specifically, for *pollution*, 6 participants in the mind-mapping group generated more than 2 complete design problem descriptions, whereas only 2 participants in the free writing group did so. In fact, there was one participant who could not meet the quantity requirement (at least 2 product ideas) after free writing for *pollution*. After spending around 9 minutes composing the first product idea *"Electric motorcycle"*, the participant kept modifying her written statements for the second design problem description and eventually deleted them all. She further shared her difficulties

Design Theme: Underwater Camping

Design Problem: Underwater Jetpack: Design a portable, power-assisted device for traversing underwater

Needs Statement:
- The need exists to travel a minimum distance of 10 large football fields
- The need exists to be operated through two joysticks
- The need exists to have a max load capacity of 500 lbs (including underwater pressure)
- The need exists to last for at least 1 week at max charge
- The need exists to travel at speeds three times greater than the fastest underwater mammal
- The need exists to be compact enough to be carried by a backpack
- The need exists to look cool

Design Problem: Water-Proof Heating Element: Design a device that generates heat and cannot be damaged by water.

Needs Statement:
- The need exists to have the device run on an electricity-free power source
- The need exists to give an indicator to show run-time and time-left on the device
- The need exists to have a shockproof design (from accidental drops)
- The need exists for the device to continue operation after prolonged water exposure
- The need exists to generate heat up to 90 degrees Fahrenheit
- The need exists for the device to have a source where the temperature can be manually controlled
- The need exists for the device to be maintainable

(a) Design problem descriptions developed by the participants in the free writing group

Design Problem: Design a canal that aids in the transportation between rooms of the underwater camp

Needs Statement:
- The need exists to be easy to use
- The need must be safe
- The need exists to be able to alert of any incoming user
- The need exists to have a specific starting and ending site
- The need exists to be designed to prevent transportation accidents
- The need exists to be efficient
- The need exists to be able to transport multiple people at the same time
- The need exists to provide entertainment (e.g. fun, decorative, music)
- The need exists to be spacious
- The need exists to contain the appropriate amount of oxygen and pressure

Design Problem: Amphibious Pods

Needs Statement:
- The need exists to accommodate 2 or more seaters
- The need exists to be battery operated
- The need exists to handle water pressure for the desired depth and spots of underwater camping
- The need exists to be shatter proof
- The need exists to have secondary motors incase main motor fails
- The need exists to be made from non-corrosive materials like carbon fiber
- The need exists to be able to communicate with other pods in case of emergency or entertainment
- The need exists to be non-polluting (e.g. paint used should not pollute water)
- The need exists to have GPS trackers

(b) Design problem descriptions developed by the participants in the mind-mapping group

FIGURE 4: The design problem descriptions developed by 4 different participants for the design theme *underwater camping*. 2 participants are in the (a) free writing group, and another 2 are in the (b) mind-mapping group.

as: *"I tried. There are so many things in my mind but I could not think of one specific product"*. We note here that while this cannot be generalized to all participants as such, the lack of organization was generally an impediment for almost all free writing participants. Those who did well with free writing did so because they naturally organized their ideas hierarchically (similar to mind-mapping).

Unlike the case for *underwater camping*, equal amount of participants from both groups (5 out of 14) developed 2 to 4 design problem descriptions within the given 20 minutes. This could be attributed to the nature of the topics — *underwater camping* possessed a larger scope of imagination, whereas *pollution* was a commonly known problem that was also complex in the sense that multiple environmental factors could be coupling with each other and there was likely no optimal solution. We further noticed that the quality of the additionally generated product ideas for *pollution* was not lost due to quantity (the scores remain competitive). Thus, mind-mapping can be particularly helpful in early design stages when designers try to develop a systematic understanding of a complex problem and order their thoughts for identifying design opportunities.

6.3 Participant Feedback

After developing design problem descriptions for each theme, the participants were asked a series of questions about their experience (Figure 5). For the theme *underwater camping*, the results show a positive agreement in terms of time given and the level of enjoyment the process was. Around 20% of the participants in the free writing group disagreed that they had enough time in identifying the design problems and needs for the theme *pollution*. A possible reason for this is that because of the complexity of the problem, three participants were not able to sort their thoughts out within the given 10 minutes of free writing causing a need for extraneous time. Moreover, we found that 5 out of 14 participants were not satisfied with the design problem descriptions they generated for the theme *pollution* after free

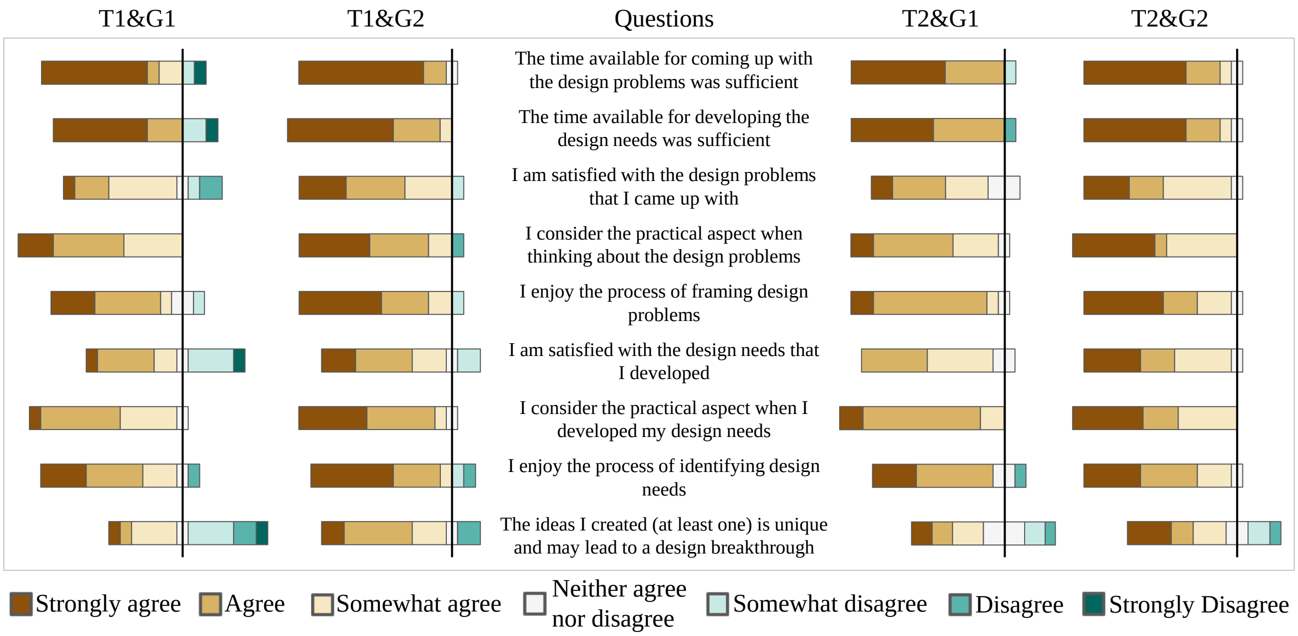


FIGURE 5: 7-point Likert scale user feedback on four different study conditions: *pollution* with free writing (T1&G1); *pollution* with mind-mapping (T1&G2); *underwater camping* with free writing (T2&G1); *underwater camping* with mind-mapping (T2&G2).

writing. They further stated: *" It was difficult to come up with ideas in the short amount of time"*; *"It was a bit difficult to stray from the impact of pollution on humans and narrow it down to a more concrete level"*. In contrast, mind-mapping proved particularly helpful in building the vision of the central problem and exploring concrete ideas efficiently during early design, even if the problem space appears convoluted. This was also corroborated by participant feedback as: *"mind-mapping definitely helped me in getting into the mindset"*; *"The tool is amazing. I can span and organize my ideas easily"*.

Majority of the participants hesitated in agreeing with the statement *the product ideas they generated (at least one) are unique and may lead to a design breakthrough.* Specifically, half of the participants from the free writing group did not have confidence in the design problem descriptions they generated for *pollution.* One participant who possessed familiarity with brainstorming tasks, shared her needs for more resources before developing product ideas by stating: *"I felt there should be a research/search process first before identifying there's no solution to the problems I designed. Without this process the design won't be ideal"*. Another participant who had extensive experience in design activities, stated that she was inhibited when considering the creative aspect of the ideas since pollution is a topic that has been widely read, researched and discussed. This brings forward the problem of possible fixation due to abundance of existing knowledge. In contrast to free writing, around 80% of the participants from the mind-mapping group expressed excitement about

PROS	CONS
Narrow down the scope of the problem space	Not easy to carry on for novice users
Perform consistently for different types of problems	Hard to keep the ideas solution neutral
Discover both explicit and hidden user needs	Identify similar design problems with free writing group (the novelty aspect)
Keep a creative mindset	

FIGURE 6: Table shows the pros and cons of mind-maps for generating design problem descriptions under our study protocol.

the product ideas they proposed. We observed this to happen mainly because most of the mind-mapping users were able to utilize the existing knowledge to make connections to non-obvious ideas. Here, it is worth noting that 10 out of 14 mind-mapping users in this study had prior experience in creating several mind-maps resulting in lesser difficulties in using the technique.

7 Limitations

There are two main limitations in this current work. First, this study restricted information collection from external resources (e.g. internet, target customers). While this was an intentional decision to control the study, we believe there is a scope of research that can investigate the effects of information foraging [39] on design problem identification. Second, the mind-mapping tool for idea exploration allows for the addition of nodes only. This was done to enable a fast idea expansion process with minimal emphasis on the modification of existing ones. However, this could potentially discomfort the users when especially they have a strong inclination to reorganize ideas. While only one participant in our study raised these concerns, we believe that including more modalities such as idea re-linking can lead to an interesting discussion on problem exploration behavior.

8 Conclusions & Future Directions

In this work, we presented a study to investigate the potential of mind-maps in identifying design opportunities in early design. Specifically, we compared it with free writing to showcase the effects of information organization. During the idea externalization phase, we observed different patterns of exploration strategies adopted by the two groups of participants. Mind-mapping users were encouraged to explore the central problem systematically, where they categorized their ideas before expanding and considering concepts of different depths and directions in parallel, whereas participants from the free writing group were inclined to put down ideas linearly without re-visiting the written concepts (Section 5). While this can be attributed to the nature of the technique, we further noticed that mind-mapping users developed unpolished product ideas (in the sense that they were generated within 20 minutes) with a higher variety of the considered needs and scope for creative outcomes (Section 4). Based on the investigation, we marked two main advantages of mind-maps for early design problem exploration and clarification (Figure 6). First and foremost, the organizational and hierarchical structure of mind-maps help designers tackle complex problems such as *pollution*. Second, mind-mapping enhances one's associative and critical thinking capabilities leading to a comprehensive exploration of needs that are both explicit and hidden.

There are several interesting research directions that we envisage continuing with this work. Our goal for the future is to improve the form of cognitive support during digital mind-mapping, by emphasizing on the structural aspects through new user interactions or feedback mechanisms that are powered by automatic graph [40] and semantic assessment. Apart from advanced technology, there is also a lack of evaluation metrics for assessing problem exploration. While we proposed one in this work based on principles of engineering design, we believe there is a need for a deeper investigation of metrics to capture the potential of the initial design opportunities identified. Finally, more work is needed to investigate "solution neutrality" where the mind-mapping users performed below expectations. Ultimately, there is a need to understand how designers frame and formulate design descriptions in the first place, and their corresponding impacts on later stages of the design process.

ACKNOWLEDGMENT

This work was supported partially by the NSF Award No. 2013612 (DUE) and the J. Mike Walker '66 Department of Mechanical Engineering at Texas A&M University, College Station. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] Murray, J. K., Studer, J. A., Daly, S. R., McKilligan, S., and Seifert, C. M., 2019. "Design by taking perspectives: How engineers explore problems". *Journal of Engineering Education,* ***108***(2), pp. 248–275.

[2] Dorst, K., 2004. "On the problem of design problems-problem solving and design expertise". *Journal of design research,* ***4***(2), pp. 185–196.

[3] Ulrich, K. T., 2003. *Product design and development*. Tata McGraw-Hill Education.

[4] Leite De Vasconcelos, L., Crilly, N., Chen, C.-C., Campos, F., and Kelner, J., 2016. "What's the benefit of problem exploration?". The Design Society.

[5] Luo, J., Sarica, S., and Wood, K. L., 2021. "Guiding data-driven design ideation by knowledge distance". *Knowledge-Based Systems*, p. 106873.

[6] Chen, L., Wang, P., Dong, H., Shi, F., Han, J., Guo, Y., Childs, P. R., Xiao, J., and Wu, C., 2019. "An artificial intelligence based data-driven approach for design ideation". *Journal of Visual Communication and Image Representation,* ***61***, pp. 10–22.

[7] Shah, J. J., Vargas-Hernandez, N., Summers, J. D., and Kulkarni, S., 2001. "Collaborative sketching (c-sketch)—an idea generation technique for engineering design". *The Journal of Creative Behavior,* ***35***(3), pp. 168–198.

[8] Fu, K., Murphy, J., Yang, M., Otto, K., Jensen, D., and Wood, K., 2015. "Design-by-analogy: experimental evaluation of a functional analogy search methodology for concept generation improvement". *Research in Engineering Design,* ***26***(1), pp. 77–95.

[9] Shah, J. J., Smith, S. M., and Vargas-Hernandez, N., 2003. "Metrics for measuring ideation effectiveness". *Design studies,* ***24***(2), pp. 111–134.

[10] Kerne, A., Webb, A. M., Smith, S. M., Linder, R., Lupfer, N., Qu, Y., Moeller, J., and Damaraju, S., 2014. "Using metrics of curation to evaluate information-based ideation". *ACM Transactions on Computer-Human Interaction (ToCHI),* ***21***(3), pp. 1–48.

[11] Zwicky, F., 1969. "Discovery, invention, research through the morphological approach".

[12] Oriakhi, E., Linsey, J., and Peng, X., 2011. "Design-by-analogy using the wordtree method and an automated

wordtree generating tool". In DS 68-7: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 7: Human Behaviour in Design, Lyngby/Copenhagen, Denmark, 15.-19.08. 2011.

[13] Linsey, J. S., Markman, A. B., and Wood, K. L., 2012. "Design by Analogy: A Study of the WordTree Method for Problem Re-Representation". *Journal of Mechanical Design,* ***134***(4), 04.

[14] McAdams, D. A., and Wood, K. L., 2002. "A quantitative similarity metric for design-by-analogy". *J. Mech. Des.,* ***124***(2), pp. 173–182.

[15] Verhaegen, P.-A., D'hondt, J., Vandevenne, D., Dewulf, S., and Duflou, J. R., 2011. "Identifying candidates for design-by-analogy". *Computers in Industry,* ***62***(4), pp. 446–459.

[16] Chen, J., 2008. "The using of mind map in concept design". In 2008 9th International Conference on Computer-Aided Industrial Design and Conceptual Design, IEEE, pp. 1034–1037.

[17] Hidayati, N., Zubaidah, S., Suarsini, E., and Praherdhiono, H., 2019. "Examining the relationship between creativity and critical thinking through integrated problem-based learning and digital mind maps". *Universal Journal of Education Research,* ***7***(9A), pp. 171–179.

[18] Buzan, T., and Buzan, B., 2006. *The mind map book*. Pearson Education.

[19] Anderson, M., Onyechi, J., Yamazaki, T., Wood, K., and Jensen, D., 2017. "Mind map for biologically inspired covert visual systems: A pilot study". In proceedings of the SW regional ASEE conference.

[20] Jensen, D., Wood, K., Bauer, A., Doria, M., Perez, K., Anderson, M., and Jensen, L., 2018. "A bio-inspired mind map to assist in concept generation for wall climbing systems: Development, assessment, and resulting prototypes". In Proc. 125th ASEE Conference.

[21] Marshall, K. S., Crawford, R., and Jensen, D., 2016. "Analogy seeded mind-maps: A comparison of verbal and pictorial representation of analogies in the concept generation process". In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol. 50190, American Society of Mechanical Engineers, p. V007T06A010.

[22] Chen, T.-J., and Krishnamurthy, V. R., 2020. "Investigating a Mixed-Initiative Workflow for Digital Mind-Mapping". *Journal of Mechanical Design,* ***142***(10), 06. 101404.

[23] Chen, T.-J., Subramanian, S. G., and Krishnamurthy, V. R., 2020. "Qcue: Queries and cues for computer-facilitated mind-mapping". In Proceedings of Graphics Interface 2020, GI 2020, Canadian Human-Computer Communications Society / Société canadienne du dialogue humain-machine, pp. 125 – 136.

[24] Bae, S. S., Kwon, O.-H., Chandrasegaran, S., and Ma, K.-L., 2020. "Spinneret: Aiding creative ideation through non-obvious concept associations". In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, CHI '20, Association for Computing Machinery, p. 1–13.

[25] Dorst, K., 2003. "The problem of design problems". *Expertise in design*, pp. 135–147.

[26] Brown, T., et al., 2008. "Design thinking". *Harvard business review,* ***86***(6), p. 84.

[27] Pahl, G., and Beitz, W., 2013. *Engineering design: a systematic approach*. Springer Science & Business Media.

[28] Cooper, R. G., and Edgett, S. J., 2009. *Generating breakthrough new product ideas: Feeding the innovation funnel*. Product Development Institute.

[29] Glier, M. W., Tsenn, J., Linsey, J. S., and McAdams, D. A., 2011. "Methods for supporting bioinspired design". In ASME International Mechanical Engineering Congress and Exposition, Vol. 54884, pp. 737–744.

[30] Diedrich, J., Benedek, M., Jauk, E., and Neubauer, A. C., 2015. "Are creative ideas novel and useful?". *Psychology of Aesthetics, Creativity, and the Arts,* ***9***(1), p. 35.

[31] Harari, O., and Graham, W. K., 1975. "Tasks and task consequences as factors in individual and group brainstorming". *The Journal of Social Psychology,* ***95***(1), pp. 61–65.

[32] Berkenkotter, C., 1982. "Writing and problem solving". *Language connections, writing and reading across the curriculum*.

[33] Flower, L. S., and Hayes, J. R., 1977. "Problem-solving strategies and the writing process". *College English,* ***39***(4), pp. 449–461.

[34] Linsey, J. S., Clauss, E., Kurtoglu, T., Murphy, J., Wood, K., and Markman, A., 2011. "An experimental study of group idea generation techniques: understanding the roles of idea representation and viewing methods". *Journal of Mechanical Design,* ***133***(3), p. 031008.

[35] Lavrakas, P., 2008. "Encyclopedia of survey research methods".

[36] Clark-Carter, D., 1997. *Doing Quantitative Psychological Research: From Design to Report*. Taylor & Francis, Inc., UK.

[37] Khan, A., and Rayner, G. D., 2003. "Robustness to non-normality of common tests for the many-sample location problem". *Advances in Decision Sciences,* ***7***(4), pp. 187–206.

[38] Kolko, J., 2018. "The divisiveness of design thinking". *interactions,* ***25***(3), pp. 28–34.

[39] Pirolli, P., and Card, S., 1999. "Information foraging.". *Psychological review,* ***106***(4), p. 643.

[40] Jamieson, P., 2012. "Using modern graph analysis techniques on mind maps to help quantify learning". In 2012 Frontiers in Education Conference Proceedings, IEEE, pp. 1–6.