ASSOCIATION, REFLECTION, STIMULATION: PROBLEM EXPLORATION IN EARLY DESIGN THROUGH AI-AUGMENTED MIND-MAPPING

A Dissertation

by

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ABSTRACT

> *The formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old problems from a new angle requires creative imagination and marks real advances in science.* — Albert Einstein

This dissertation aims at developing a computational framework to support the process of problem exploration in early design. To do so, we investigate digital mind-mapping as a tool for problem exploration and develop new algorithms and interaction workflows by leveraging large knowledge databases. The central premise of this work is that channeling the designer's thinking process through intelligent stimulation using such databases can augment designers' ability to reason about the problem at hand and creatively synthesize new ideas to address the problem.

Design problems are typically ambiguous, ill-defined, unstructured, and open-ended. Therefore, learning about the problem and exploration of the problem domain is critical in early design to build a well-developed understanding of the context toward fruitful solution exploration in design. Despite the importance of problem understanding in design, little research has been devoted to investigating problem exploration activities in-depth and drawing a clear connection on the effects of such activities on the resulting design outcomes. Most current efforts focus exclusively on implementing methods for ideation, conceptualization, and concept evaluation wherein the solution space takes prominence. In this regard, this dissertation aims to complement this with a study of problem exploration techniques (mind-mapping and free writing) and evaluation in early design. We highlight the importance of problem-based exploration and learning, and share insights on how the structure and associative capability afforded by mind-maps affect ideation on the problem statement, product opportunity gap, and the needs around a given design context.

It is common for designers to tend to commit to solutions too early and limit the potential of discovering creative and novel ideas in early design. This tendency is further pronounced with the advent of several digital design tools that are feature-rich and focus on design conceptualization and solution formulation, rather than design problem exploration. Additionally, much of the research in design theory and methodology has also mostly focused on conceptualization techniques such as C-Sketch and morphological matrix, that aim to support the formation of new solution concepts through modification and re-interpretation of rough initial ones. To complement these, in this dissertation, we emphasize the importance of problem exploration and brainstorming tasks towards design opportunity identification during early design. This is studied with the use of mind-maps, a technique that helps designers express their thoughts by making connections or associations between ideas around a given context. Further, we propose novel human-computer collaborative mind-mapping workflows for enhancing design experiences through novel textual, verbal and visual computer supports. Specifically, we designed and implemented two cognitive support mechanisms to help designers in inspecting design problems and generating ideas. Human-subject studies were conducted to examine how these systems perform and user perception. Based on the extensive investigation, this dissertation further shares insights on how to promote reflection in problem exploration by stimulating association across ideas, and develops design implications for intelligent AI-augmented workflows during early design exploratory tasks.

DEDICATION

This dissertation is dedicated to my beloved parents

Kun-Fa Chen and *Mei Lo*

Who raised me to be sincere and persevere, and always encouraged me to go on every adventure, especially this one. Without you, none of my success and honor would be possible.

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1. INTRODUCTION

1.1 Goals & Objective

Design problems are largely ill-structured, and open-ended. They do not have right or wrong solutions rather good or bad solutions, and have incomplete, changing, and contradictory requirements. The way to approach them is different from those that occur in a classroom or a laboratory during an experiment, where the problems are usually well-structured and have defined goals. Solving them requires a great deal of construction and restructuring of the problems by the designer to discover opportunities for innovative solutions. Conklin [2] notes: *"the more novel the problem, the more the problem-solving process involves learning about the problem domain"*. Studies have underscored the importance of problem-based learning for designers to identify what they need to learn in order to solve a problem [3]. This learning phase is generally called *problem exploration* in early design, where designers develop new perspectives and insights within the iterative process of identifying features or needs and re-framing the scope, leading to the discovery of innovative design opportunities. However, although the design literature often promotes the importance of problem-based exploration and understanding, the benefits these activities bring have not previously been investigated in-depth. Most current efforts in the community focus exclusively on improving design practices during later stages, including implementing methods for ideation [4, 5], conceptualization [6, 7], and concept evaluation [8, 9]. To this end, there exists a need to address the correlation between the exploration and generation phases of design. Recently, Dorst [10] further notes: *"creative design seems more to be a matter of developing and refining together both the formulation of a problem and ideas for a solution"*. He raised a concern about whether design is still a process running linearly from 'a problem' to 'a solution'. This concern is evidenced by the development of many digital design tools which focus on building solutions of specified problems through modification and re-interpretation of existing ones leading to limitation on the exploration process.

Inspired by these, ***this dissertation seeks to study computational means to support problem exploration and study the effect of such support on opportunity identification in early design. Specifically, we examine how to use cyber-human systems to stimulate one's associative thinking capability, as well as enable the reflection and synthesis of ideas, insights, and knowledge during early design stages.*** Toward this boarder goal, the specific objective of this dissertation is to make use of the benefits that problem exploration activities bring to investigate intelligent user interfaces which provide cognitive support during the idea expansion process. To that end, this dissertation involves two key elements. First, the design of an experiment for problem-based learning and the evaluation of its efficacy. Second, the design, development, and evaluation of novel algorithms and interactive methods for human-computer collaboration in digital mind-mapping.

1.2 Motivation: Design Problem Identification

In product development cycle, a design opportunity is a product idea that addresses some unsolved problems or unmet needs [11]. 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. Drawings or sketches of a possible product concept may sometimes be included as well. Proper identification of such design opportunities is key to innovation, which emphasizes the importance of problem-based exploration and learning during early design phases. That being said, a majority of people find it difficult, mainly because of the fact that design problems are usually ill-structured, open-ended, and have too many degrees of freedom. Ideally, a product opportunity that could potentially lead to success is identified only when designers possess a well-developed understanding of the problem space that is being addressed. In this regard, problem exploration activities could be served as a foundation about how value might be created in the following design phases.

1.2.1 Mind-Mapping as a Problem Exploration Tool

In this dissertation, we explore the idea problem exploration through a specific design tool, namely mind-mapping, that originated in psychology, but is widely popular in design practice. Rather than typical writing forms that start at the top of the page and proceed in a linear fashion, mind-maps look more like *"explosions of thought fragments"* [12]. A mind-map starts at the center of an empty sheet with a key word, phrase or problem, and grow radially outwards as ideas come up. Mind-maps are inherently exploratory and *any mind-map is potentially infinite*, as noted by Buzan [12]. We can easily take any node (image or keyword) in a mind-map as the root node (central idea or problem) for a new mind-map. The context in mind-maps also naturally allows for ambiguity that is common in early design; mind-map users typically externalize ideas quickly using keywords, phrases and even rough sketches, drawings or symbols. This allows designers to express their mental model around a central idea or problem to others while providing rooms for creative thinking and subject to interpretation [13]. This also serves the purpose of exploring beyond the scope of solution-space in early design.

In design, the use of mind-maps has proven helpful in allowing designers to move back and forth between the problem and solution spaces while working on examining existing situations and identifying potential opportunities [14]. They are popular tools for problem exploration and early design ideation as it visualize ideas in a network/tree-type structure to enable critical thinking and learning about a central problem [15]. Specifically in the early stages, designers can use mind-maps to conceptualize the problem space through the combination of two distinct modes of idea exploration: logical, depth-oriented and lateral, breadth-oriented. This form of exploration reveals the non-linear, jumpy nature of our brain's thinking process and further unfolds our mind's ability to create new ideas.

With the above in mind, ***this work focuses on leveraging the power of mind-maps to help designers express their ideas by making connections or associations between ideas around a given context, and reflecting on those ideas to understand the design context better.*** *"Seeing logical associations between seemingly unrelated things is a hallmark of creativity"*, states Clark [16]. Especially for design synthesis, finding connections and patterns between elements is critical in driving the innovations of design [17]. Having said this, current computer-supported mind-mapping tools focus on making the operations of constructing the maps easier (e.g. linking nodes, reorganization, etc.) rather than supporting the underlying cognitive processes [18]. This research operationalizes AI-based methods to enable stimulation of associations and reflections that are inherent in mind-mapping.

1.2.2 Challenges with Mind-Mapping

Mind-mapping can be challenging, especially for novices for a number of reasons including but not limited to (1) lack of knowledge in the domain of a given design task, (2) unstructured and ill-defined task that requires self-creativity and adaption, (3) inability to readily recall known concept, (4) inability to envisage relationships across concepts due to complex couplings between variables, and (5) high dimensionality of the problem space [19, 20]. In order to address these challenges but still allow the users to think independently and critically during problem exploration, we aim to provide computer support in a subtle way that is not intruding the user's own line of thinking.

1.3 Motivation: Supporting Problem Exploration in the Information Age

In this work, we define problem exploration as the process of developing an understanding of the problem space for identifying initial design opportunities and needs. Problem exploration is recognized as a critical activity for bringing in the creative elements to a new product. It helps designers determine the right design problem to solve, and ideally, the right method to solve the identified problem. In the following, we discuss how to utilize big data nowadays to develop human-computer workflows that provide cognitive supports during the design problem exploration and understanding processes.

1.3.1 Computer's Role in Design Activities

Today, it is possible to find almost any type of information through simple internet search. The capability of search engine is unprecedented and would have been difficult to imagine a couple of decades ago. However, even with the explosive rate of advancement of search and recommendation technologies, the fundamental challenge for ones to navigate the vast networks of information still remains. Specifically, for exploratory tasks such as early design problem exploration, knowing what to search for is, in itself, not straightforward. Also, excessive reliance on the search results may, in turn, lead to fixation on a set of information which further undermine the possibility of generating novel and “out-of-box” ideas.

Clark and Chalmers [21] once note *“If, as we confront some task, a part of the world functions as a process which, were it clone in the head, we would have no hesitation in recognizing as part of the cognitive process, then that part of the world is part of the cognitive process. Cognitive processes ain’t (all) in the head”* when they first introduce the notion of *extended mind*. In other words, the combination of the mind and its surrounding completes the cognitive system of a subject. With the booming technologies we face today, it is not difficult to imagine that the vast information and the interaction with intelligent artifacts (e.g. computer, mobile phone) are literally part of our mind.

Researchers in the field of human computer interaction (HCI) have been dedicated to finding the subtle balance in between the information provided and the interaction design to promote one’s critical thinking capabilities in a nature and intuitive way. Here, the computer can serve as (1) a functional-focused media which increases the efficiency of traditionally time-consuming works, (2) a supportive system which provides relevant information based on explicit actions from the human, and (3) an active collaborator who engages with the human in specific tasks. While recent works in the field of Computer-aided Design focus on the demonstration of both functional and supportive systems to explore possible solutions [22, 23, 24, 25, 26], this dissertation aims to fill the gap in between supportive and active systems for exploratory tasks, and develop guidelines of advanced interactive systems for human computer collaboration.

1.3.2 Problem Exploration and Information

In early engineering design stage, designers use many popular techniques such as SCAMPER [27], C-Sketch [28], morphological matrix [29], etc to come up with creative solutions. These techniques are more structured in the sense that they support the formation of new concepts through modification and re-interpretation of rough initial ideas. This, however, inevitably leads to fixation on a type of particular concept and limit the exploration process. Brainstorming, on the other hand, specifically focuses on the quantity of ideas while keeping the three rules in mind: (1) defer judgment, (2) encourage wild ideas, and (3) challenge assumptions [30, 31, 32]. In a typical brainstorming session, designers sit together to generate large number of ideas using visual (e.g. sketches, mind-maps) or textual (e.g. annotations) representations in a short amount of time. It is more of a free-form method that favors open-ended problems, and tends to be covered in the initial stages of design. Specifically for ill-structured design problems, brainstorming can help explore the problem space properly and push the boundary.

With the omnipresent store of digital information nowadays, generating ideas in a data-driven way allows the designers to expand their knowledge space and discover possible novel directions for design. Kerne et al. [33] further define such activity as *information-based ideation* and introduce several digital tools such as *TweetBubble* [34] and *IdeaMACHE* [35] to investigate creative production in exploratory tasks for everyday ideation practices (e.g. internet browsing).

However, digital tools for unstructured tasks such as brainstorming are under-investigated. Especially when the design problems are ill-defined, designers' ability to bring in new perspectives, to properly frame the scope, and to identify the needs are critical but not straightforward. To enable innovation in the data-oriented and AI-driven way, digital tools for creative problem exploration must augment designers' capability to explore new problems and synthesize new ideas by partnering with them rather than serving as a passive resource of digital objects on the internet. Therefore, the second goal of my research is to (1) establish novel human-computer collaborative workflows to navigate vast and complex information networks that enable designers to identify, understand, and reason about design problems, and (2) investigate the cognitive principles underlying creative problem-solving tasks in such workflows.

1.4 Research Methodology

In this work, our general methodology involves: (a) human-subject studies to understand human behaviors during exploratory tasks such as mind-mapping, (b) based on the behavioral observations, the design of a new algorithm or a new type of human-computer interaction (or both) to support digital mind-mapping, (c) the implementation of the novel algorithm/interaction as a prototype tool, (d) another human-subject studies to evaluate the effectiveness of the algorithm and/or the interaction workflow in supporting the mind-mapping task.

In this document, while the algorithmic and interactive workflow development varies for each technical phase, we follow a common research methodology for human-subject evaluations. We are interested in both qualitative as well as quantitative aspects of the user's experience with the tools developed in this research.

1.4.1 Evaluation & Metrics

In order to quantitatively measure the effectiveness of the tools for design activities, we adopted several evaluation metrics that are well-established in the design literature, namely, the quality [36, 37], quantity, variety and novelty [38] of the ideas generated. The assessment of the quality of the outcome mind-maps is described as follows:

- **Structure:** It primarily focuses on the breadth, depth, and the balance between the two. Maps that are well-explored in both breadth and depth receive higher scores.
- **Exploratory:** This metric evaluates the relatedness of linked ideas to the central problem of the map. The flow of ideas from abstract in the center to concrete toward the periphery (leaf nodes on the map) leads to a higher score.
- **Communication:** This metric evaluates the effectiveness of representation of mind-mapped ideas. Appropriate key-words utilized during idea exploration help convey a clearer intent of the mind-map. A higher score is established for higher usage of appropriate key-words.
- **Extent of Coverage:** Here, we evaluate the effort made by pair to create meaningful relationships between the ideas. A higher score reflects a more dedicated effort towards creating an understanding between the primary ideas established in the mind-map. Whereas, a lower score reflects minimal effort towards creating a well connected mind-map.

Since our focus in this work is not toward solution generation, the existing metrics for novelty and variety in mind-mapping as demonstrated by Linsey et al. [38] need to be adapted for a fair evaluation. Specifically, we assess all ideas regardless of them being solutions in contrast to the current work that assesses only those ides that hinted toward a solution to the given problem. With this modification, we use the following metrics as detailed by Linsey et al. [38].

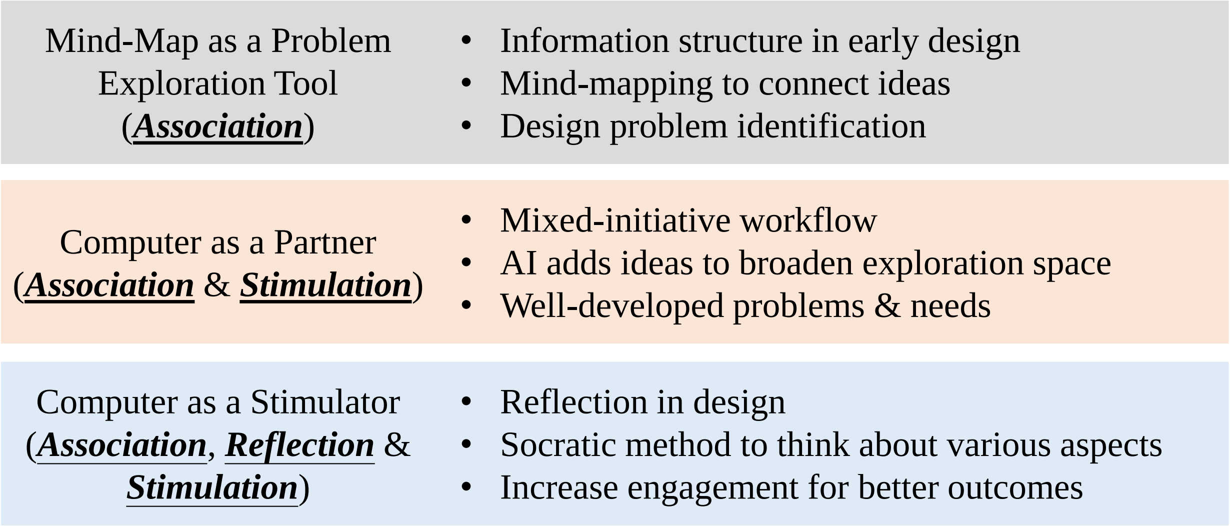
- **Variety:** The raters were asked to create an exhaustive list of category of explored ideas after thoroughly going through all the mind-maps created by participants. The Variety score is then given by the percentage of categories that is presented in the given mind-map.
- **Novelty:** The Novelty score for the ideas were calculated by considering the number of other similar ideas present in the same category — lower number of ideas in a category, higher the novelty. Novelty is calculated using $N_j = 1 - \frac{C_i}{T}$, where N_j is the Novelty score of the j^{th} idea, T is the total number of ideas, C_i is the number of similar ideas in the i^{th} category.

In general, these metrics were given to at least two expert designers to help evaluate the study outcomes, which are mind-maps in our case. They independently evaluated all the mind-maps for each of these metrics. Further, they were encouraged to discuss and come to a consensus on their grading rubric by sharing a common set of idea category list. The modified values of the metrics were then checked for reliability between the two raters (Cohen' s Kappa and Pearson's correlation [39]).

While there are several metrics in design research that are used for evaluating design conceptualization, our particular focus on pre-conceptualization stage and problem-space exploration required a deeper qualitative methodology to study the process of mind-mapping in addition to the quality of the maps generated. The qualitative methodologies in this research consist of a wide variety of tools and techniques including demographic surveys, open-ended questions and interviews, task-related questionnaires, user feedback on the usefulness and usability of the digital tools, and video protocol analysis.

1.5 Contributions

This dissertation presents two main contributions. First, we promote the importance of problem exploration activities and introduce the efficacy of mind-mapping in ***helping people make associations and connections between ideas as well as enabling the capabilities of visioning design***



Mind-Map as a Problem Exploration Tool (***Association***)	• Information structure in early design • Mind-mapping to connect ideas • Design problem identification
Computer as a Partner (***Association*** & ***Stimulation***)	• Mixed-initiative workflow • AI adds ideas to broaden exploration space • Well-developed problems & needs
Computer as a Stimulator (***Association***, ***Reflection*** & ***Stimulation***)	• Reflection in design • Socratic method to think about various aspects • Increase engagement for better outcomes

Figure 1.1: The overview of this dissertation. First, I will discuss how well mind-mapping is suitable for problem exploration as a tool to help people structure information and connect ideas so as to identify design opportunities effectively. Second, I propose a human-computer collaborative workflow for digital mind-mapping, where computer serves as a partner to the human collaborator to stimulate new thoughts and help people develop a comprehensive understanding of the central problem. Third, I explore the idea of computer as a stimulator to encourage people to reflect on the ideas in the given context, and increase engagement for better exploration outcomes.

opportunities using an empirical study. For that, we compare mind-mapping with another unstructured problem exploration technique to draw significant conclusions. Second, to support the underlying cognitive processes during early problem exploration phase, ***we study the scenario of how a person would collaborate with a computational agent during mind-mapping, get inspired from the stimulations provided, and reflect on the ideas in a given context.*** For that, we explored two types of human-computer collaboration workflows: *computer as a collaborator*, and *computer as a stimulator*. For each of these cases, algorithms were designed to emulate specific behaviors from a a computational agent with access to an external knowledge-base (eg. ConceptNet) for providing support in textual form during exploratory tasks. Specifically, this dissertation contributes in the following several aspects:

- **Human Behavior in Problem Exploration:** This work strives to understand human behavior for problem exploration during early design. We identify the effects of mind-maps that are often recommended but without empirical justification, and strategies that mind-map creators adopted towards gaining the overall understanding of the problem space. Further, in the context of design problem identification, we draw from principles of engineering design [11, 40] to formulate new metrics to quantitatively assess key elements in the product ideas generated after problem exploration.

- **Collaborative Workflows for Supporting Problem Exploration:** This work utilizes the investigations from the human behavior during mind-mapping tasks to inform the design of human-computer collaborative workflows for enhancing experiences during early design. To enable such human-computer collaboration in a natural and intuitive way, we designed novel interaction scheme to provide support explicitly (based on user actions) and implicitly (based on our computing models).

- **Information-Based Support Mechanisms for Exploratory Tasks:** This work utilizes the vast information on the Internet to provide textual stimuli in the forms of (1) direct information retrieval of concepts, and (2) processed concepts (eg. via semantic processing to generate questions). we develop methodologies to detect the focus of an evolving mind-map and make contextual queries from open-sourced knowledge databases to expand the space of idea exploration.

2. BACKGROUND & LITERATURE REVIEW*

2.1 Problem Exploration in Design

Problem exploration is the process that leads to the discovery of opportunities and insights that drive innovative products, services and systems [43]. Silver et al. [3] underscore the importance of problem-based learning for students to identify what they need to learn in order to solve a problem. Recent methods in early design are generally focused on increasing the probability of coming up with creative solutions by promoting divergent thinking. For instance, brainstorming specifically focuses on the quantity of ideas without judgment [30, 31, 32]. There are other popular techniques such as SCAMPER [27], C-Sketch [28], and morphological matrix [29], that support the formation of new concepts through modification and re-interpretation of rough initial ideas. However, this leads to design fixation for a specific and narrow set of concepts; thereby curtailing the exploration process. In contrast, mind-mapping is a flexible technique that can help investigate a problem from multiple points of view. In this paper, we use mind-mapping as means for problem exploration, which has been proven to be useful for reflection, communication, and synthesis during idea generation [44, 45]. The structure of mind-maps thus facilitates a wide-range of activities ranging from note-taking to information integration [46] by highlighting the relationships between various concepts and the organization of topic-oriented flow of thoughts [47, 48].

2.2 Mind-Maps: Structure & Applications

Davies [49] studied three different variations of structured diagrams, namely, concept mapping, mind mapping, and argument mapping and noted that while each was different in terms of formalism, each augments one's ability to process and integrate information. Of these three kinds, mind-maps tend to be more informal, both in content and structure and are therefore suitable for

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*The content in this chapter has been reprinted with permission from American Society of Mechanical Engineers, Inc. and Association for Computing Machinery, Inc., and has been extracted from "Investigating a Mixed-Initiative Workflow for Digital Mind-Mapping" by Ting-Ju Chen and Vinayak R. Krishnamurthy, in Journal of Mechanical Design (JMD) [41]. DOI: `https://doi.org/10.1115/1.4046808`; "QCue: Cues and Queries for Computer Facilitated Mind-Mapping" by Ting-Ju Chen, Sai Ganesh Subramanian, and Vinayak R. Krishnamurthy, in 46th Annual Conference on Graphics Interface (GI) [42]. DOI: `https://doi.org/10.20380/GI2020.14` situations where little is known about the problem at hand. The main advantage of mind-maps is that they enable learning about a certain topic by offering visual means to perform rapid idea expression and divergent exploration [50, 15, 51]. Their hierarchical structure makes them useful for a wide variety of applications ranging from document drafting [52], project planning [53], and decision making [54, 55, 56]. In fact, this structural quality has been shown to be particularly valuable in design data organization [57]. In the area of engineering education, mind-maps are found to be superior over conventional teaching methods in recalling technical concepts [58]. Zampetakis et al. [59] discuss the utility of mind-maps in the learning process of engineering students.

2.3 Mind-Maps for Design Ideation

Mind-mapping, being a general mechanism for externalizing ideas, can be useful in different parts of early design and for serving different functions in the process. Mind-maps promote *active learning* and *meaningful engagement*, two factors that are important for problem exploration, design conceptualization, and prototyping [60]. The fundamental cognitive advantage of mind-maps in design, perhaps, is that they help connect logical and imaginative thinking [61]. Several works [45, 62, 63] have explored the utility of mind-maps for design reflection, note-taking, idea communication, and idea synthesis. Recently, Jensen et al. [64] applied mind-maps during design ideation and developed prototypes for mechanical climbing system before a “down-select” process and affirmed its effectiveness. Researchers have also recognized their capability in assisting students to structure the thinking process and tackle complex problems during collaborative design activities [14]. Apart from their structure, mind-maps can be further enriched by colors, images, arrows, and dimension to reflect personal interest and individuality [65]. Given our specific focus mixed-initiative interactions for mind-mapping, we have constrained the variations in the visual variables, restricting the idea representation to a simple node-link diagram with words (and potentially phrases) as the node content.

2.4 Digital Mind-Mapping

Several works have investigated the effect of interactivity offered by digital tools on idea generation and collaboration in mind-mapping. For example, Lopes et al. proposed *planTEXT* [66] to offer integrated digital support for the planning, writing and revision activities during technical writing process. Karim et al. [67] investigated mobile-assisted mind-mapping technique (MAMMAT) using *MindMup* [68] and unfold its advantages in developing ESL undergraduate students' writing skills. Chief among them is work by Faste and Lin [18] who evaluated numerous existing mind-mapping software applications [69], performed ethnographic studies with a variety of users, and developed a framework of principles to guide future development of digital mind-mapping. They argue that contextual creative guidance is currently missing and necessary in digital tools to promote better design outcomes. However, Buisine et al. [70] note that merely offering a digital medium does not necessarily enable a significantly different outcome in terms of creativity. They further showed that there is no significant difference in idea production between digital tabletop-based and traditional paper-and-pencil mind-mapping workflows. Speaking of the advantages of digital mind-mapping tools, Orehovavcki et al. [71] address the quality in use of Web 2.0 applications. They found that participants feel highly satisfied with Web 2.0 applications that have the following attributes: ease of use, effectiveness, controllability, interactivity, navigability, customizability, efficiency, information content coverage, understandability, and reliability.

2.5 Computer-Based Cognitive Support

Significant efforts have been made to engage, as well as, facilitate critical thinking and learning for individuals. This is mainly done using digital workflows that involve pictorial stimuli [72, 73, 74], heuristic-based feedback generation [75], text-mining [76, 77, 22, 78], and speech-based interfaces [79, 80, 81]. Few works [82, 41] have also used gamification as a means to engage the user in the idea generation process. Specifically, in engineering design and systems engineering, there are a number of computer-based systems that support user's creativity during design conceptualization [83, 84, 85, 86]. However, most of these works targeted towards highly technical and domain-specific contexts and are limited in tackling with more open-ended exploratory tasks using interactive workflows.

While there are works [87, 88, 89] that have explored the possibility of automatic generation of mind-maps from speech and texts, little is known in terms of how additional computer support will affect the process of creating mind-maps. Prior works discussing computer supported mind-mapping [70, 18] have evaluated numerous existing mind-mapping software applications. They found that pen-and-paper and digital mind-mapping have different levels of speed and efficiency based on various factors such as user intent, ethnography, nature of collaboration. As a case in point, works by Kerne's group on curation [90, 91, 92] and web-semantics [93, 94] stand closely relevant to information based-ideation. These works are not particularly aimed at mind-mapping as a mode of exploration, but they share our premise of using information to support free-form visual exploration of ideas.

Recent works discuss several methods and studies on computer-supported mind-mapping for facilitating the idea exploration process. For example, the *Spinneret* presented by Bae et al. [95] demonstrated how computer can produce non-obvious ideas by exploring a knowledge graph in the neighborhood of a given concept through a biased random walk. Chen et al. [96] study mind-mapping for problem exploration in design from the point of collaboration. Their work puts forth some key findings (eg. idea expansion strategies, team dynamics, etc.) and insight on how mind-maps evolve in collaborative design tasks. Following on the same, they proposed a *computer as a partner approach* [41], where they demonstrate human-AI workflow for mind-mapping wherein the human and an intelligent agent take turns adding ideas to a mind-map. While these are all exciting prospects, we note that there is currently little information regarding how intelligent/proactive systems could be used for augmenting the user's cognitive capabilities for free-form mind-mapping without constraining the process. Recently, Koch et al. [97] proposed the idea of *cooperative contextual bandits* (CCB) that provides cognitive support in forms of suggestions (visual materials) and explanations (questions to justify the categories of designers' selections from search engine) to users during mood board design tasks. While CCB treats questions as means to justify designers' focus and adapt the system accordingly, we emphasize the associative thinking capability brought forth by questions formed out of semantic relations with the ideas being explored.

2.6 Textual Stimulation in Design

Researchers have investigated different methods to stimulate one's thinking process during ideation and creative problem-solving. Above all, textual stimulation is found to be helpful in generating creative results potentially due to its ambiguous nature; allowing a subjective interpretation. For example, to foster creativity by stimulating one's mind's associative power, Han et al. [73] demonstrated the idea of *combinational creativity* in design by incorporating semantic elements with images and showing the combinational/blended ideas to the users. They first allow users to input several key elements (eg. design keywords, semantic relations, randomness level, etc.) as criterion for the computer to crawl open-source images with a descriptive text, and conclude that such blended stimulation is helpful for both novice and experienced designers in generating creative ideas efficiently. Further, Borgianni et al. [98] strengthened the power of textual stimulation through a systematic experiment on the effects of three forms of stimulation (visual, textual and combined) on ideation. They made two main observations on textual stimulation: (1) it leads to higher quantity of ideas, and (2) it plays a primary role (increases semantic distance of ideas) in the combined stimuli scenario. In contrast, an exploratory study conducted by Cardoso and Badke-Schaub [99] revealed that images/photographic representation of stimulation seemed to have led designers to develop less original ideas because it is less abstract (contains realistic product details).

In one of their seminal works, Goldschmidt et al. [100] conducted a comparative study and showed that designers are able to generate original and good quality ideas while exposed to textual stimulation regardless of their relevance to the design theme. Recently, textual stimulation has been greatly used in the design community and found to have positive addition across different design phases; even though designers do not favor it [101]. For example, Sun et al. [102] examined designers' thinking processes using electroencephalography (EEG) during a sketching ideation study and found that, with textual stimulation provided, the designers were able to come up with more creative elements in their idea sketches. In engineering design, Linsey et al. [63] demonstrated the idea of design-by-analogy using *WordTree* and showed its power on design problem re-representation. Further, He et al. [103] proposed a core-periphery word cloud method to visualize textual concepts for the purpose of augmenting creative ideation in the early design stages. These works build the foundation of textual stimulation in design and elaborate on the effects of different structuring methods.

2.7 Semantic Networks in Engineering Design

There is a direction of work that closely relates to mind-mapping through knwoedlge databases is rooted in semantic network generation through engineering and technology knowledge-bases. Many such semantic networks have been explored in engineering design literature to structurally represent design-related information to assist designers in exploratory tasks. For example, Fu et al. [57] proposed a methodology to map the functional and surface content of the patents from design repository databases in node-link structures for analogy-based design inspiration. *B-Link* [23] and *innoGPS* [22] provide relational representations of retrieval results from databases (WordNet, U.S. patent database, etc.) to users for stimulating concept analogy and synthesis during design ideation. Recently, Sarica et al. [78] established *TechNet* — a technology semantic network based on design patents and provide an application programming interface (API) to allow users to access information in TechNet for engineering knowledge discovery. TechNet also provides interfaces to create context-aware relational representations based on a user query in the form of a graph, a tree, a paragraph, or a list. While these works make a significant stride in bridging the gap between design conceptualization and knowledge-retrieval, they are fundamentally different from our work in two ways. First, our primary focus is to facilitate continuous interaction, evolution, and adaptation of the outcome in a conversational workflow. Second, our goal is to (a) provide and study the role of cognitive assistance to a user by drawing from a given semantic network and (b) emulate *collaborative behavior* in an exploratory task.

2.8 Collaborative Brainstorming

Collaboration invokes positive participation experience for any brainstorming task [104, 105, 106, 107]. Our ultimate long-term goal with this work is to embody our findings within digital tools for mind-mapping with support for asynchronous, potentially remote collaboration between human and intelligent agents. Several works have discussed effectiveness of digital tools for idea-generation and collaborative tasks [108]. These works fall under the broader category of Electronic Brainstorming [109] overcoming *impasse* related shortcomings of the traditional brainstorming process. Digital brainstorming tools are further categorized as Computer Supported Coworking (CSCW) tools [110] discussing multiple technology assisted collaboration scenarios. In relation to mind-maps, we currently focus on asynchronous and co-located aspect of the CSCW matrix [111].

Shneiderman et al. [112] discusses an eight-step activity framework to utilize creativity support tools. This is to overcome challenges of domain related *impasse* during concept generation. The framework is general and applicable to both individual and collaborative ideation tasks. Stefik et al. [113] discuss collaboration using digital creativity tools in comparison to traditional chalkboards. In recent times, researchers have shown interest in exploring the visual schema of collaboration leveraging speech attributes from group based verbal discussions [72, 114, 115, 116]. Further, few works explore interactive modalities in digital collaboration [117, 118]. Although, several aforementioned works focus on digital collaboration, very few have tried understanding the fundamentals involved in the process.

3. MIND-MAP AS A PROBLEM EXPLORATION TOOL[*]

3.1 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 [119]. 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 [120, 11].

Given the importance assigned to problem exploration [121] 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 [4, 5], conceptualization [6, 7], and concept evaluation [8, 9]. As a result, techniques such as sketching, brain-writing, c-sketch [6], morphological matrices [29], word-trees [122, 63], design by analogy [123, 124] and many others are primarily studied as tools to develop design concepts to solve the problem. In this work, 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 [125, 126]. 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

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[*] The content in this chapter has been reprinted with permission from American Society of Mechanical Engineers, Inc. and has been extracted from "Investigating Mind-Mapping as a Tool for Problem Exploration in Early Design" by Ting-Ju Chen, Shantanu Vyas, and Vinayak R. Krishnamurthy, in 34nd International Conference on Design Theory and Methodology in International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC).

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 [127] 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 [128, 129, 130] and creative ideation [41, 42, 95]. 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 [10]. 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 work 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.

3.1.1 Approach & Contributions

This work presents an empirical study 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 [121]. 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.

3.2 Evaluation Methodology

3.2.1 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 [131]. 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.

3.2.2 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 [8, 9], 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 [131] and principles of engineering design [11, 40] 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 [132]. No critical need is missed or forgot-

ten. 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 [132]. 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” [133].
- **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 [134].

3.3 Study Design

3.3.1 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 [11]. 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 this chapter. 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 [135]. 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* _________.

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.

3.3.2 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 [136, 137].

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).

3.3.2.1 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 [42]:

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.

3.3.2.2 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 [11]. 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.

3.3.3 Evaluation Metrics

Apart from our proposed ***Design Problem Rubric*** (Section 3.2), we also adapted Shah's novelty and variety metrics [8, 38] 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 [11].

3.4 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

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 3.1: 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.

3.2 & 3.3.3). 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* ($\sim$23%) and *underwater camping* ($\sim$22%) themes using the metrics provided [138]. 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 [39].

3.4.1 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 [139]. 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 3.1). 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.

3.5 Observational Analysis: Problem Exploration

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.

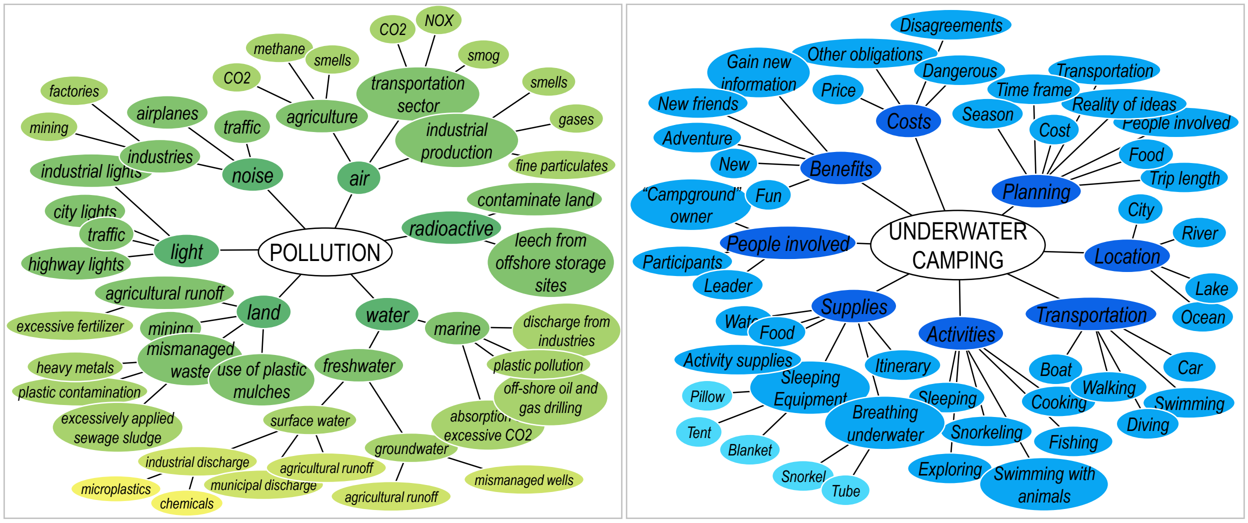
3.5.1 Topic-Dependent Behavior

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.

3.5.2 Technique-Dependence 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 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 [140] — 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* (Figure 3.2(b)). 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. Imme-



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

Figure 3.2: 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.

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.

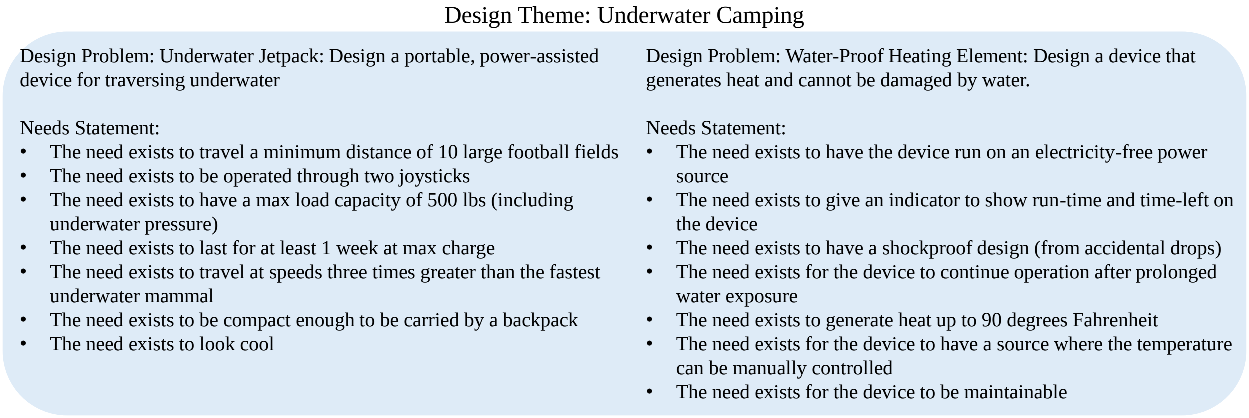
Needs Statement:
- The need exists to float
- If the design uses nets, the need exists to avoid plastic nets if possible to avoid more pollution
- The need exists to run on plastic
- The need exists to be remote operated or human operated
- The need exists to have a way to capture plastics and store 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 3.3: 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.



Design Theme: Underwater Camping

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

Needs Statement:

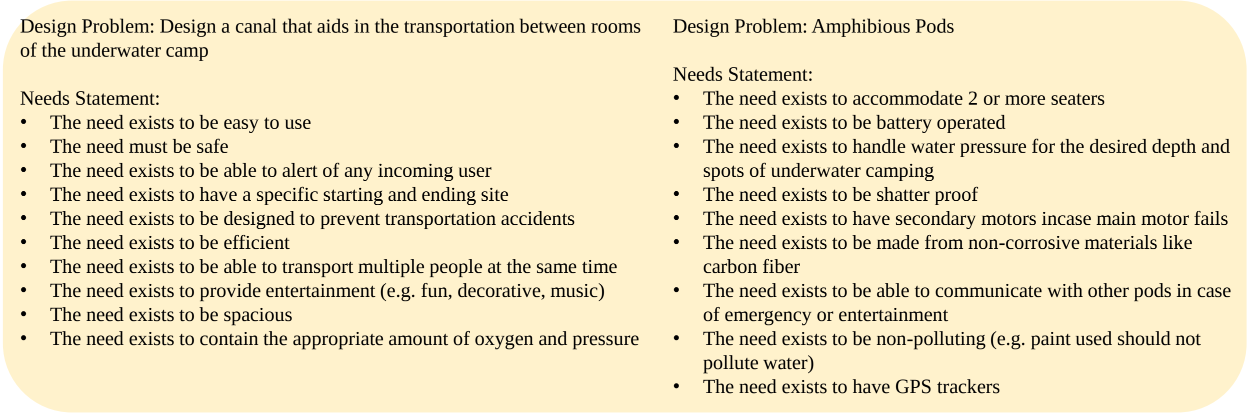
- The need exists to travel a minimum distance of 10 large football fields
- The need exists to be operated through two joysticks
- The need exists to have a max load capacity of 500 lbs (including underwater pressure)
- The need exists to last for at least 1 week at max charge
- The need exists to travel 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 3.4: 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.

diately 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. 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 3.2(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 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.

3.6 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.

3.6.1 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 3.1). 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**-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

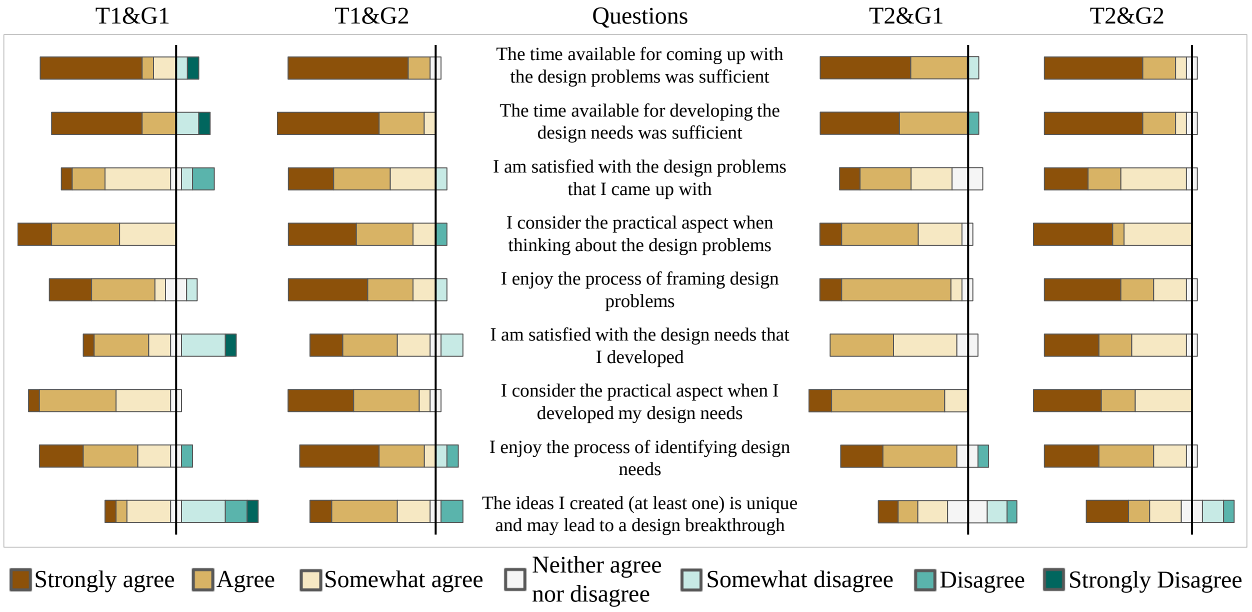


Figure 3.5: 7-point Likert scale user feedback on four different study conditions: *pollution* with free writing (T1&G1); *pollution* with mind-mapping (T1&G2); *underwater camping* with free writing (T2&G1); *underwater camping* with mind-mapping (T2&G2).

complicated in nature, such as *pollution.*

3.6.2 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 3.3). Another participant developed one product idea *"Ocean plastic removal"* after identifying the issues of plastics in different types of pollution during mind-mapping (Figure 3.4). 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 3.1, 3.3 & 3.4).

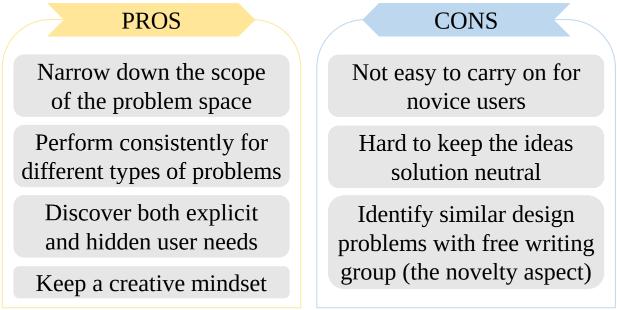
We further observed that mind-mapping users tended to be more engaged in coming up with various product opportunities as indicated by the quantity score (Figure 3.1). Specifically, for *pollution*, 6 participants in the mind-mapping group generated more than 2 complete design problem descriptions, whereas 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 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.

3.6.3 Participant Feedback

After developing design problem descriptions for each theme, the participants were asked a series of questions about their experience (Figure 3.5). 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 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 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



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

had prior experience in creating several mind-maps resulting in lesser difficulties in using the technique.

3.7 Limitations

There are two main limitations in this current work. First, this study restricted information collection from external resources (e.g. internet, potential 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 [141] 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 addressed these concerns, we believe that including more modalities such as idea re-linking can lead to an interesting discussion on problem exploration behavior.

3.8 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 3.5). 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 3.4). Based on the investigation, we marked two main advantages of mind-maps for early design problem exploration and clarification (Figure 3.6). 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 [142] 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.

4. COMPUTER AS A KNOWLEDGE-BASE: QUERY EXPANSION

4.1 Introduction

Here, our goal was to investigate the effect of query expansion (the process of reformulating a given query to improve retrieval of information) and to observe how users react to conditions where suggestions are actively provided during mind-mapping. We posit that in a digital setting where the user has access to vast knowledge databases, the cognitive processes underlying mind-mapping could be effectively supported by systems that allow for not just querying singular concepts from the database but by allowing the user to expand upon those queries. Based on this, we implemented an interface (query-expansion interface) to record the usage of suggestions retrieved from ConceptNet [143] and conducted a user study using this interface. ConceptNet is a semantic network that contains a graph-based representation with nodes representing real-word concepts as natural language phrases (e.g. block a door, be abandoned, etc.), and edges representing semantic relationships.

4.1.1 Identification of Gap

While there has been significant work on the cognitive and technological aspects of mind-mapping, there is currently little understanding of how to support content creation in mind-maps by leveraging the vast amount of information available on the Web. This work aims at filling this gap by investigating query expansions as a means to augment users' capabilities to create digital mind-maps.

4.2 Query-Expansion Interface

The idea behind our interface is based on query expansion enabled by ConceptNet. In comparison to content-retrieval analysis (Wiki) or lexical-semantic databases such as WordNet [144], ConceptNet allows for leveraging the vast organization of related concepts based on a diverse set of relations resulting in a broader scope of queries. Using this feature of ConceptNet, we developed a simple web-based tool for query-expansion mind-mapping (QEM) wherein users could add nodes (words/phrases) and link them together to create a map. For every new word or phrase, we used the top 50 query results as suggestions that the users could use as alternatives or additional nodes in the map. Our hypothesis was that ConceptNet suggestions would help users create richer mind-maps in comparison to pen-paper mind-mapping.

4.3 Evaluation Tasks

We designed our tasks for (a) comparing pen-paper mind-mapping and QEMs with respect to user performance, preference, and completion time and (b) to explore how the addition of query-based search affects the spanning of ideas in a typical mind-map creation task. Each participant was asked to create two mind-maps, one for each of the following problem statements:

- *Discuss the problem of different forms of pollution, and suggest solutions to minimize them*: This problem statement was kept generic and conclusive, and something that would be typically familiar to the target participants, to compare the creation modalities for simple problem statements.

- *Modes of human transportation in the year 2118*: The intent behind this open-ended problem statement was to encourage users to explore a variety of ideas through both modalities, and observe the utility of query based mind map tools for such problem statements.

The topics for the problem statements were selected to provide users with familiar domains while also leaving scope for encouraging new ideas from the participants.

4.3.1 Participants

We recruited 18 students (8 females) from engineering majors between 18 to 32 years of age. Of these, 6 participants were familiar with the concept of mind-maps (with a self-reported score of 4 on a scale of 10). We conducted a between subjects study, where 9 participants created mind-maps for a given problem statement using QEM.

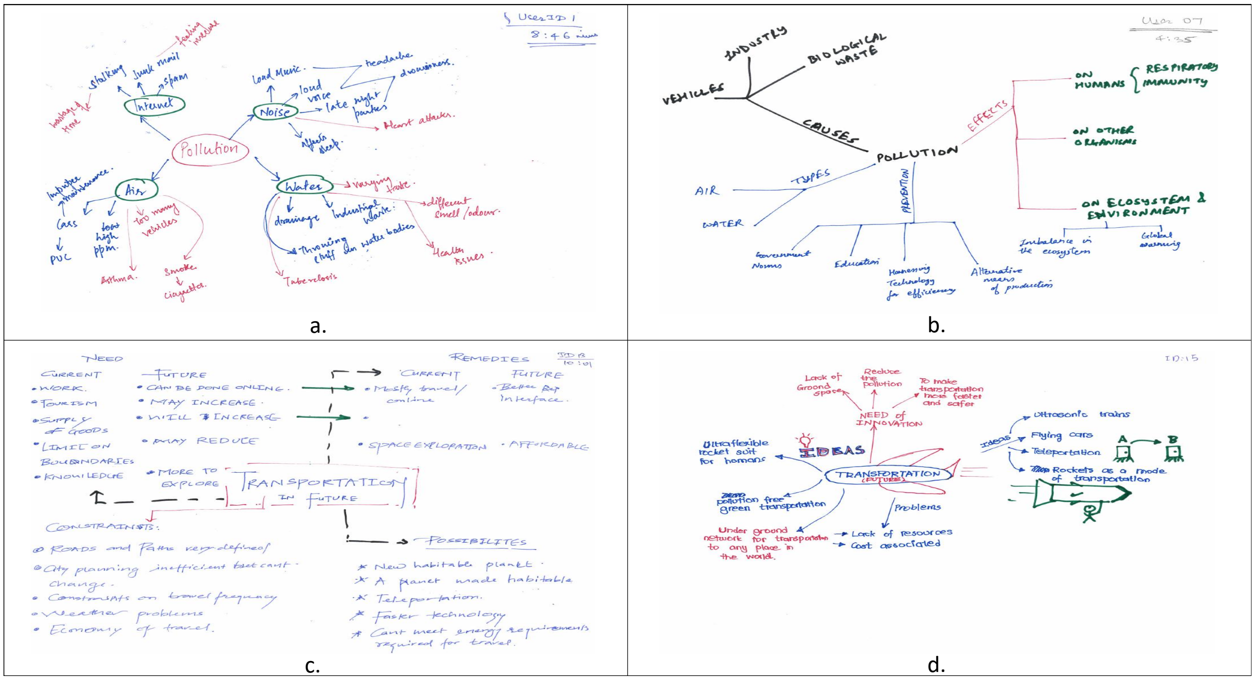


Figure 4.1: Sample user created traditional mind-maps for (a),(b) pollution; (c),(d) transportation

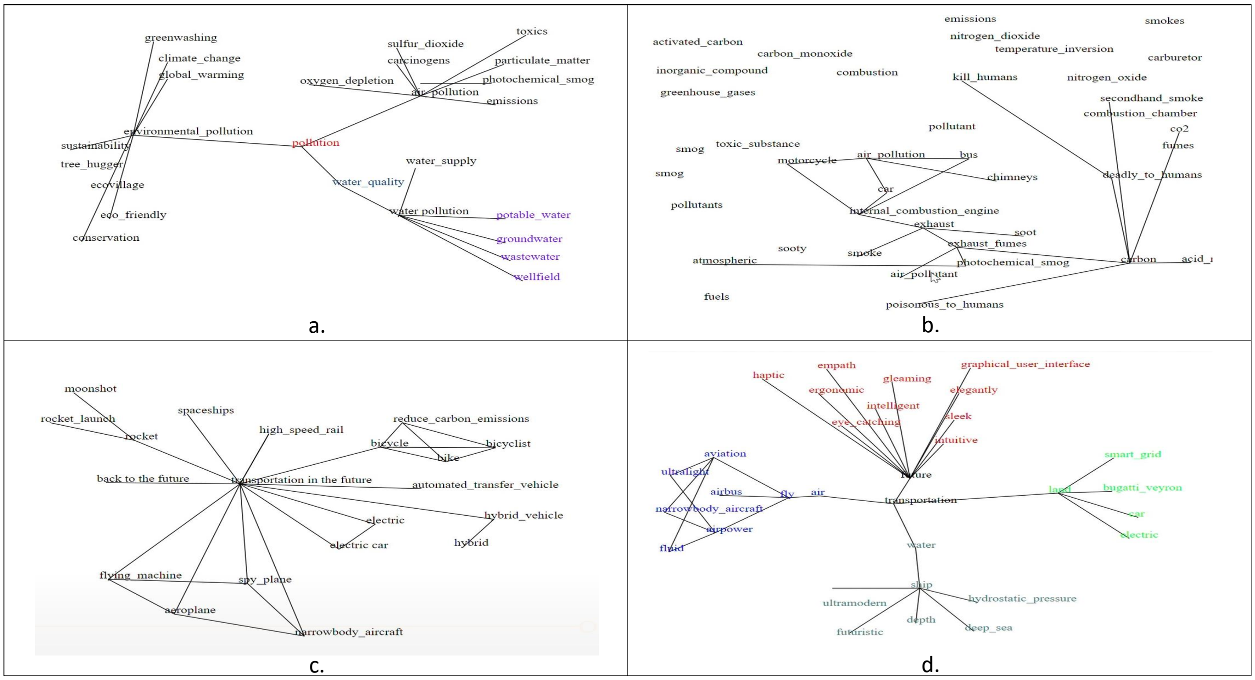
4.3.2 Procedure

The total time taken during the experiment varied between 30 to 35 minutes. Participants in the QEM group were first introduced to the interfaces and were encouraged explore the interface. Subsequently, the participants created the mind-map for the assigned problem. They were allowed a maximum of 10 minutes for one problem statement. Finally, on completion, each participant answered a series of questions in terms of ease of use, intuitiveness, and effectiveness of the assigned mind-map creation modality.

4.4 Key Findings

4.4.1 User Feedback

We did not find consensus regarding self-reported satisfaction with the mind-maps created by participants in pen-paper mind-mapping. Moreover, while pen-paper mind-mapping participants agreed that the time for map creation was sufficient, nearly 50% did not agree with being able to span their ideas properly. On the other hand, 90% QEM participants reported that they were



a. b. c. d.

Figure 4.2: Sample user created extended mind-maps for (a),(b) pollution; (c),(d) transportation

satisfied with their results. Over 80% of the QEM participants agreed to be able to easily search for related words and ideas, and add them to the mind-map. In the post study survey, QEM users suggested adding features such as randomizing the order of words searched for, ability to query multiple phrases at the same time, and ability to search for images. One participant mentioned: "*The interface wasn't able to do the query if put a pair of words together or search for somebody's name viz. Elon Musk*".

4.4.2 Users' Over-dependency on Query-Expansion

As compared to pen-paper mind-mapping, we observed two main limitations in our query-expansion workflow. First, the addition of a new idea required the query of the word. While we had implemented this to simplify the interactions, this resulted in a break in the user's flow of thought further inhibiting diversity (especially when the digital tool is able to search cross-domain and provide a big database for exploring). Second, we observed that users relied heavily on search and query rather than externalizing their personal views on a subject. Users simply continued searching for the right keyword instead of adding more ideas to the map. This also increased the overall time taken for creating maps using query-expansion. This was also reported by users with statements such as: *“I relied a lot on the search results the interface gave me"* and *“I did not brainstorm a lot while creating the mind map, I spent a lot of time in finding proper terms in the search results to put onto the mind map”*.

5. COMPUTER AS A COLLABORATOR FOR DIGITAL MIND-MAPPING*

5.1 Introduction

Mind-maps are now widely recognized as thinking tools for creative tasks such as conceptual design [146, 147]. Nonetheless, creating a mind-map can be challenging especially for beginners either due to a combination of lack of domain knowledge, personal inhibition, early convergence, and fixation [148, 149, 150, 151]. This chapter seeks to enable and understand how humans and computers can creatively *co-generate* ideas with equal participation to explore concepts around a design problem.

Our work draws from research by Yannakakis et al. [152] that proposes the use of human-computer collaboration tools not solely to demonstrate mixed-initiative *co-creativity* (MI-CC) but as a means to foster human creativity itself. Inspired by this view, we study a simple yet powerful workflow in the context of exploratory tasks in early design. Mind-mapping is a versatile tool that can be used throughout design by creating a network of concepts or ideas surrounding a central problem. In design literature, it has been studied for design conceptualization and solution space exploration [63, 130, 64]. In this work, we seek to complement the current literature in design theory, by focusing on investigating the usage of mind-maps during *problem-space exploration* since it is a crucial step in opening designers to ideas that seem out of scope but can potentially be useful. From this viewpoint, mind-maps are especially suitable for problem exploration in that they allow an unconstrained exploration of a variety of ideas along with the relationships between those ideas in a hierarchical fashion. Our focus, therefore, is specifically on the pre-conceptualization stage where a crisp problem statement is not yet available to the designer.

The rules of creating a mind-map are rather simple: one starts with a central idea and creates

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*The content in this chapter has been reprinted with permission from American Society of Mechanical Engineers, Inc. and American Institute of Aeronautics and Astronautics, Inc., and has been extracted from "Investigating a Mixed-Initiative Workflow for Digital Mind-Mapping" by Ting-Ju Chen and Vinayak R. Krishnamurthy, in Journal of Mechanical Design (JMD) [41]. DOI: `https://doi.org/10.1115/1.4046808`; "Mini-map: Mixed-Initiative Mind-Mapping via Contextual Query Expansion" by Ting-Ju Chen, Sai Ganesh Subramanian, and Vinayak R. Krishnamurthy, in AI and HMI in Engineering Design Conference in American Institute of Aeronautics and Astronautics Scitech Forum (AIAA-Scitech) [145]. DOI: `https://doi.org/10.2514/6.2019-2347` two to three *branches* leading to related ideas repeating the process for each newly added idea. Furthermore, there are now several digital tools [153] that can be used to create and document mind-maps. However, instead of providing cognitive assistance for enhanced mind-mapping, these tools primarily serve as digital extensions of traditional pen-and-paper mind-mapping. Despite extensive knowledge databases on the web, there is currently limited computational support to augment users' ability to fully explore the vast information sources available at their disposal.

We present Mini-Map [145], a digital workflow for **m**ixed-**ini**tiative mind-**map**ping wherein a human designer and a computer program take turns to create a mind-map for a given design problem. Mini-Map is based on a sequential interaction workflow where a human user and a computer algorithm take turns to add ideas to an evolving mind-map. Subsequently, we study how such a workflow leads to collaborative behavior between a designer and an Intelligent Agent (AI) while taking equal participation during mind-mapping. Mini-Map is powered by ConceptNet [1, 154, 155], which is presently one of the largest commonsense knowledge base that covers assertions between concepts through rich relational ontology.

5.1.1 Mixed-initiative Co-creativity

The notion of *mixed-initiative interaction* was brought out first by Novick et al. [156]. Yannakakis et al. [152] further developed the concept of *co-creativity*, which implies that both the computer and the human proactively contribute toward the development of ideas to solve a problem. The vision in such a scenario is that the computer fosters the human's creativity through the iterative process of interactions, and vice versa. Drawing from this concept, many creativity support systems are designed and implemented based on robust corpus-trained machine learning techniques or evolutionary approaches [157]. For example, the *Drawing Apprentice* proposed by Davis et al. [158] uses deep-learned object recognition model to explore the potential of computers as co-creators in collaborative drawing tasks. Recently, Alvarez et al. [159] discusses how employing mixed-initiative workflow using evolutionary approach improves the quality diversity of generating dungeons in computer games. Huang et al. [160] proposed a mixed-initiative framework for multi-channel music composition using deep learning algorithms. Apart from creativity support, Nguyen1 et al. [161] also utilizes the efficiency and scalability of information retrieval and machine learning techniques to train classification models using specific databases to enhance decision-making process through human-AI partnership.

5.1.2 Identification of Gaps

There have been growing interests in enabling mixed-initiative systems in the domain of *game design* [162, 163, 164]. Most of these works are essentially targeted toward procedural content generation in computer games. While there are recent advances in aerospace design domains such as the *Daphne* system [165], there is currently little known about how human-computer co-creativity could be materialized for engineering and product design domains in early conceptualization. Furthermore, there is also a need for qualitative insights on how designers would perceive intelligent systems that could aid idea exploration in future design tools. Our work is a step toward filling this knowledge gap.

5.2 Methods & Tools

Two observations inform our technical approach. First, merely providing the user with the ability to query vast knowledge databases is not sufficient for supporting the cognitive processes underlying mind-mapping. The user should have a mechanism to expand upon those queries. Second, mind-maps lend themselves to a natural graph based structure with ideas (words/phrases) as nodes and their relations as the links or edges. Therefore, the knowledge database should preferably contain a rich set of relationships between the different data entities. Based on these, our approach is to use ConceptNet, a semantic network that contains a graph-based representation with nodes representing real-word concepts as natural language phrases (e.g. *block a door*, *be abandoned*, etc.), and edges representing semantic relationships.

In comparison to engineering databases, our choice of ConceptNet was due to two main reasons. First, ConceptNet consists of explicit semantic relationships between nodes that are derived from WordNet and enriched through an Open Mind Common Sense project [154]. This feature plays a crucial role in our algorithm. Second, our goal is primarily to emulate collaborative behavior during problem exploration with the intention of making our workflow useful to wider audience. Here, ConceptNet offers a balanced level of specificity in terminology. In particular, while it does not provide highly specific technical terms in comparison to systems such as TechNet [78], it still offers better specificity when compared to data-sets such as WordNet. Therefore, the combination of a comprehensive canonical relationship types with the wide coverage of knowledge made ConceptNet a more suitable choice for our context of problem space exploration. Note that throughout this chapter, we use *idea* to represent the content being added to the mind-map as a node, *concept* to represent the retrieval result from ConceptNet or a fundamental unit of knowledge .

5.2.1 Problem Formulation

We assume a mind-map to be a tree (an acyclic graph), say $M(V, E)$ with a set of nodes V_M and edges E_M and the construction of a mind-map can be viewed as an iterative sequence of breadth-first (i.e. exploring different aspects of a problem) and depth-first (i.e. adding detailed and concrete ideas to different aspects of a problem). The root node of this tree is the central problem around which we aim to emulate this behavior in a collaborative fashion wherein a human and an automated agent are collectively working to diversify ideas around the root node. We formulate the process of mixed-initiative mind-mapping as a collaborative interactive activity that is being participated equally by a human and an intelligent agent (AI). Given a central topic, the aim for the human and AI collaborators is to expand the map by exploring different aspects of the topic (breadth-first), and refine each of these aspects by adding detailed ideas (depth-first). In order to do this, the collaborators are given a seed topic as the root node of M and the human and AI players take turns to add nodes to M. Furthermore, each player is allowed exactly one node addition per turn.

Given any state of M (the simplest being a given root node representing the central idea), there are two primary algorithmic steps that are needed for creating a mini-map. The first step is **target search** wherein the AI needs to determine a target node (a node where a new node will be added). Subsequently, the second step is **content generation** wherein the AI needs to define the content (words and phrases) that will be added to the target node to ultimately expand the space of ideas around the central problem.

The algorithm for Mini-Map was developed in an iterative manner wherein we experimented with several alternatives for target search and content generation and conducted small scale pilot studies (with $5-7$ participants with preliminary experience in mind-mapping). Our preliminary studies with these alternatives that informed the development of our final algorithm is elaborated in the following [145].

5.2.2 Algorithmic Iterations

In this work, we take an iterative approach for the development of the Mini-Map algorithm. Specifically, our final algorithm for Mini-Map was developed based on three prior iterations. We combined different alternatives for target search and content generation in each iteration and conducted small scale pilot studies with users. The observation of the resulting mind-maps and issues raised by users allowed us to refine each subsequent iteration culminating in our final algorithm. Below, we provide a detailed account of our iterations and the key insights we gained in terms of the AI-behavior we observed.

5.2.2.1 Iteration 1: Random Target and Median Content

In our first iteration, we applied a simple rule for selecting targets to add a new node to (Figure 5.1). Given the current state of a map M with nodes V_M and edges E_M, we first randomly select a concept $v \in V_M$. Then, we retrieve a set $Q = \{q_i | (v, q_i) \in E(C), i \in [1, k]\}$ and sort it in decreasing order of the edge weights in ConceptNet (i.e. $w(v, q_1) \geq w(v, q_2) \geq \cdots w(v, q_k)$). For content generation, we select the concept with the median edge weight and add to the selected node. The computation terminates when there are no further concepts where the AI can add a node (this is guaranteed since there is only one median element in a given set). Given a target node, the seemingly obvious choice would be to query the target node and generate content based on the highest weighted results given by ConceptNet. This approach clearly leads to more abstract concepts being added to the map as it grows — a scenario that is in contrast with how mind-mapping is typically performed. For instance, for a central topic such as "*Aircraft*", adding a node

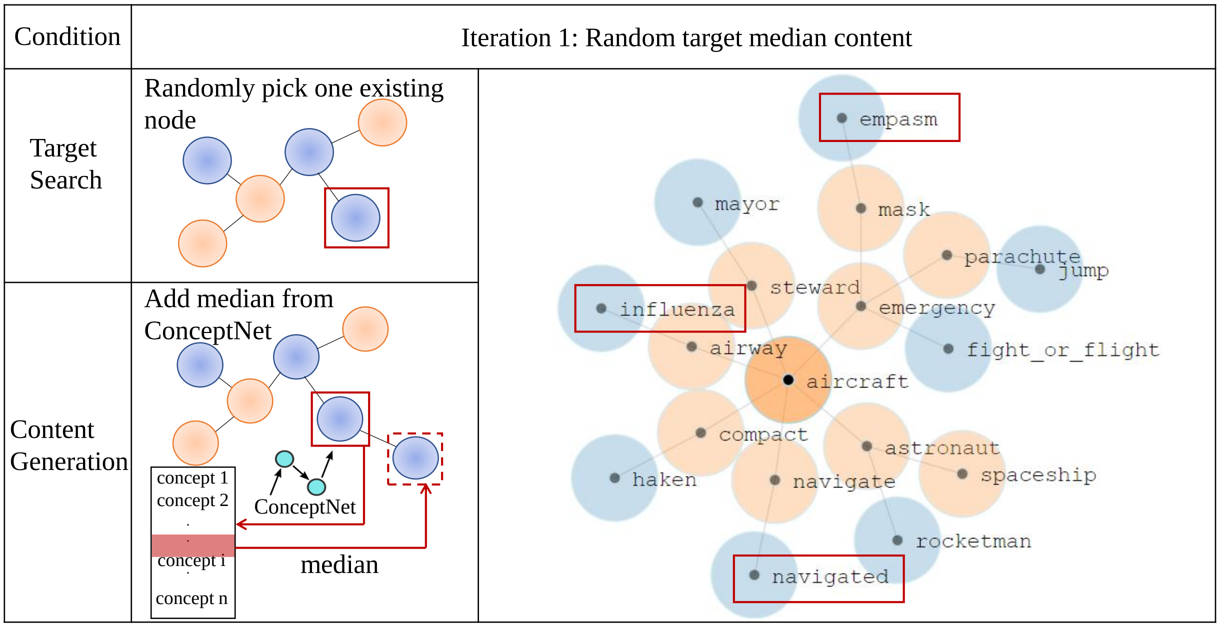


Figure 5.1: Illustration of iteration 1 in our approach. The resulting mind-map shows several disadvantages: users hard to keep up responses from AI because of random target search; the AI is unable to generate multiple ideas to one concept; and the generated content might be out of context (which are highlighted in red boxes: *influenza*, *navigated*, *empasm*, etc.)

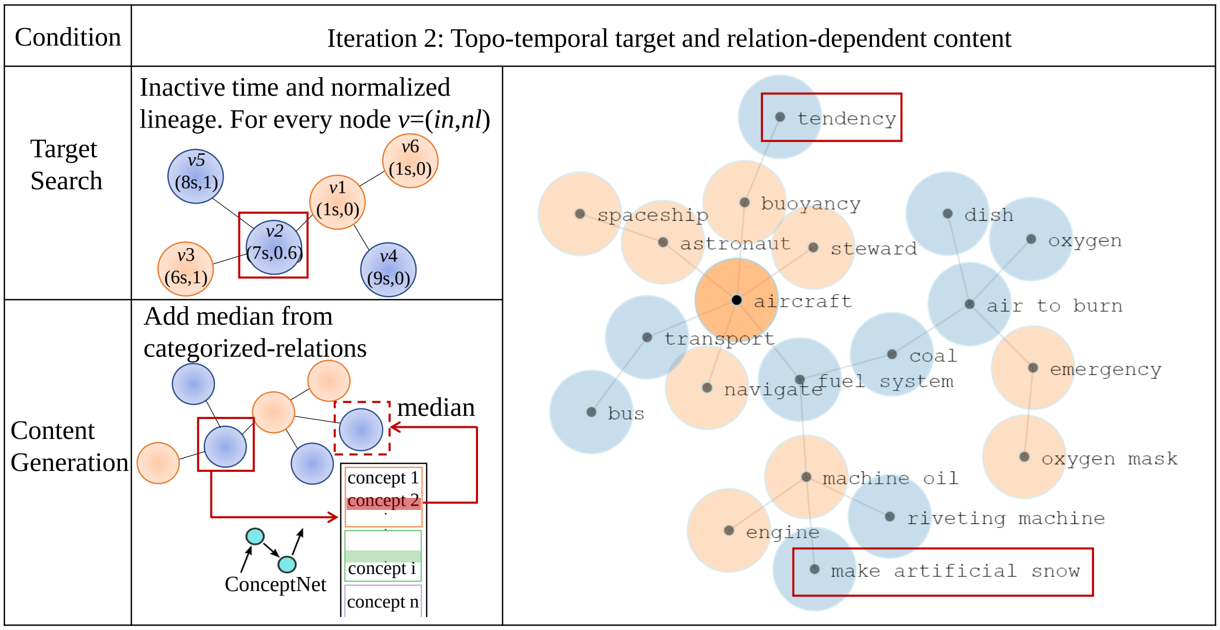


Figure 5.2: Illustration of iteration 2 in our approach. The resulting mind-map shows a main disadvantage: the AI generates content with little or no relevance to the context of current mind-map (which are highlighted in red boxes: *buoyancy* is a type of *tendency*, *make artificial snow*, etc.)

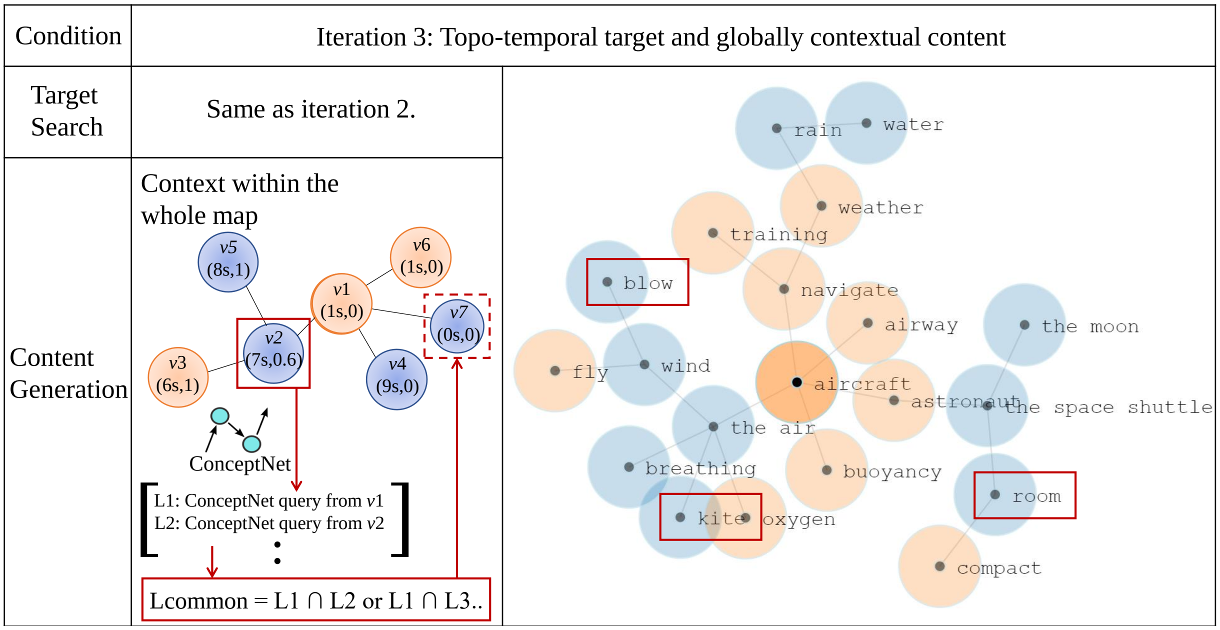


Figure 5.3: Illustration of iteration 3 in our approach. The resulting mind-map reveals several disadvantages: the AI can not response to last added node due to measure from inactivity in target search, and the generated contents become abstract as mind-map grows (which are highlighted in red boxes: *kite* from *the air* and *fly*, *blow* from *wind* and *breathing*, *room* from *wind* and *space*).

"*fly*" leads the intelligent agent to add the word "*sky*" followed by "*blue*" and "*a colour of the rainbow*)". The primary reason for choosing the median weighted edge is the observation that the edge weight distribution of the linked concepts in ConceptNet is skewed. Hence, taking the median instead of other statistical aggregates such as mean results in a more robust result in terms of preserving the relatedness as well as diversity of the added concepts.

Our naive approach provided some interesting results (Figure 5.1) for the central topic *Aircraft*. As can be seen, the method is able to produce reasonable maps that can potentially lead to technically feasible solutions to the problems. However, we also observe that the AI partner sometimes adds nodes that may not be relevant to the current design context (e.g. "*navigated*" in response to "*navigate*") or related concepts that may not be useful in arriving at solutions (e.g. "*fight-or-flight*" in response to "*emergency*"). The second limitation of the naive method is the fact that the AI partner can not add more than one node to a given existing concept in the existing map. This is merely the result of the fact that there is only one median that we can choose for a given ConceptNet query

5.2.2.2 Iteration 2: Topo-Temporal Target and Relation-Dependent Content

In order to overcome the obvious shortcomings of random target search, our second iteration investigated a method for target search based on the topological and temporal evolution of a given mind-map. Here, for each node $v \in V_M$, we introduce two penalty terms, namely, inactivity ($in(v)$) and normalized lineage ($nl(v)$). Here, $in(v)$ is computed based on the time elapsed since last activity that occurred at node v (i.e. addition of a child node). Upon addition of a child node to v, we reset $in(v) = 1$ and linearly decrease $in(v)$ at every computation cycle until it reaches 0. Further, $nl(v)$ is computed by normalizing total count of all descendents of v. It is 1 for a leaf node of M and 0 for the root node. By applying a threshold to these penalties, the AI determines the target nodes that lie below the threshold.

In order to enable the AI to add multiple nodes to target node, we further subdivide a given query list into the defined relation-categories and add median-weighted concepts from each of these categories starting from the highest to lowest weights. This also allows the AI to preserve both the relevance (higher weights) and novelty (lower weights) in the resulting mind-map (Figure 5.2). However, we found that the content generation with this approach usually led to addition of concepts with little or even no relevance to the context of current mind-map. For instance, "*buoyancy*" leads to "*tendency*" and "*machine oil*" leads to "*make artificial snow*".

5.2.2.3 Iteration 3: Topo-Temporal Target and Globally Contextual Content

Considering the behavior results from iteration 2, we modified our content generation rules keeping the target search the same as iteration 2. Our intent was to take into account the context of the currently evolving mind-map during the generation of new content. For this, at any given state of the mind-map, we compile a list of queries that are common across all concepts in the mind-map. Subsequently, we use the subdivided median weight approach similar to iteration 2 for this common list. This ensures that the generated contents share common properties from the existing context in a mind-map (Figure 5.3). From iterations 2 and 3, the measure of time in deciding potential targets make the AI not response to any last added node by user, since they just got active. This phenomenon results in user feedback such as *"make me lose my train of thought"*. Also, we found out if choosing from overlapped concepts from the whole context, the results are also going to become abstract as the mind-map grows, hence lose focus. For example, *kite* was generated based on *fly* and *the air*, *blow* from *wind* and *breathing* (Figure 5.3).

5.2.3 Final Algorithm: Target Search

The driving principle that informs our target search approach is to find a balance between exploring different aspects of a problem and in-depth exploration along each of those aspects. For this, our main goal is to model the behavior of the AI player in such a way that the mind-map M evolves in a breadth-first fashion in the initial stages of mind-mapping and transitions into a depth-first target selection during the later stages of the evolution of M. In our preliminary studies, we experimented with three alternatives for target search as enumerated below:

1. *Random Target Search:* The AI randomly selects a node from the map.
2. *Topo-temporal Search:* The AI searches for the target based on the topological and temporal properties of the existing nodes of M. Preference is given to nodes that have either not been explored for a long duration of time in conjunction with how far they are from the root node (Section 6.2.3).
3. *Guaranteed Minimal Expansion:* Here, the idea was to give preference to nodes that have not crossed a certain threshold of expansion (measured by the number of children).

Contrary to our initial intuition that the topo-temporal approach will provide the most reasonable behavior, we found our expansion based approach to be most highly rated by participants in our preliminary studies.

5.2.3.1 Expansion Threshold

One of the main challenges we seek to address is to avoid imbalanced addition of nodes to the map leading to heavily biased exploration of ideas (i.e. either high-breadth, low-depth or vice versa). In our studies with traditional mind-mapping (without computer intervention), we

Algorithm 1 Target Search

```
**Input:** Current mind-map $M = (V_M, E_M)$
**Input:** Bi-ordered Index Set $X \in Z^3$
**Output:** Target Node $v_T \in V_M$
**Output:** Updated Bi-ordered Index Set $X \in Z^3$
if $X = \emptyset$ then
    $X \leftarrow \emptyset \in Z^3$
    for $v_i \in V_M$ do
        $x_1 \leftarrow$ depth of $v_i$
        $x_2 \leftarrow$ number of children of $v_i$
        $x_3 \leftarrow i$
        $\mathbf{x} \leftarrow (x_1, x_2, x_3)$
        $X \leftarrow X \cup \{\mathbf{x}\}$
    end for
    $X \leftarrow Sort(X,\ descending\ order\ in\ x_1)$
    $D_{max} \leftarrow$ maximum depth of $M$
    for $d \in [1, D_{max}]$ do
        $X \supset X_d \leftarrow \{\mathbf{x} = (x_1, x_2, x_3) \in X | x_1 = d\}$
        $X_d \leftarrow Sort(X_d,\ descending\ order\ in\ x_2)$
    end for
end if
for $d \in [1, D_{max}]$ do
    $X \supset X_d \leftarrow \{\mathbf{x} = (x_1, x_2, x_3) \in X | x_1 = d\}$
    for $\mathbf{x}^j = (x_1^j = d, x_2^j, x_3^j) \in X_d$ do
        if $x_2^i < 3$ then
            $i \leftarrow x_3^j$
            $v_T \leftarrow v_i \in V_M$
            $x_1^i \leftarrow x_1^i + 1$
            return $v_T, X$
        end if
    end for
end for
```

observed that users tended to explore ideas in specific and narrow directions that they felt more familiar with. To overcome this issue, we developed a target search strategy based on *expansion threshold*. We thus developed our target search algorithm to encourage users to brainstorm along non-obvious directions and perform divergent idea exploration. Therefore, we intended the AI player to specifically identify potential target nodes so as to enforce a breadth-first strategy (i.e. nodes closer to the root get preference) in a manner that ensures that every node has at least a prescribed minimum number of children (Figure 5.4(a), Algorithm 1). Specifically, the AI would traverse the mind-map starting from the root and will prefer the target closest to root with less than an *expansion threshold* (i.e. a pre-determined number of child nodes). We further designed the expansion threshold to be *three* based on our observation from the pilot study and a trial and error process. In these trials, we compared the mind-maps created with Mini-Map to the maps generated by human-human pairs with the goal of determining an appropriate threshold to maintain the structural balance. Specifically, for an expansion threshold of two, we observed that there was a clear lack of diversity in the main branches (i.e. the nodes directly attached to the root node). For a threshold of four, we further observed that the breadth of the maps was higher than those we had observed in the human-human pairs. While the users in our pilot experiments did not raise concerns regarding this issue as well, the expansion threshold of three child nodes was determined to be reasonable. Note that this algorithm has a guaranteed termination criterion since there are always leaf nodes in M (i.e. nodes with no child nodes).

5.2.4 Final Algorithm: Content Generation

Our basic approach for determining what new content to add to a target node is to utilize the notion of query expansion and pseudo-relevance feedback via ConceptNet [143]. ConceptNet is a large graph of concepts where two concepts are directly connected with an edge if there is a semantic relation between them. Furthermore, each edge also has a *weight* that signifies the strength of the relationship. Our choice is based on the potential of ConceptNet for making more complex, multi-step inferences that are helpful in query formulation and the identification of poorly performing queries. Other existing methods for query expansion rely mostly on content-retrieval

Algorithm 2 Content Generation

```
Input: Target Node $v_T \in V_M$
Input: Relation Descriptor Set $R(v_T)$
Output: Concept $c \in V_C$ from ConceptNet graph $C = (V_C, E_C)$
Input: Relation Descriptor Set $R(v_T)$
$P_v \leftarrow$ list of nodes on the shortest path between $v_T$ and Root Node
$L_{common} \leftarrow \emptyset$
for $p_i \in P_v$ do
    $L_i \leftarrow \{(c_j, r_j, w_j) | (p, c_j) \in E_C\}$ ($r_j$ is the type of relation, $w_j$ is edge weight)
end for
$L_{temp} \leftarrow \bigcap_{i=1}^{|P_v|} L_i$
$L_{temp} \leftarrow Sort(L_{temp}, alphabetical\ order\ of\ r_i)$
for all $r \in R$ do
    $L_{temp} \supset L_r \leftarrow \{l_i = (c_i, r_i, w_i) \in L_{temp} | r_i = r\}$
    $L_r \leftarrow Sort(L_r, descending\ order\ of\ w_i)$
    $W_r \leftarrow \sum w_i \forall l_i \in L_r$
end for
$RL \leftarrow \{L_{r1}, L_{r2}, \dots\}$
$RW \leftarrow \{W_{r1}, W_{r1}\}$
$L_{common} \leftarrow Sort(RL, descending\ order\ of\ RW)$
$R(v_T) \leftarrow Sort(R(v_T), descending\ order\ of\ RW)$
if Depth of $v_T$ = 0 then
    $c \leftarrow r_1 \in R(v_T)$
else
    $c \leftarrow c_j \in L_{r1} | w_j = median(w_j \forall l_j \in Lr1)$
    $R(v_T) \leftarrow R(v_T) - \{r_1\}$
end if
return $c$, $R(v_T)$
```

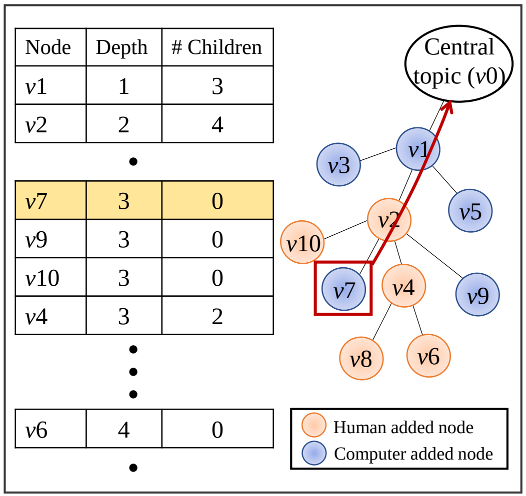
analysis (Wiki) or lexical-semantic database such as WordNet [144]. However, although WordNet is widely used to provide hypernym relations in a hierarchical fashion, ConceptNet allows for the organization of related concepts based on a diverse set of relations (such as "*IsA*", "*HasA*", "*UsedFor*", "*CapableOf*") resulting in a broader scope of queries that WordNet synsets would not allow.

5.2.4.1 Path Dependent Context

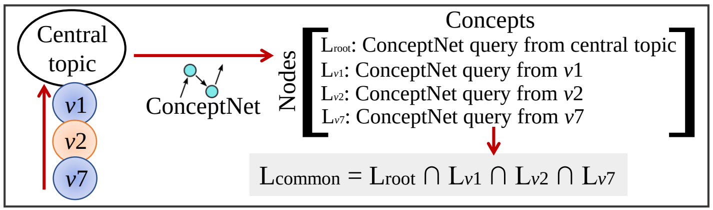
Given a target node, the simplest method to query for new content would be to search for concepts that are closely related to the target in the database (ConceptNet in our case). However, we argue that adding a new node to some chosen target is conceptually akin to expanding the "*line-of-thought*" starting from the central problem (root node of M) itself. Therefore, the first part of our content generation algorithm was to encapsulate this line-of-thought by computing the path from the target node to the root node and search for a concept that was common across all nodes on this path (Figure 5.4(b)).

Our approach is further reinforced by our observations of our preliminary studies [145] wherein we either used the entire mind-map (all nodes) to determine a shared concept (i.e. a global context) or we used only the target node to determine the content (i.e. a local context). In the first case, the resulting content is abstract as expected. This was further noted by our pilot study participants who stated: *"out of context"*, *"became too abstract as the map grows"*. This is natural because the concepts in the entire mind-map, since reasonably dissimilar, are bound to be connected only by the most generic concepts. The issue with using only the target node was that the newly added content did not usually relate to the rest of the mind-map. For example, *"emergency"* leads to *"fight-or-flight"*, and *"machine oil"* leads to *"make artificial snow"* for the central topic *"Aircraft"*.

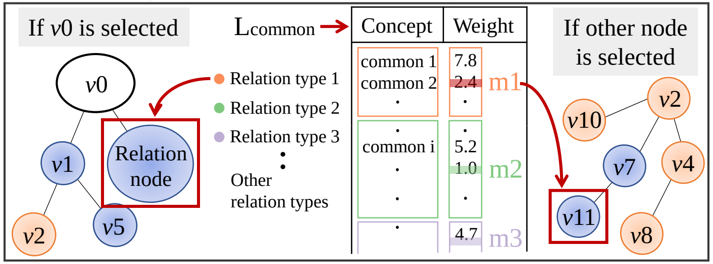
Our path-dependent algorithm adds ideas that represent different aspects of the target node and avoid repetition of very similar or very dissimilar ideas being added. To do this, three steps were taken. First, given a target node $v_T \in V_M$, we compute the path from the target node to the root node, search for concepts that are common on this path, and create L_{common} (Figure 5.4(b)). Second, all entries in L_{common} are listed categorically based on the 25 relationships provided by



(a) Mini-Map target search



(b) Go along to central topic. Obtain query lists from ConceptNet



(c) Categorize & sort. Add content from relation type / median weight

Figure 5.4: Illustration of target search and content generation algorithm using retrieved weighted relations through ConceptNet Open Data API. (a) Consider a branch from current mind-map, find "where" to add based on sorted depth and number of children of all nodes. (b) Trace back to the central topic (root). Retrieve query results (L) from ConceptNet with respect to each node. Find common concepts across the retrieved results. (c) Categorize the common concepts and sort it by weights. Computer adds a new node from either relation type or median weight.

ConceptNet. We sort these categories based on the sum of weights of the concepts each category contains. Third, the entries in each category are further ordered with decreasing weight. The last two steps give us a doubly-sorted list (Figure 5.4(c), steps $1-16$ in Algorithm 2). This algorithm takes the relation categories provided by ConceptNet as different aspects of a target node, where the weights represent their strength of connection. The usage of these two properties (relation category and weight) is further described in the following two subsections.

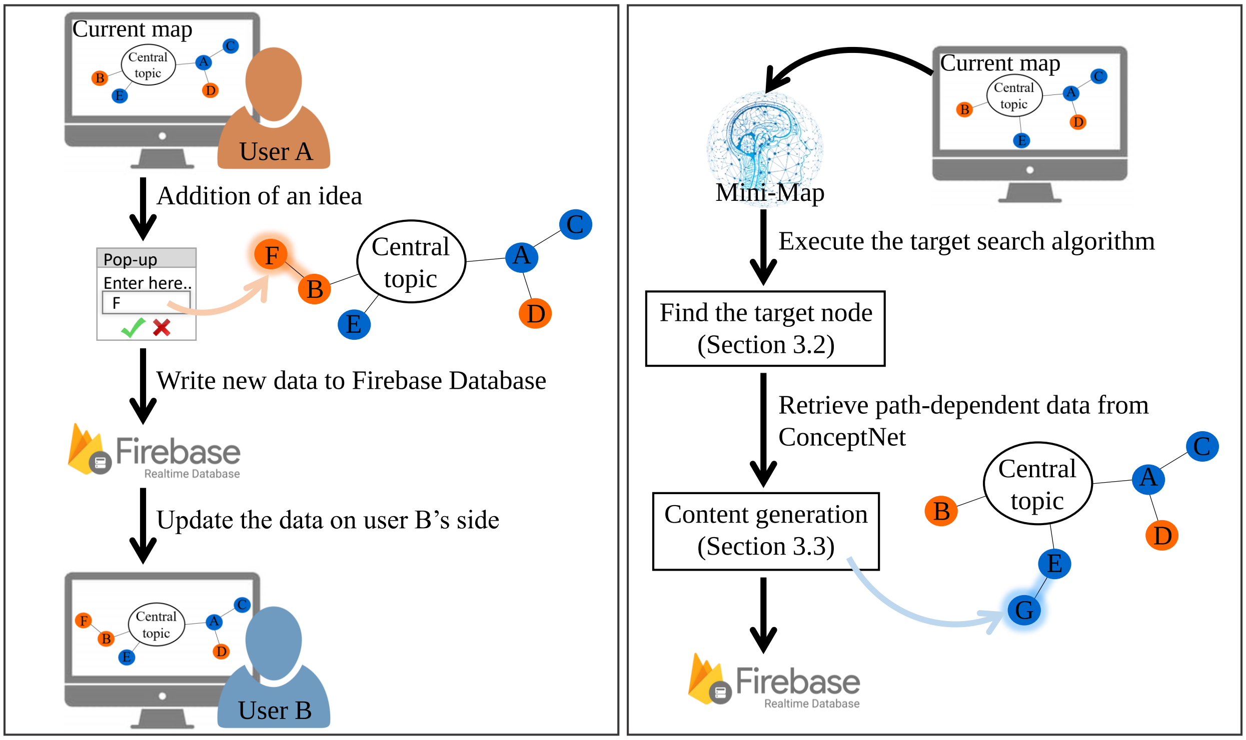
5.2.4.2 Selecting Content for a New Node

Given a list of common ConceptNet queries along a path, we subdivide the list into relation-categories for allowing AI player to be able to add a diverse set of nodes to an existing concept. In each relation-category, the seemingly obvious choice would be to generate content based on the highest weighted result. However, this approach clearly leads to more generic concepts being added to the map as it grows — a scenario that is in contrast with how mind-mapping is typically performed. For instance, for a central topic such as *"Aircraft"*, adding a node *"fly"* leads the

AI player to add the concept *"sky"* followed by *"blue"* and *"a colour of the rainbow"*. These concepts have weights that are high up in the order in ConceptNet potentially because they are more general and therefore have significantly higher number of links in comparison to other more specific nodes. We also observed that the edge weight distribution of the linked concepts in ConceptNet is skewed towards a standard value of 1, when the highest edge weight can be larger than 10. Therefore, our approach takes median-weighted concepts from ConceptNet and adds them as ideas in the mind-map. This choice avoids repetition of very similar ideas and allows for diversification. Furthermore, this choice is more robust than using statistical aggregates such as mean in terms of preserving the relatedness (higher weights) and novelty (lower weights) of the added concepts. For example, for the concept "*heat*", the highest and lowest weighted relations in ConceptNet are *energy* and *what makes something hot*. On the other hand, the concept that is close to median weight is *geothermal energy*. This median-weighted concept provides two aspects of thinking — energy and context related to earth's interior — on the central topic *Solar Energy*.

5.2.4.3 Using ConceptNet Relations as Nodes

In a typical mind-map, the nodes connected to the central idea usually determine the type of details that will be consequently added. For instance, for a topic such as *Pollution*, one may first add nodes such as *causes*, *effects*, *mitigation* etc. instead of mentioned what the causes are or what the effects will be or how to mitigate pollution. This is difficult to achieve by simply adding median-weighted queries from ConceptNet. We observed that the relationship types in ConceptNet are themselves helpful to users in organizing their ideas, particularly during early phases of mind-map evolution. We capture this by enforcing the AI player to add ConceptNet *relations* as content nodes as the first several main branches from central topic contained in the root node (Figure 5.4(c), steps 17 to 22 in Algorithm 2).



(a) Workflow of user A adding one node in **HH** group. (b) Workflow of Mini-Map adding one node in **HC** group.

Figure 5.5: Flow showing an example of the front-end (user interaction) and back-end (data processing) pipeline in **HH** and **HC**. In **HC**, the user does exactly the same thing as user A does in **HH**.

5.3 Implementation Details

5.3.1 Front-end Design

- *Visual Eencoding:* Similar to traditional pen-and-paper mind-maps where the size of the central topics are always larger than the ideas generated, the font size of the central topics are 1.5 times the font size of its direct children in our study. This size choice is by-and-large heuristic and is based on informal user feedback from our studies with mind-mapping interface development. From main branches to details, we further encode varying font size and color gradient to visually represent the emphasis of the information. Ideas added from different users will be given a different color scheme, which helps users easily recognize the flow of thoughts. Ideas are spatially organized in the mind-maps using forced-link structure in D3JS. Such force-directed layout can help produce elegant spreading of nodes and reasonable visibility of links even with large data-set.

- *User interactions:* We designed a sequential interaction workflow for users to collaboratively create a mind-map; users take turns to add nodes. In each turn, user can only add one node by double-clicking on any of the existing nodes. An input dialogue box pops up after double-clicking. Once a valid answer is submitted, our system creates a new child node with the double-clicked one being its parent node. A link is created automatically between them. This offers users minimal manipulation in the construction of a tree type structure. On the other hand, while it is not your turn, an layer appears on top of the interface to prevent any interactions.

5.3.2 Back-end

- *Firebase pipeline:* Mini-Map was implemented using Firebase Database REST API written in JavaScript (Figure 5.5). All data pertaining to a mind-map (node content, node position, links between nodes, etc.) is stored in the Firebase real-time database with a corresponding user identification code. In a collaborative setting where two human users are working with the same mind-map, Mini-Map employs a listener function to scan Firebase database at intervals of 3 seconds. Specifically, our interface checks for changes in the mind-map data, and updates the current mind-map based on the latest data found from Firebase.

- *MiniMap.js library:* For the interaction management, we implemented our own library (MiniMap.js) that reads and writes a JSON data structure specifically designed for mind-mapping. The data structure includes two components: a node object and a link object. The *Node* object has several attributes including screen position, properties (unique label, parent, children, depth, etc.) and time-stamped events (when a node was added and modified). The *Link* object has several attributes including source node, target node, and a unique label. Whenever a mind-map is imported or loaded into the workspace, the JSON file is read by Mini-Map and the corresponding mind-map is regenerated.

- *ConceptNet API:* In order to implement the content generation algorithm (section 5.2.4), we used the ConceptNet Open Data API in conjunction with the JSON-LD API (Link-ed Data structure). These APIs allow for querying a word or a phrase through HTTP request and provides a URL to a page containing all related words and phrases to the query in a linked data format. For each concept in the linked data, */en/* stands for its language code, *rel* contains corresponding relation such as "*UsedFor*", "*CapableOf*", etc., and the strength with which this relation expresses this concept is stored in *weight*. The linked data also provides human-readable label in *start* and *end*.

5.4 Experiment 1: Human-Computer Collaborative Mind-Mapping

In this work, we conducted two user studies. The first study is a comparative study. The goal was to understand how humans interact with their collaborator and explored human behavior in a controlled experimental setup. The second study is an extension from the problem identification study in the previous work (Chapter 3). The goal for the second study was to understand whether Mini-Map users are able to build a well-developed understanding of the problem through using Mini-Map, hence improves their performance on developing problems and needs. We will discuss the setup and results for the two studies in a sequential manner in the following.

The study tasks for the first study were designed with two major goals in mind. First, we wanted to measure how our approach compares with a typical human-human collaboration scenario in terms of quality, variety, and novelty of ideas generated through mind-mapping. Second, we wanted to understand the ways in which our approach could facilitate a human-like collaboration experience for design applications.

5.4.1 Participants

With these goals in view, we performed a user study with two distinct groups of participants. The first group (**HH**) comprised of 28 human participants who were asked to create mind-maps in pairs (i.e. 14 human-human pairs). The second group (**HC**) of participants comprised of 14 individuals who co-created their mind-maps with Mini-Map as the collaborator. Our participants were primarily undergraduate and graduate students from engineering, sciences, and architecture majors to help us sample from a wide variety of disciplines and age groups.

5.4.1.1 Choice of Dyad

To explore human-computer partnership in a controlled set-up for mind-mapping, we chose pairs (or dyads) as a natural and simple unit system to study. While our goal is not to study whether dyads can create better mind-maps than individuals, we did find previous works on collaborative brainstorming that support our choice. Osborn's early view [166] on collaborative brainstorming was that a group of individuals can produce better results in terms of both quantity and quality by minimizing the effects of criticism from self and others. However, the size of the group comes at a cost — the loss of productivity in brainstorming. A meta-analysis conducted by Mullen et al [167] further reinforced that this loss is relatively small for dyads and increases rapidly with group size.

5.4.1.2 Study Conditions

In the **HH** group, the participants were seated in two different rooms. Therefore, both the **HC** and **HH** participants did **not** know the type of agent (human or AI) they are collaborating with. In order to simulate human-like behavior for the **HC** group, we delayed the response from the computer by 5 to 10 seconds. This was based on our observations in our pilot experiments without computer intervention.

5.4.2 Procedure & Participant Tasks

The total duration of the experiment varied between 30 to 35 minutes. Our pre-task procedure involved:

1. A demographic survey
2. A verbal description of the purpose of the study
3. Introduction of the features of the software system
4. Practice with the system for 5 minutes to allow participants some time to get acquainted with the software

Participants were encouraged to ask questions for any further clarifications regarding the study. Following the pre-task procedure, the main task for the participants was to create a total of 2 mind-maps for two pre-defined central topics (therefore, one mind-map per topic). The participants were given 10 minutes to work on each mind-map. We recorded the participants' screen activity for each mind-mapping task. The participants were asked to follow basic principles of mind-mapping along with the sequential node addition rule we set. The participants were also requested to externalize ideas/concepts rapidly in keeping with the general spirit of brainstorming.

5.4.2.1 Choice of Topics

Based on a preliminary study with various topics, we chose *Solar Energy* and *Space Travel* as the topics for the user study. *Solar Energy* is a specific topic and we want to test whether our algorithm is able to add constructive nodes in any given context. *Space Travel*, on the other hand, is a general topic which stimulates the user to imagine and explore various directions. We further aimed to observe how differently our algorithm aided the user in organizing their thoughts in specific and open-ended domains.

5.4.3 Data Collected

We collected a total of 56 mind-maps from the study (14 each for *Solar energy*-**HC**, *Solar energy*-**HH**, *Space travel*-**HC**, and *Space travel*-**HH**). Upon completion, each participant was asked to complete a feedback questionnaire based on their experience during the mind-map creation tasks. Here, we wanted to understand the differences in perception of the mind-mapping process from our participants in the **HH** and **HC** groups. For this, we conducted a "*peer evaluation*" from each participant at the end of the mind-mapping session. Our peer evaluation is based on the recent work by Gilon et al [168].

In addition to questions regarding the interface and collaborator, the users were also asked to predict whether their collaborator is a human or computer. The reasons behind every participant's choice was also elicited and collected. The aim of this question was to gain insights on how the users perceived their collaborator's typical behavior and what would constitute human-like behaviour in mind-mapping.

5.4.4 Metrics

5.4.4.1 Metrics based on Semantics

We used *ConceptNet Numberbatch* to perform automatic semantic analysis on ideas generated across the 56 mind-maps. It is a word embedding model that is known to counteract several known biases and stereotypes (ethnic bias, gender bias, etc.) that are commonplace in current methods. The Numberbatch model learns from what people say by applying a retrofitting and merging process [169] with two popular sources of English word embedding and one knowledge graph — word2vec Google News embeddings (100B words) [170], GloVe embedding (840B words) [171], and ConceptNet 5.5 [1] which contains over 21 million edges and 8 million nodes. With this level of improvement, ConceptNet Numberbatch is, to our knowledge, the state-of-the-art embedding to compute word vectors and perform fair semantic comparison between words or phrases. With each word having its unique vector representation, we subsequently use cosine distance (1–cosine similarity) to measure semantic distance between the respective central topic and each idea in the resulting mind-maps.

5.4.4.2 *Metrics for Rating Mind-Maps*

The mind-maps created at the end of the user study were evaluated by three expert raters. The raters selected were unaware of the study design and any information regarding study assumptions and hypotheses other than final mind-maps created. Further, the mind-maps generated by **HC** and **HH** study were randomized and de-identified before being assigned to the raters. All the raters were senior graduate research students (a prospective faculty member in one case) in engineering and product design disciplines and were asked to rate each mind-map based on well-established metrics. From the mind-map assessment rubric [37], we adapted the *Structure*, *Exploratory*, *Communication*, and *Extent of Coverage* metrics for a comprehensive assessment of the quality of the mind-maps. The raters were asked to evaluate every mind-map based on each of these metrics on a scale of 1 to 4. In addition to the mind-map assessment rubric, we adapted the novelty and variety metrics from Linsey et al. [38] for evaluating the ideas generated from our studies. Each rater first constructed a list of clusters (say: $C_1, \ldots, C_n$) and subsequently calculated the variety score of each mind-map as the percentage of clusters present in the respective mind-map. The novelty score for the ideas were calculated by considering the number of other ideas present in the same cluster. That is, lower the number of ideas in cluster, higher the novelty. The following formulae was used for evaluation of the novelty, where N_j is the Novelty score of the j^{th} idea, T is the total number of ideas, C_i is the number of similar ideas in the i^{th} cluster and n is the number of clusters occupied by the j^{th} mind-map.

$$N_j = \frac{T - C_i}{T}$$

5.4.4.3 *Rating procedure:*

The raters were given all the mind-maps and the specific grading rubric. Initially, we asked two raters to independently evaluate all the mind-maps for each of these metrics. We also encouraged them to discuss and come to a consensus on their grading rubric. After checking for reliability of

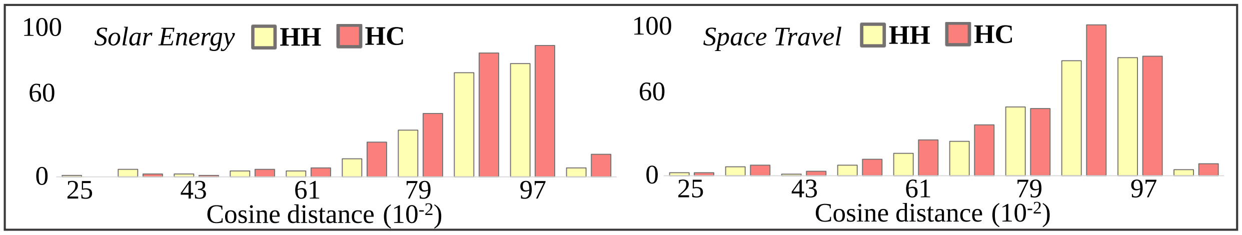


Figure 5.6: Distribution of cosine distances for word vectors between ideas and corresponding central topic in **HH** and **HC**.

agreement between the two raters, we found that they did not possess a good agreement specifically for the metrics *Structure*, *Exploratory*, *Communication*, and *Extent of Coverage*. Therefore, we recruited an additional rater to improve the reliability. This additional rater followed the same rating process — worked independently, discussed, and fine-tuned scores based on their consensus. The modified values of the metrics were then again checked for reliability using the Fleiss' kappa coefficient [172].

5.5 Results & Discussion

Here, we discuss two methods, semantic analysis and expert ratings, for measuring the differences between the mind-maps generated by the **HH** and **HC** groups.

5.5.1 Semantic Analysis

For each topic, we used t-SNE to visualize word embedding collected from mind-maps created in both groups of users (**HH** and **HC**) using the pre-trained model from Numberbatch (English only, 300 dimensions) [169]. For a given topic, we observe that most of the generated ideas seem to cluster in the proximity of identifiable regions and close to central topics regardless of **HH** or **HC** group. This indicates that the maps generated by the **HC** group have content similar to those created by the **HH** group. However, the structure of the mind-maps is observably different in **HC** as compared to **HH**; users in **HH** tended to link more ideas directly to the central topics while users in **HC** were confined to the standard radial layout. Such non-hierarchical structure of the **HC** participants can be used as an effective design thinking tools [62].

Condition	Structure (1-4)	Exploratory (1-4)	Communication (1-4)	Extent of Coverage (1-4)	Quantity (raw)	Variety (0-1)	Novelty (0-1)
HH Solar Energy	2.41	2.5	2.38	2.21	21.50	0.67	0.16
HH Space Travel	2.59	2.36	2.48	2.52	28.29	0.68	0.20
HC Solar Energy	3.12	3.2	2.83	3.05	34.71	0.78	0.21
HC Space Travel	3.55	3.33	3.19	3.48	44.43	0.82	0.19
Average **HH**	2.5	2.43	2.43	2.37	24.9	0.68	0.18
Average **HC**	3.34	3.26	3.01	3.27	39.57	0.8	0.20

Figure 5.7: The values of various metrics were averaged across topics and type of the collaborator. This table summarizes the mean values of various metrics calculated by the raters.

Using the Numberbatch vector space embedding, we performed semantic similarity comparison by measuring cosine distance between word vectors of ideas with their corresponding central topics. There are two main observations to be made regarding the corresponding semantic distance distribution with *Solar Energy* and *Space Travel* (Figures 5.6). First, the maximum distance in *Solar Energy* recorded for **HH** (1.1173), is very close to that recorded for **HC**. In *Space Travel*, however, the maximum distance is 1.0867 for **HH**, whereas **HC** gets a higher score of 1.125. Thus, Mini-Map is able to both generate problem-specific content for typical problems and is also helpful in exploring atypical open-ended topics. Second, apart from the measured maximum distance (which can be interpreted as a measure of breadth of ideas covered in a mind-map), we observe interesting trends in the distribution of distances between word vectors across **HH** and **HC** groups (Figures 5.6). Ideas from both groups display high frequency in the distance range between 0.52 to 1.06. However, for mind-maps from the **HC** group, the frequency stays higher than those from **HH** up to the maximum distance ranges observed for both *Solar Energy* and *Space Travel*. This suggests that Mini-Map is capable of introducing diversified but still related content to users in the creation of mind-maps.

5.5.2 Mind-map Ratings

Initially, The Cohen's kappa value for the *Structure*, *Exploratory*, *Communication*, and *Extent of Coverage* were found to be in the range of 0.3 - 0.4, showing only fair level of agreement and reliability between the two raters [173]. With the addition of one more rater, we further calculated Fleiss' kappa coefficient to assess the agreement since the mathematical foundations of Cohen's kappa make it to be mainly suitable for two raters [174]. The Fleiss' kappa coefficients for these metrics were improved to be in the range of 0.76 - 0.82 presenting substantial agreement among the ratings [175]. Also, the Pearson's correlation between raters for variety and novelty scores was found to be above 0.8 (0.83 and 0.92). This value of correlation coefficient is identified strong [173].

Two-way ANOVA was conducted with two independent variables — (1) type of collaborator and (2) choice of topic. While we did not assume the data to be normally distributed, we note that ANOVA is generally less sensitive to normality [139], particularly for low sample sizes. We found that the p-values across the **HH** and **HC** groups were near zero for nearly all metrics (except for novelty whose p-value across **HH** and **HC** was 0.12). However, the p-values across topics were not less than 0.05 showing that the differences were not significant across the topic. Results show that the mean of the scores given by the raters for all metrics except novelty was greater in **HC** study compared to **HH** for both the topics (Figure 5.7). This suggests that Mini-Map helped the users to develop a better mind-maps overall. Specifically, the high values of *Structure* indicate that the mind-maps created using Mini-Map helped the user create a well-organized map. We believe this to be the case because of our expansion threshold strategy in the target search algorithm. Other important metrics that showed significant improvement from **HH** to **HC** groups are *Exploratory* and *Extent of Coverage*. This indicated the effectiveness of the content generation algorithm. The considerable increase in the value of *Quantity* (raw) shows that the Mini-Map algorithm could potentially help the users to generate more ideas within a stipulated time compared to a human collaborator. Also, higher values of *Variety* scores in **HC** suggest that the median-weight algorithm has assisted the user to explore diverse directions. Such differences were not observed significantly for *Novelty* scores. This could mean that although the Mini-Map algorithm allowed one to cover more number of ideas, the number of unique ideas was similar to the **HH** group.

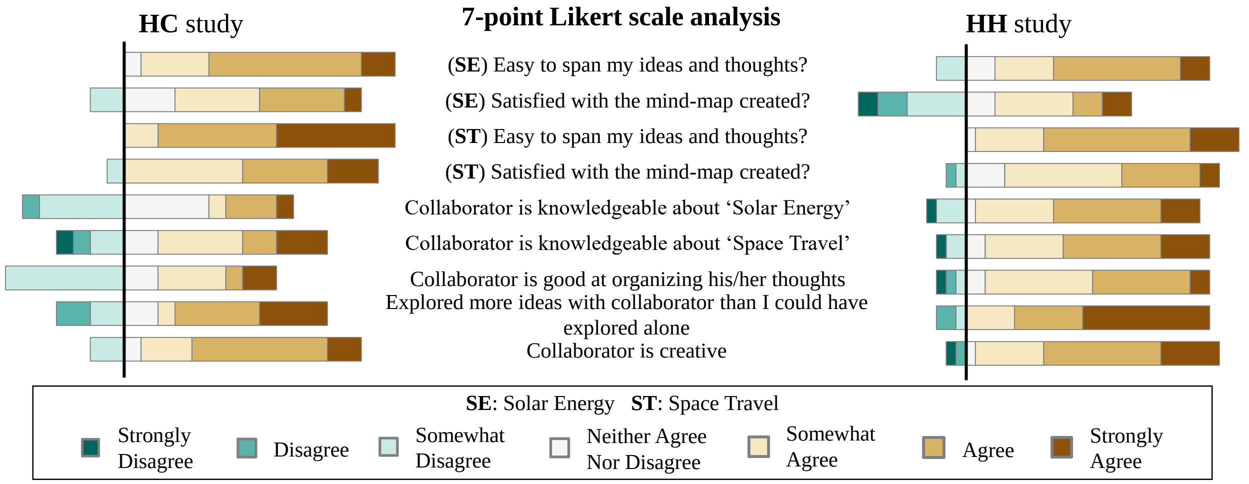


Figure 5.8: 7-point Likert scale feedback from the user study conducted. The brown bars towards the right of the central line indicate positive responses and blue bars to the left indicate negative responses.

5.5.3 Qualitative User Feedback

We elicited the participant's experience in collaborative mind-mapping using a 7-point likert scale survey questions (Figure 5.8). In terms of ease of expansion of ideas and thoughts, the results show that Mini-Map was equally conducive compared to a human collaborator. Interestingly, in the **HH** study for the topic *Solar Energy*, around 40% of the participants were not satisfied with the mind-maps they created compared to **HC** study (about 10%). This might potentially be because of the mismatch of ideas that the two users wanted to externalize causing a dissatisfaction in the quality of the mind-map created, from the perspective of the user. Moreover, the response time was totally dependent on the human collaborator in **HH** studies. Given a limited time, delayed responses from the users might have curbed the user to develop a mind-map to their fullest potential — which likely causes a dissatisfaction between the users in the **HH** study.

Majority of the users felt that the collaborator was creative in both **HH** and **HC** study. This shows that the median-based algorithm used for idea generation gave interesting responses commensurate with human-level creativity. Though a bit lower in the **HC** study, majority of the users from both the studies felt that the collaborative mind-mapping would be a better environment for exploring more ideas than individual mind-mapping. These results suggests that Mini-Map is at par with a human collaborator not only in terms of assisting the users to developing greater number of ideas, but also by giving intriguing responses. As per one participant from **HH** study, *"Integration of ideas from the collaborator increased the overall quality of the mind-map"*. Another user from **HC** study stated: "*My collaborator was Smart and creative, helped explore ideas - and gave perspectives I hadn't thought of*". Thus, a controlled collaborative setup, like our system, can be particularly helpful in early design stages.

Up to 50% of the users *Somewhat disagreed* that the collaborator was not good at organizing their thoughts in the **HC** study. Potential reason for this observation include the difference in approach of making mind-maps of the user compared to the Mini-Map algorithm. This is contrasting to the outcome from the inter-raters claiming that mind-maps created by the **HC** fared significantly well in terms of metrics like Structure and Extent of coverage. Although our algorithm does not go well with the user approach wise, it guides the user to create a better mind-map overall. This is also corroborated by the fact that majority of the participants were satisfied with the mind-maps they created at the end of the **HC** study.

In **HC** study, one general observations was that the context of the node generated slowly started to depend on the nodes added by the human as time progresses. A participant of **HC** study stated: *"At first it was making too good of thoughts. Then it made some dull contributions"*. So, if the nodes added by the human is well related to the central topic, then the nodes added by the computer maintained the context and gave valuable responses. However, in some cases the connection between the nodes added by human were not explicit. This might not always be identified with the limited semantic data base available, resulting in content generated using median weight method. In **HH** study, there all more than 80% of the users felt that their partner was knowledgeable. However, there were mixed responses from the user about the collaborator's knowledge in the **HC** study. In the topic *Space Travel*, about 75% of the responses were neutral or above. One user stated: *"It was helpful for the topic Space Travel as I had minimal knowledge on that"*. The responses regarding the collaborator's knowledge were slightly more negative for the topic *Solar Energy*. Since this is a more specific topic, there could have been a greater room for diversifying, thereby increasing the possibility of losing context to the idea generated by the median weight method.

5.5.4 User's Perception of the Collaborator

From the study survey, 5 out of 14 users predicted their collaborator to be a human in the **HC** study conducted. This result is rather surprising since 35% of participants choose to believe that the computer was a human even though it is not our goal. Interestingly, 12 out of 28 users from the **HH** study predicted their collaborator to be computer. Interesting reasons for predicting Mini-Map to be human includes feedback such as *"Smart and creative"* and even *"sly humour"*.

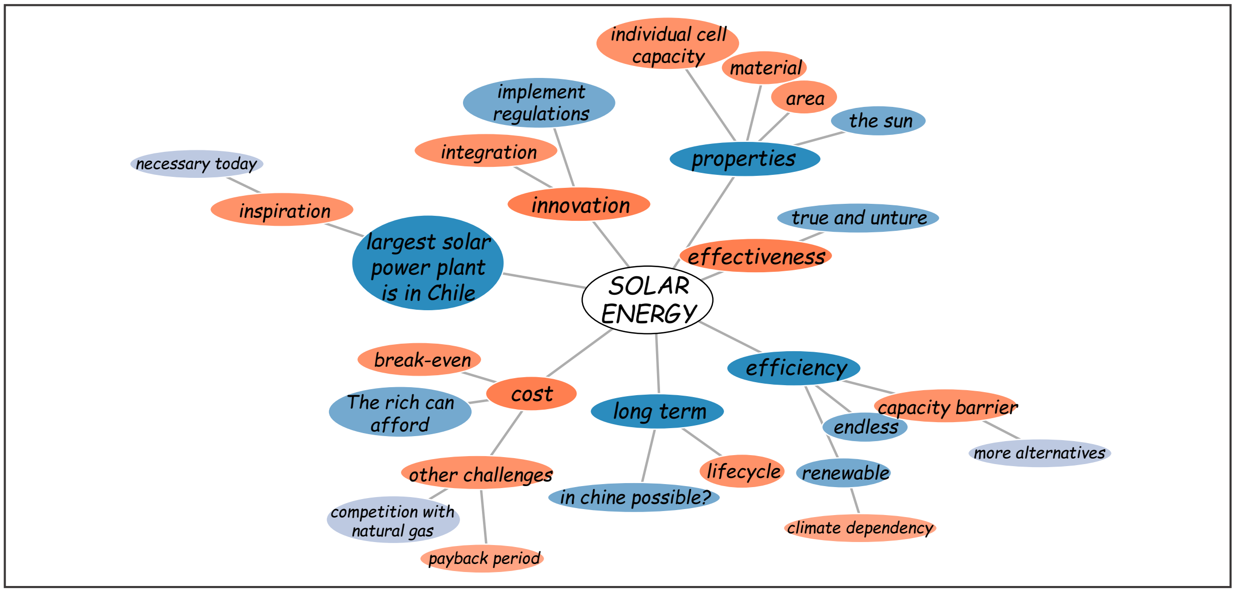
In both **HH** and **HC** study, 35.7% (5 out of 14) and 42.8% (12 out of 28) of the participants predicted their collaborator wrongly. Therefore, there may exist uncertainty in claiming human-like behavior in Mini-Map algorithm just from this answer. However, open-ended feedback from the users helped us elicit the reason behind their prediction of the type of collaborator, develop understanding of how Mini-Map can simulate the useful aspects of human-like behaviors, and ways in which Mini-Map can prove to be more helpful than a human collaborator.

5.5.5 Median-weighted Node vs Relation Node

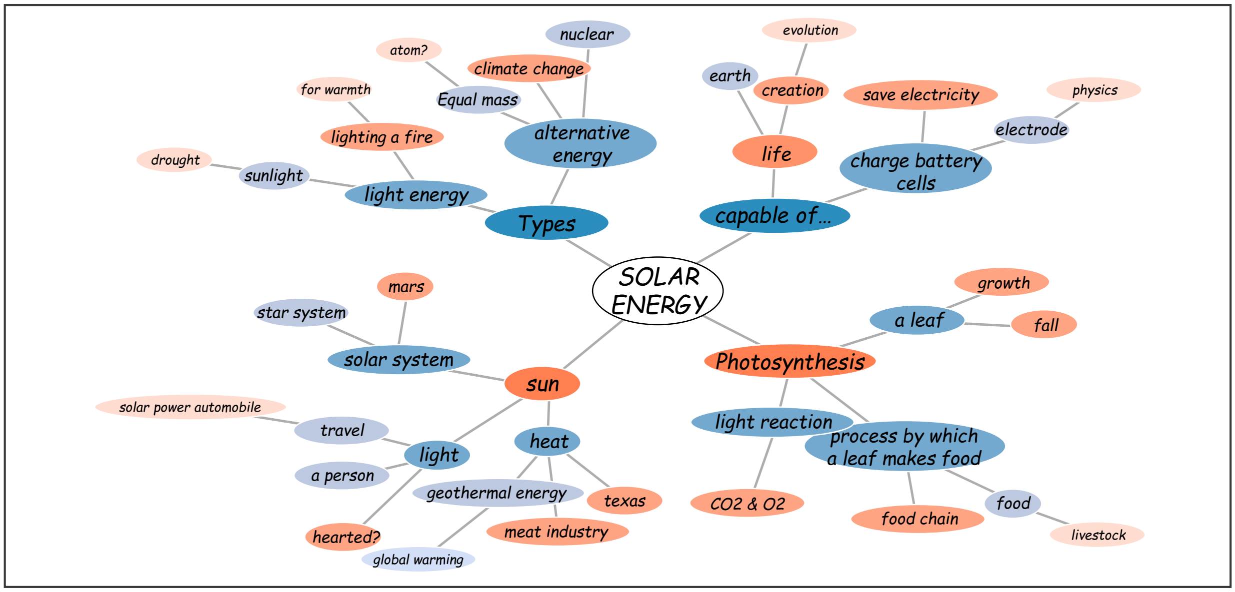
Adding relationship node was mainly found to be helpful for categorizing the central ideas into branches. For example, user responses suggests that nodes like *'Space Travel has...', 'Requirement'*, in the topic *Space Travel* and nodes like *'Capable of...'* in *Solar Energy* specifically gave fundamental directions to think about the given central idea. Additionally, these nodes could have assisted the users to get started with mind-mapping analogous to initiating a discussion to increase a person's engagement. Moreover, one of the user's statement: *"I felt some part like a conversation"* might allude to the relationship type nodes.

5.6 Experiment 2: Problem Identification Study

In this study, we wanted to understand whether Mini-Map helps the users in developing design opportunities. We followed the same study setup and protocol as we introduced in our previous work with the only change being the usage of Mini-Map as the digital mind-mapping tool (Section

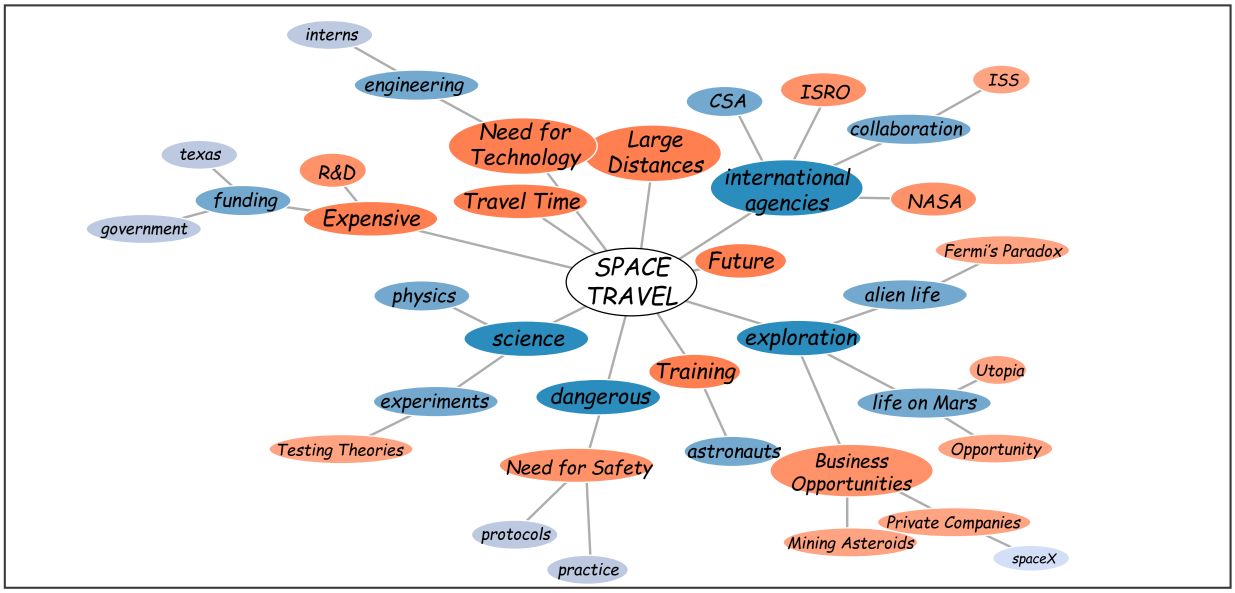


(a) Mind-map created with *Solar Energy* in **HH** group

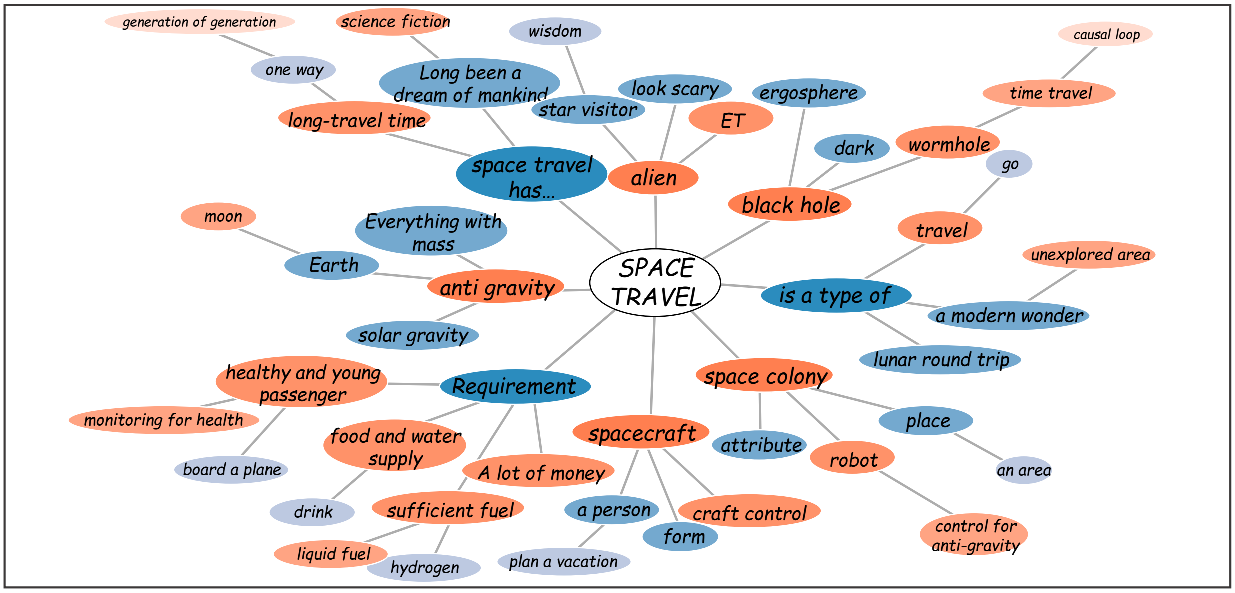


(b) Mind-map created with *Solar Energy* in **HC** group

Figure 5.9: Sample user created mind-maps with central topic *Solar Energy* in (a) HH and (b) HC. In (b), orange nodes represent user added nodes, and blue nodes represent Mini-Map added nodes.



(a) Mind-map created with *Space Travel* in **HH** group



(b) Mind-map created with *Space Travel* in **HC** group

Figure 5.10: Sample user created mind-maps with central topic *Space Travel* in (a) HH and (b) HC. In (b), orange nodes represent user added nodes, and blue nodes represent Mini-Map added nodes.

3.3). Specifically, we recruited 12 participants to explore the problem space using Mini-Map before generating product ideas with the themes *pollution* and *underwater camping* (the Mini-Map group of participants, abbreviated as **G3**). Before the creation of mind-maps, the participants were allowed 2 to 5 minutes to get acquainted with the tool. We used the same evaluation metrics as our prior work to assess the quality of the developed design problem descriptions after mind-mapping (Section 3.2). Specifically, the metrics are *Identification of Gap, Development of Needs, Comprehensiveness, Solution Neutral, Scope for Creative Outcomes,* and the *Variety* and *Novelty* of the product ideas generated.

5.6.1 Results & Discussion

In total, 12 Mini-Map users created 64 design problem descriptions, where 32 belong to the *pollution* theme and the remaining 32 belong to the *underwater camping* theme. We asked the same inter-raters from our prior work (Section 3.4) to evaluate the design problem descriptions using our proposed metrics (Section 3.2). 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. Following the standard rating protocol, the scores for each metric were calculated after the two raters met a strong consensus on their evaluation scheme (Cohen's Kappa = 0.9-1, Pearson's correlation = 1). For more details about the rating process, refer to the description in our prior work (Chapter 3).

5.6.2 Ratings

Overall, we can see that Mini-Map users show visible improvements in developing product ideas after mind-mapping, specifically in identifying user needs based on metrics such as Comprehensiveness and Variety (Figure 5.11). To draw conclusions from the ratings statistically, we performed two-way ANOVA with two independent variables: (1) type of technique, and (2) choice of design theme. We found that, across exploration techniques (**G2** and **G3**), p-values for metrics discussing Comprehensiveness (p=0.035) and Novelty (p=0.049) were less than 0.05 for the theme *pollution* showing significant difference. However, most p-values were above 0.05 for metrics discussing Identification of Gap (**T1**-1; **T2**-1), Development of Needs (**T1**-0.1; **T2**-0.19), Solution Neutral (**T1**-0.61; **T2**-0.94), and Scope for Creative Outcomes (**T1**-0.51; **T2**-0.35) for both the design themes indicating no significant difference. This provides an initial insight on how the usage of Mini-Map can help the designers develop a comparatively comprehensive understanding of the problem space of a problem that is complex in nature. Also, how Mini-Map affects positively on the process of coming up with original product ideas. That being said, we further found that p-values across the themes were also above 0.05 for nearly all metrics, except for Creative Scope whose p-value across **T1** and **T2** for Mini-Map was 0.01. While *underwater camping* is a topic that is more open-ended in nature, this shows how Mini-Map users were stimulated and had their creative thinking capabilities improved after mind-mapping with an active virtual collaborator.

5.6.3 Design Problem Descriptions

After creating one mind-map, each participant was asked to develop at least two design problem descriptions within the given 20 minutes. Each design problem description consists of one design problem statement and several needs statements to deliver one product idea (refer to Section 3.3 for more details about the study procedure).

In general, we noticed that Mini-Map users were able to elaborate on the needs of a design opportunity with more concrete details, as compared with mind-mapping users without computer support. Specifically, with two similar product ideas generated, Mini-Map users showed capabilities in identifying user needs in a variety of aspects, including those that are uncommon. For example, both the participants (one from the mind-mapping group and another one from the Mini-Map group) thought about wildlife protection for the product addresses issues of environmental pollution. Here, the Mini-Map user was able to identify needs for wildlife protection in two aspect: *protect wildlife from being harmed*, and *protect the product from being attacked by aggressive animals*, while the pure mind-mapping user was considering the former one mainly (Figure 5.12). This showcases that Mini-Map was able to help the users relate to relevant ideas while exploring the problem space, hence gain a deeper understanding on the problem that is being addressed. That being said, we noticed that the design problem descriptions generated after the use of Mini-Map

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
Pollution (Mini-Map)	3.03	3.16	2.97	2.97	3.1	32	31%	0.86
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
Underwater Camping (Mini-Map)	3.44	2.97	2.78	3.41	3.52	32	29%	0.85

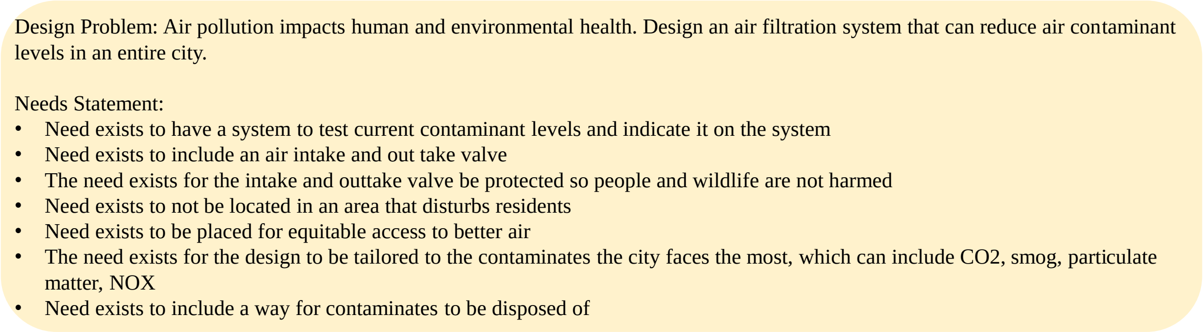
Figure 5.11: The scores of various metrics were averaged across themes. In this table, we put the three study conditions, including the ones that were discussed in our prior work (Chapter 3), together to compare. This table summarizes the mean scores of various metrics calculated by the inter-raters. 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.

still score below expectations on the metrics Solution Neutral. We believe this could be resulted from the generation of specific ideas (as *answers*) from the computer's end during mind-mapping. This leads us to the following research question: instead of adding answers directly to the map, can we design a system that encourages critical thinking and learning from the user's end?

5.7 Conclusions and Future Directions

At its core, Mini-Map presents a digital mind-mapping work-flow for co-generating ideas with an intelligent agent as a collaborating partner. Technically, we make two main contributions in the work-flow of the Mini-Map. First, we incorporated guidelines on how to mind-map for identifying target nodes. Second, we demonstrated a relation-dependent and path-dependent method to extract relevant content from ConceptNet to enable mind-map evolution. The user study conducted consists of two groups of participants (**HH** and **HC**) to understand and evaluate the processes and outcomes in collaborative mind-mapping. We found that Mini-Map could perform to the level of a human collaborator, in terms of assessment from both semantic (Numberbatch embedding)

Design Theme: Pollution

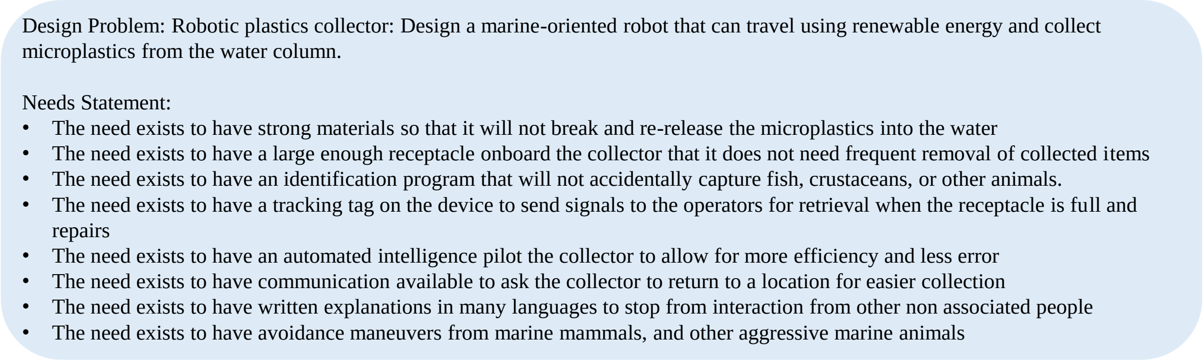


Design Problem: Air pollution impacts human and environmental health. Design an air filtration system that can reduce air contaminant levels in an entire city.

Needs Statement:

- Need exists to have a system to test current contaminant levels and indicate it on the system
- Need exists to include an air intake and out take valve
- The need exists for the intake and outtake valve be protected so people and wildlife are not harmed
- Need exists to not be located in an area that disturbs residents
- Need exists to be placed for equitable access to better air
- The need exists for the design to be tailored to the contaminates the city faces the most, which can include CO2, smog, particulate matter, NOX
- Need exists to include a way for contaminates to be disposed of

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



Design Problem: Robotic plastics collector: Design a marine-oriented robot that can travel using renewable energy and collect microplastics from the water column.

Needs Statement:

- The need exists to have strong materials so that it will not break and re-release the microplastics into the water
- The need exists to have a large enough receptacle onboard the collector that it does not need frequent removal of collected items
- The need exists to have an identification program that will not accidentally capture fish, crustaceans, or other animals.
- The need exists to have a tracking tag on the device to send signals to the operators for retrieval when the receptacle is full and repairs
- The need exists to have an automated intelligence pilot the collector to allow for more efficiency and less error
- The need exists to have communication available to ask the collector to return to a location for easier collection
- The need exists to have written explanations in many languages to stop from interaction from other non associated people
- The need exists to have avoidance maneuvers from marine mammals, and other aggressive marine animals

(b) Design problem description developed by the participants in the Mini-Map group

Figure 5.12: The design problem descriptions developed by 2 different participants for the design theme *pollution*. One from the (a) free writing group, and another one are in the (b) Mini-Map group.

and subjective (structure, exploratory, communication, extent of coverage, variety, novelty) perspectives. In addition, even though our primary purpose was not to show a system that fooled the user in believing that the collaborator was human, our system was able to . This could be a promising prospect for future mixed initiative systems for novice users to learn and develop skills in unstructured design tasks.

There are several promising research directions that we envisage continuing with research. Our goal in the future is to improve target search algorithm in Mini-Map by incorporating brain computer interfaces (BCI) or a cognitive model. Such approach can provide us with information on identification of user attention level and preferences for a certain contents in the mind-map, hence adjust Mini-Map's behavior accordingly. In addition to implementing a reasoning model, we are also interested in making our study crowd-sourcing since numerous time was taken in collecting user data in a controlled experimental setup. Also, crowd-sourcing helps in collecting significant amount of data for a comprehensive analysis. Moreover, we look forward to develop a database specific to design ideation that would bring the most out of the Mini-Map workflow.

The current state-of-art in human automation interactions (Siri, Cortana, Alexa, and Google Assistant) are modeled based on the metaphor of an intelligent assistant — these are solution-oriented systems that provide answers to reasonably well-formulated problems. While there have been a few works on mixed-initiative design for specific domains such as AI based game development [176], the context of the game is fixed and the designer is only being helped with the detailing of the game rather than finding out what the game should do in the first place. We believe that the next major advances in mixed-initiative interactions should focus on systems that help find good problems. We believe that our work takes a major step toward that goal by demonstrating human-computer collaboration for highly unstructured tasks such as mind-mapping.

6. COMPUTER AS A STIMULATOR FOR DIGITAL MIND-MAPPING*

6.1 Introduction

Problem exploration is critical in helping designers develop new perspectives and driving the search for solutions within the iterative process of identifying features/needs and re-framing the scope [177]. Generally, it requires a combination of two distinct and often conflicted modes of thinking: (1) logical, analytical, and detail-oriented, and (2) lateral, systems-level, breadth-oriented [140]. Most current efforts in computer-facilitated exploratory tasks focus exclusively on one of these cognitive mechanisms. As a result, there is currently a limited understanding of how this breadth-depth conflict can be addressed. Maintaining the balance between the breadth and depth of exploration can be challenging, especially for first-time users. For atypical and open-ended problem statements (that are commonplace in design problems), this issue is further pronounced ultimately leading to creative inhibition and lack of engagement.

Effective and quick thinking is closely tied to the individual's imagination and ability to create associations between various information chunks [178]. Incidentally, this is also a skill that takes time to develop and manifest in novices. We draw from existing works [179, 180, 181, 100, 182, 183, 184, 97] that emphasize on stimulating reflection during exploration tasks. Quayle et al. [179] and Wetzstein et al. [180] indicate that the act of responding to questions can create several avenues for designers to reflect on their their assumptions and expand their field of view about a given idea. Adler et al. [185] found asking questions in sketching activity keeps the participants engaged and reflecting on ambiguities. Asking of one question leads to the asking of further questions thereby bringing forward already held ideas in one's mind [181]. Goldschmidt [100] further demonstrated that exposing designers to text can lead to higher originality during idea generation.

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Our approach is informed by the notion of *reflection-in-design* [180, 179], that takes an almost Socratic approach to reason about the design problem space through question-based verbalization. We apply this tenet in a digital setting where the user has access to vast knowledge databases, the cognitive processes underlying mind-mapping can be enriched to enable an iterative cycle between exploration, inquiry, and reflection. Our key idea is to explore two different ways in which such textual stimuli can be provided. The first is through a simple mechanism for query expansion (i.e. asking for suggestions) and followed by means for responding to computer-generated stimuli (i.e. answering questions). Based on this, we present a workflow for mind-mapping wherein the user, while adding and connecting concepts (*exploration*), can also query a semantic database to explore related concepts (*inquiry*) and build upon those concepts by answering questions posed by the mind-mapping tool itself (*reflection*). Our approach is powered by ConceptNet [1], a semantic network that contains a graph-based representation with nodes representing real-word concepts as natural language phrases (e.g. bring to a potluck, provide comfort, etc.), and edges representing semantic relationships. Using related entries to a given concept and also the types of relationships, our work investigates methods for textual stimulation for mind-mapping.

6.1.1 Identification of Gap

While several digital tools [69] have been proposed to facilitate mind-mapping activity, mind-map creators can still find it challenging due to several following reasons: inability to recall concepts related to a given problem, inherent ambiguity in the central problem, and difficulty in building relationships between different concepts [19, 20]. These difficulties often result in an unbalanced idea exploration resulting in either too broad or too detail-oriented mind-maps. In this work, we aim to investigate computational mechanisms to address this issue. We propose *QCue*, queries and cues for computer-facilitated mind-mapping.

6.2 Methodology

Inspired by the query-expansion work (Section 4), the design goal behind *QCue* is to strike a balance between idea expansion workflow and cognitive support during digital mind-mapping. We aim to provide computer support in a manner that stimulated the user to think in new directions but did not intrude in the user's own line of thinking. The algorithm of generating computer support in *QCue* was developed based on the evolution of the structure of the user-generated map over time to balance the breadth and depth of exploration.

6.2.1 Workflow Design

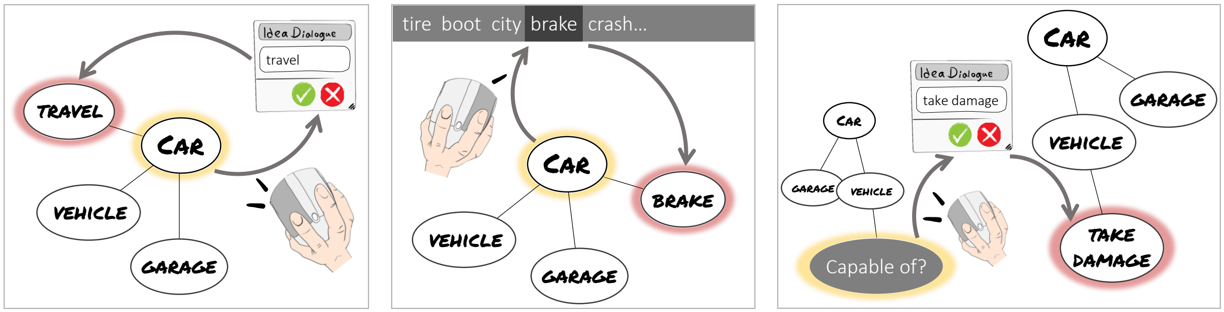
QCue was designed primarily to support divergent idea exploration in ideation processes. This requires an interface that would allow for simple yet fast interactions that are typically natural in a traditional pen-paper setting. We formulate process of mind-mapping as an iterative two-mode sequence: generating as many ideas as possible on a topic (breadth-first exploration), and choosing a smaller subset to refine and detail (depth-first exploration). We further assume our mind-maps to be strictly acyclic graphs (trees). The design of our workflow is based on the following guiding principles:

- In the initial phases of mind-mapping, asking questions to the user can help them externalize their assumptions regarding the topic, stimulate indirect relationships across concepts (latent relations).
- For exploring ideas in depth during later stages, suggesting alternatives to the use helps maintain the rate of idea addition. Here, questions can further help the user look for appropriate suggestions.

6.2.2 Idea Expansion Workflow

We provided the following interactions to users for creating a mind-map using *QCue*:

- Direct user input: This is the default mode of adding ideas to the map wherein users simply double-click on an existing node (n_i) to add content for its child node (n_j) using an input dialog box in the editor workspace. A link is created automatically between n_i and n_j (Figure 6.1(a)). This offers users minimal manipulation in the construction of a tree type structure.



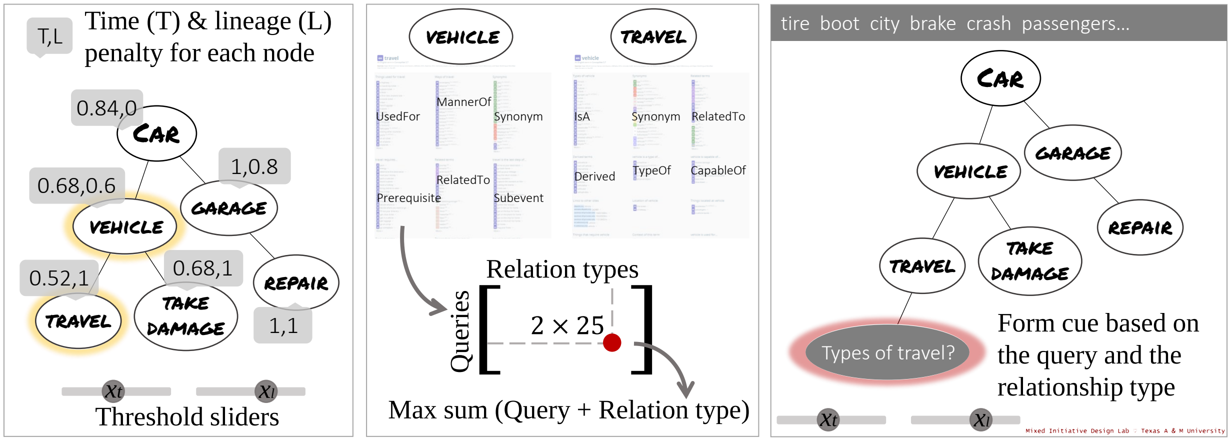
(a) Direct user input (b) Input based on suggestions (c) Input based on response to cue

Figure 6.1: Illustration of three mechanisms to create a new node. (a) user double-clicks a node and enters a text entry to create a new child node. (b) single right-clicking an existing node allows the user to use top suggestions from ConceptNet to create a new child node. (c) user double-clicks a cue node to response for a new node addition. Yellow shade denotes selected node; red shade denotes newly created node.

- *Asking for suggestions:* In situations where a user is unclear about a given direction of exploration from a node in the mind-map, the user can explicitly query ConceptNet with the concerned node (right-click on a node to be queried). Subsequently, we extract top 10 related concepts (words and phrases) from ConceptNet and allow users to add any related concept they see fit. Users can continuously explore and expand their search (right-clicking on any existing node) and add the result of the query (Figure 6.1(b)).

- *Responding to cues: QCue* evaluates the nodes in the map and detects nodes that need further exploration. Once identified, *QCue* automatically generates and adds a *question* as cue to user. The user can react to this cue node (double-click) and choose to either answer, ignore, or delete it. Once a valid answer recorded, the interface replaces the clicked node with the answer (Figure 6.1(c)).

- *Breadth-vs-depth exploration:* Two sliders are provided on the *QCue* interface to allow adjustment of exploratory directions guided by the cues (Figure 6.2(a)). Specifically, users can use the sliders to control the position of newly generated cues to be either breadth or depth-first anytime during mind-mapping.



(a) Scout ($T < x_t$, $L < x_l$)

(b) Find weighted relations from ConceptNet & categorize them

(c) Generate a cue node. Shown in the full UI of QCue

Figure 6.2: Illustration of the cue generation algorithm using retrieved weighted relations through ConceptNet Open Data API [1]. Yellow shade denotes computer selected potential node; red shade denotes computer generated cue. This algorithm is executed at regular intervals of 2 seconds.

6.2.3 Cue Generation Rationale

There are three aspects that we considered to design our cue-generation mechanism. Given the current state of a mind-map our challenge was to determine (1) *where* to generate a cue (which nodes in the mind-map need exploration), (2) *when* a cue should be generated (so as to provide a meaningful but non-intrusive intervention) and (3) the *what* to ask the user (in terms of the actual content of cue). To find out *where* and *when* to add cues, we draw from the recent work by Chen et al. [145] that explored several algorithms for computer-generated ideas. One of their algorithmic iterations — which is of particular interest to us — involves using the temporal and topological evolution of the mind-map to determine which nodes to target. However, this approach is rendered weak in their work because they modeled the mind-mapping process as a sequential game with each player (human and computer) takes turns. In our case, however, this is a powerful idea since the human and the intelligent agent (AI) are not bound by sequential activity —- both work asynchronously. This also reflects from our core idea of using computer as a facilitator rather than a collaborator. Based on these observations we designed our algorithm to utilize the topological and temporal evolution of a given mind-map in order to determine the potential nodes where we want the user to explore further. For this, we use a strategy similar to the one proposed by Chen et al. [145] that uses two penalty terms based on the time elapsed since a node was added to the mind-map and it's relative topological position (or lineage) with respect to the central problem.

Tesnière et al [186] note that *continuous thoughts can only be expressed with built connections*. This is our driving guideline for composing the content of a cue. Specifically, we observe that the basic issue faced by users is not the inability to create individual concepts but the difficulty in contextualizing broad categories or topics that link specific concepts. Here, we draw from works that identify semantic relations/connections between concepts to build human-like computer systems [187] and perform design synthesis [17]. We further note that the most important characteristic of mind-maps is their linked structure that allows users to associate and understand a group of concepts in a short amount of time. Therefore, our strategy for generating cue content is to simply make use of semantic *relationship types* already provided in ConceptNet. Our rationale is that providing relationship instead of concept-instances will assist the user in two ways: (1) help them think broadly about the problem thereby assisting them in generating much higher number of instances, and (2) keeping a continuous flow of thoughts throughout the creation process. Specifically, we developed our approach by taking the provided 25 relationship categories along with the weighted assertions from ConceptNet into consideration. Note that we did not take all relations from ConceptNet (34 in total) because some may be too ambiguous to users such as *RelatedTo*, *EtymologicallyDerivedFrom*, *ExternalURL*, etc. The algorithm is detailed in the following sections.

6.2.3.1 Time Penalty

Time penalty (T) is a measure of the inactivity of a given node in the map. It is defined as the time elapsed since last activity (linked to a parent or added a child). For a newly added node, the time penalty is initialized to 1 and reduced by a constant value (c) at regular intervals of the computational cycle. Once the value reaches 0, it remains constantly at 0 thereafter. Therefore, at any given instance, time penalty ranges from 0 to 1. A default threshold for time penalty was set and adjustable for users by using the provided slider on the *QCue* interface. Users can perform breadth-first exploration on ideas that have been recently visited by increasing the threshold value.

Given the initial condition $T(n_i) = 1.0$, we compute the time penalty of any node $n_i \in N_M$ at every interval Δt as $T(n_i) \rightarrow \max(T(n_i) - c, 0)$.

6.2.3.2 Lineage Penalty

Lineage penalty (L) is a measure of the relative depth of nodes in a given mind-map. It is defined as the normalized total count of children of a given node. Each node has a lineage weight (x_i) that equals to 0 upon addition. For every additional child node that added to a given node, this weight is increased by 1 ($x_i \leftarrow$ number of children of n_i). To compute the lineage penalty for every node, all these weights are normalized (ranges from 0 to 1) and then subtracted by one ($L(n_i) = 1 - \frac{x_i}{max(x_i)}$). Therefore, lineage penalty is 1 for leaf nodes and 0 for the root node, and ranges from 0 to 1 for the others. ***QCue***'s support based on this can help exploration towards leaf nodes.

6.2.3.3 Cue Generation using ConceptNet

Given any state of a mind-map, there are three primary algorithm steps that are needed for generating cues in the form of questions using ConceptNet semantic network. First, ***QCue*** scouts out a good location (node) to facilitate exploration using the two penalties. Subsequently, the spotted nodes are queried from ConceptNet to retrieve corresponding weighted relations for *content determination*. Finally, based on the determined content, ***QCue*** generates a cue node to ultimately guide the user and help expand the idea space during mind-map creation.

- *Scouting:* For every node in the current state of a mind-map, we compute its *time penalty* and *lineage penalty*. Then, based on the current adjusted thresholds (x_t, x_l) where x_t and x_l denote thresholds for time and lineage penalty respectively, ***QCue*** spots potential nodes (N_E) for exploration. Specifically, if $T(n_i) < x_t$ or $L(n_i) < x_l$ then $N_E \leftarrow N_E \cup \{n_i\}$ (Figure 6.2(a)). If no node is within the thresholds, all nodes in the current mind-map are considered as potential nodes.

- *Content determination:* In this step, we further query the spotted nodes (N_E) from ConceptNet. A list of query results containing weighted relations is retrieved for each potential node

(Figure 6.2(b)). In order to find the node which has the maximum potential of associative capability, we subdivide each list categorically based on the 25 relationship types provided by ConceptNet. Subsequently, we select one subdivision which has the highest sum of relation weights and use it as basis for a new cue's content (Figure 6.2(b)). Note that if a subdivision has been used to generate a cue node, it will be removed from future selection pool.

- Cue generation: Using the selected subdivision from *content determination*, *QCue* formulates a new cue based on fixed templates (Figure 6.2(c)). To avoid repetition of cues generated during mind-map creation, we specifically construct at least three templates (combinations of query + verb + relationship type) for each relationship category provided by ConceptNet. Example cues based on a query — *knife* — and a relationship type — *CapableOf* — are as follows: *"What can knife do?"*, *"What is knife capable of doing?"* and *"Which task is knife capable of performing?"*.

6.2.4 Implementation

Our *QCue* interface is a Javascript web application that runs entirely on the browser using NodeJS and D3JS. We incorporated JSON-LD API (Linked Data structure) offered by ConceptNet in our interface. The nodes of ConceptNet are words and phrases of natural language. Each node contains an edge list which has all the relations such as *UsedFor* stored in *rel* with its corresponding weight stored in *weight*, and a human-readable *label* stored in *start* and *end*. As user queries a word or phrase in natural language (as one node), we look for all the relations in this node, filter them with English-only, and then extract the non-repetitive human-readable labels out.

On the *QCue* interface, users can spatially organize ideas in the mind-map by dragging ideas with forced-links around the editor workspace. Such force-directed layout produces an aesthetically pleasing graph while maintaining comprehensibility, even with large dataset. Users are also allowed to adjust sliders to shape their exploration preferences by either wider or deeper. *QCue* employs a listener function to run the cue generation algorithm at fixed intervals of 2 seconds. We also developed an web-based interface for TMM which is essentially the same as *QCue* but without any computer support (cues and queries).

- *Data format and storage:* Each mind-map is stored in a local folder with a distinct user ID. To store the structure of a mind-map, we defined a JavaScript prototype containing nodes, links, timestamps and other appearance data (e.g. color, size, font etc.). We can regenerate a mind-map by importing the file data into *QCue*. Videos of the mind-maps are also stored within the respective folders to be used in further analysis.

- *Choice of penalty and threshold:* To find an appropriate default value for the constant c in *time penalty* and the thresholds for the two penalties, we conducted several pilot studies (Section 6.3.1) to observe how people mind-map in a regular setting (TMM) and how people get acquainted with *QCue*. The final assignments are: c = 0.08, x_t & x_l = 0.6 when t = 0.

6.3 Evaluation Methodology

6.3.1 Pilot Study

We conducted a pilot study with 12 participants where our intention was to observe (1) how users react to the cue-query workflow, (2) determine ideas and problem statements that could serve as our evaluation tasks, and (3) determine appropriate initial parameters (such as lineage and time thresholds). In order to observe user's thinking process while creating a mind-map, we designed four different problem statements namely, *pollution*, *toys in the future*, *camping underwater*, and *wedding on space station*. We encouraged the users to explore the basic idea, cause, effect and potential solutions of the given problem statement.

Participants were both surprised as well as interested in topics such as *weddings on space station* and *underwater camping*. Specifically, they indicated need for time to prepare themselves before beginning the mind-mapping task. On the other hand for topics such as *pollution* and *toy*, they showed immediate inclination toward starting the session. Since we wanted to test the robustness of our algorithm with respect to the topic given, we decided to conduct the user study with two topics of opposite extremes. Namely, *pollution* (**T1**) - a seemingly familiar topic and *underwater camping* (**T2**) - rather a more abstract topic.

Condition	Structure (1-4)	Exploratory (1-4)	Communication (1-4)	Extent of coverage (1-4)	Quantity (raw)	Variety (0-1)	Novelty (0-1)
TMM T1	2.11	2.14	2.33	2.11	31	0.56	0.22
TMM T2	2.42	2.42	2.06	2.25	34	0.45	0.32
QCue T1	3.11	3.03	2.56	2.72	38	0.71	0.27
QCue T2	2.67	2.67	2.64	2.44	41	0.63	0.32
Average TMM	2.27	2.28	2.2	2.18	32.5	0.51	0.27
Average *QCue*	2.89	2.85	2.6	2.58	39.5	0.67	0.3

Figure 6.3: Table of average ratings for each metric by four user conditions: TMM, QCue with T1 and T2.

6.3.2 Participants

In the user study, we recruited 24 undergraduate and graduate students from all across a university campus. Our participants came from engineering, architecture, and science backgrounds and were within the age range of 19-30 years. 6 of these participants had prior experience with creating mind-maps. We conducted a between-subjects study, where 12 participants created mind-maps for a given central topic using TMM, and the remaining 12 using *QCue*.

6.3.3 Tasks

In total, across the two experimental conditions, 24 participants created 48 mind-maps — one for each central topic. The total time taken during the experiment varied between 30 and 40 minutes and the two central topics were randomized across the participants. After describing the setup and the purpose of the study, we described the features of the assigned interface and practically demonstrated its usage. For each participant and task **M**, we recorded a video of the task, the completion time, and the time-stamped ideas generated by the users for each mind-map. Each participant performed the following tasks:

P *Practice*: To familiarize themselves with the interaction of the assigned interface, the participants were given a brief demonstration of the software and its function. They are allowed to practice the interface for 5 to 10 minutes, with guidance when required.

M *Mind-mapping with **T1** & **T2***: Participants were asked to create mind-map using the assigned interface. The duration of mind-mapping session was 10 minutes for each central topic. Participants were encouraged to explore the central topic as fulfill as they could. The workspace was cleared after completion of each mind-map.

Q *Questionnaire*: Finally, each participant answered a series of questions regarding their exploration of central topic before and after the creation of each mind-map, perception of each of the interfaces in terms of ease of use, intuitiveness, and assistance. We also conducted post-study interviews to collect open-ended feedback regarding the experience.

6.3.4 Metrics

Mind-maps recorded during the study were de-identified. The designed metrics assessed all ideas generated in each mind-map based on four primary aspects: **quantity, quality, novelty and variety** [188, 38]. The **quantity** metric is directly measured as the total number of nodes is a given mind-map. The **variety** of each mind-map is given by the number of idea categories that raters find in the mind-map and the **novelty** score is a measure of how unique are the ideas represented in a given mind-map [38, 96]. For a fair assessment of the **quality** of mind-maps for both central topics, we adapted the mind-map assessment rubric [37] and the raters evaluated the mind-maps based on the four major criteria: structure, exploratory, communication and extent of coverage. These metrics are commonly used to evaluate ideation success in open-ended design tasks [189].

- **Structure:** It primarily focuses on the breadth, depth, and the balance between the two. Maps that are well-explored in both breadth and depth receive higher scores.

- **Exploratory:** This metric evaluates the relatedness of linked ideas to the central problem of the map. The flow of ideas from abstract in the center to concrete toward the periphery (leaf nodes on the map) leads to a higher score.

- **Communication:** This metric evaluates the effectiveness of representation of mind-mapped ideas. Appropriate key-words utilized during idea exploration help convey a clearer intent of the mind-map. A higher score is established for higher usage of appropriate key-words.

- **Extent of Coverage:** Here, we evaluate the effort made by pair to create meaningful relationships between the ideas. A higher score reflects a more dedicated effort towards creating an understanding between the primary ideas established in the mind-map. Whereas, a lower score reflects minimal effort towards creating a well connected mind-map.

Here, we would like to point out to similar metrics that have been used in HCI literature on creativity support. For instance, Kerne's elemental metrics [33] for information-based ideation (IBI) are adapted from Shah's metrics [188]. While the metrics we chose have been used in previous mind-mapping studies, they also have some connection with creativity-support index (CSI) [190, 191] and ideational fluency [33] (for example, holistic IBI metrics are similar to the "structure" metric and our post study questions are functionally similar to CSI tailored for mind-mapping).

6.3.5 Raters

We initially recruited two raters for assessing the user-created mind-maps. Later, we added an additional rater to improve the overall validity and robustness of the evaluation outcomes. These raters were senior designers in the mechanical engineering design domain with considerable design experience from coursework and research projects. The raters were unaware of the actual study design and the tasks, also, they were not furnished with information related to the general study hypotheses. The 48 mind-maps created across both interfaces were presented to each rater in a randomized order. For every mind-map assessed, the raters evaluate them on a scale of 1-4 based on each criterion discussed above. Every created mind-map is then assigned a score from a total of 16 points, which is used further for comparing the overall quality with respect to other mind-maps.

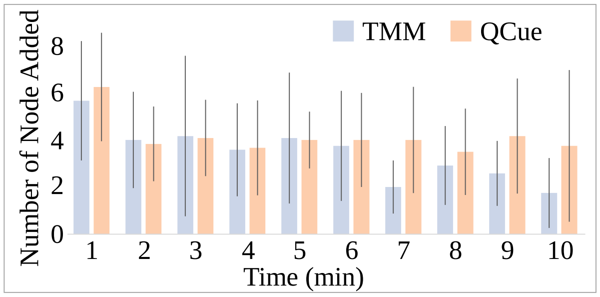
For a given central topic, the evaluation depends on knowledge of the raters and their interpretation of what the metrics mean. In our study, three raters independently performed subjective ratings of every idea/concept in a mind-map. This evaluation technique has the advantage of capturing aspects of creative work that are subjectively recognized by raters, but are difficult to define objectively. After the independent evaluation by the three raters, they had several virtual meetings to discuss and come to a consensus on their ratings.

6.4 Results

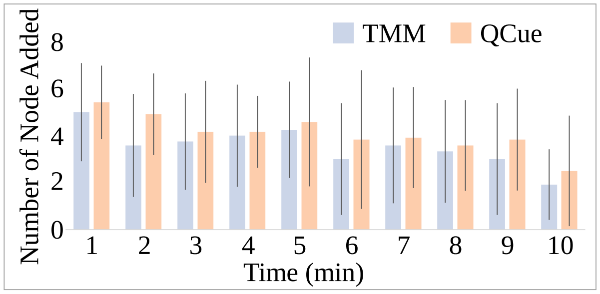
6.4.1 Ratings for User-Generated Mind-Maps

In metrics admitting integer values (structure, exploratory, communication and extent of coverage), we calculated the Fleiss's kappa for ensuring inter-rater agreement. The Fleiss's kappa value was found to be between the range of $0.79 - 0.85$ showing a substantial inter-rater agreement level [172, 175]. For metrics admitting real/scalar values (variety and novelty), we calculated the Pearson's correlation coefficient to find the degree of consensus between the raters' ratings. This coefficient was found to be close to 0.8 which indicates a high correlation of agreement [39].

Overall, the ratings for *QCue* were relatively higher than TMM across all metrics (Figure 6.3). Two-way ANOVA was conducted with two factors of comparison: (1) the choice of topic (*pollution* or *underwater camping*) and (2) the choice of interface (*QCue* or TMM). Although the data for certain metrics were non-normal, we proceeded with ANOVA since it is resistant to moderate deviation from normality. The mean ratings for structure were higher for QCue (2.89) in comparison to TMM (2.27, p-value 0.0038). Similarly the mean scores for the exploratory metric is also higher for *QCue* (2.85) with respect to TMM (2.28, p-value 0.029). This suggests that the mind-maps created using *QCue* were relatively more balanced (in depth and breadth) and more comprehensively explored. Further, we recorded a better variety score in *QCue* (0.67) relative to TMM (0.51, p-value 0.0011). Finally, we also recorded a larger number of nodes added in *QCue* (39.5) relative to TMM (32.5, p-value 0.048). In general, the overall ratings are higher in *QCue* for both topics (Figure 6.3, especially for *pollution* — mean structure value increases to 3.11 from 2.11). These observations indicate that the cue-query mechanism assisted the users in (1) exploring diverse aspects of the given topics, (2) bringing forward already held ideas and thoughts in their minds, and (3) making non-obvious yet meaningful relationships across ideas.

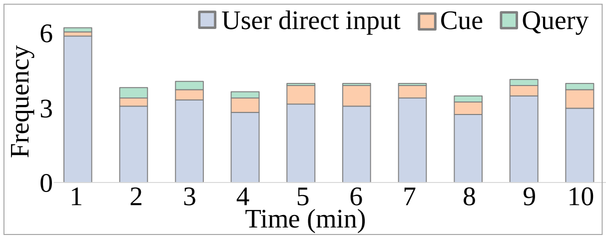


(a) Pollution

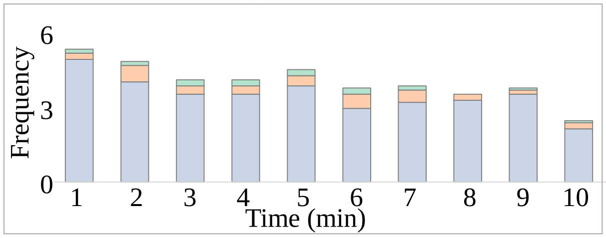


(b) Underwater camping

Figure 6.4: General trends on how users generating ideas towards different topics (T1 and T2) during TMM and QCue. Each bar represents an average count of the total nodes in the given time frame (per 1 minute).



(a) Pollution



(b) Underwater camping

Figure 6.5: Comparison of trends on how users generating ideas towards T1 and T2 using the three modes (user direct input, cue node response and query).

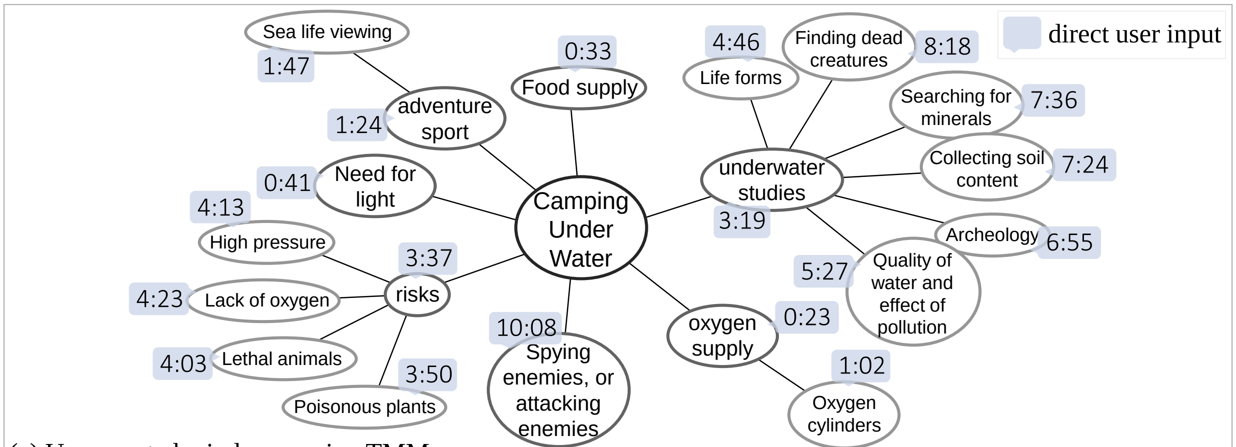
6.4.2 Temporal Trend for Node Addition

In general, the rate of node addition decreased over time in the TMM workflow regardless of the topics. For *QCue*, the node addition rate was comparatively steady indicating that cues and queries helped sustain user engagement for exploration during even later stages of the tasks (Figure 6.4).

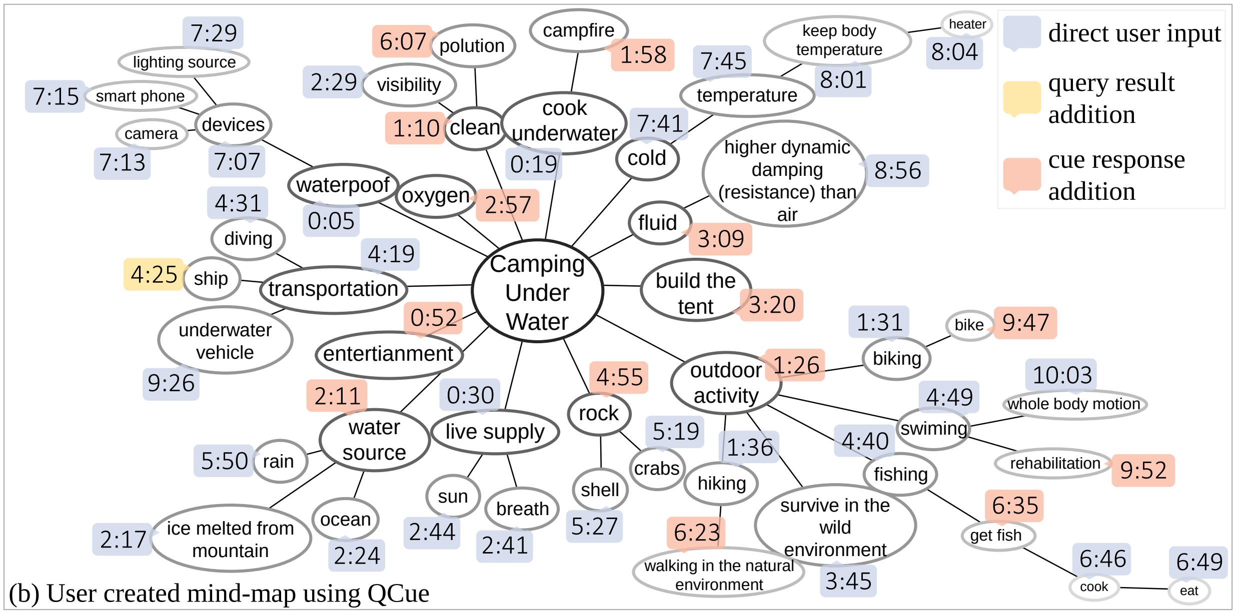
While there are three modes for node addition using *QCue*, as expected, the number of cues and queries used depended on users' familiarity with the central topic in the tasks. Overall, we observed that the users tended to ask for queries in the first few minutes of mind-mapping, and proceed with the usage of cue nodes in the middle stages of the given time (Figure 6.5). For *pollution*, the number of answered cue nodes increases with time. Specifically, users appreciated cues between the 5 and 6 minutes mark for *pollution*. For *underwater camping*, we noticed an increasing amount of the cue nodes answered specifically in the 2 and 6 to 7 minutes mark. This indicates two primary usage of cues. First, when the users have explored their prior knowledge of the topic and reach an impasse during the middle stages of mind-mapping (5 to 7 minutes mark in our case), cues help them reflect on the existing concepts and discover new relationships to generate ideas further. Second, for open-ended problems such as *underwater camping*, cues helped users in exploring different directions of exploration around the central idea in the beginning. This impacted the exploration of ideas in the later stages of the task. On the other hand, surprisingly, we found that the percentage of the number of nodes added from query mode is lower than the cue mode. This suggests that users were generally more engaged when they were actively involved in the cycle of exploration and reflection based on cues in comparison to receiving direct answers provided by query.

6.5 Results: Assessment of the Process

Our quantitative results gave a comprehensive account on the performance of *QCue* over TMM, as well as, highlighted some key trends observed across different users for our given mind-mapping topics. While interesting, we wanted to observe, understand, and analyze the mind-



(a) User created mind-map using TMM



(b) User created mind-map using QCue

Figure 6.6: Two user created mind-maps with underwater camping (T2) as central topic using (a) TMM and (b) QCue. The label represents timestamp upon node addition and type of addition.

mapping process as performed by the users. Therefore, we carefully and systematically studied the mind-mapping process by going through the video recordings collected from the user study (N=48). We analyzed the videos with our primary emphasis on key process factors such as adding an idea, user apprehension in adding an idea, breadth vs. depth exploration, querying for suggestions, and asking for a question. Prior works have showcased similar analysis strategies to study the underlying cognitive aspects in knowledge exploration and conceptualization activities [97, 192]. In the following sections, we explain the overall observations made across all user created mind-mapping activities and bring forth some key examples which are of interest for computer-supported cognitive processes.

6.5.1 Mind-Map Evolution across Interfaces and Topics

We observed different user strategies contributing to the evolution of the mind-maps as created across the two participant groups — TMM and *QCue*. Most TMM users explored the idea space asymmetrically during their mind-mapping sessions; which means they proceeded in directions comfortable to them. This is also evident in the several long branches as seen in the resulting TMM maps. On the other hand for *QCue*, we observed that instead of going in one direction, user performance relatively consistent in performing breadth-first exploration while maintaining the overall structure (Figure 6.3, **structure:** TMM-2.42, *QCue*-2.67). We believe that *QCue's* cue-based approach helped motivate the users to explored outside the comfort zone of their thoughts and ideas, thus, providing a suitable space to make associations between concepts and perform system-level thinking.

In addition to maintaining an overall balanced mind-map structure, we observed significant differences in user approach for mind-mapping tasks based around the two topics provided for the study. Typically, mind-maps evolved in favor of ideas where users were familiar with the central topic. For topics such as *pollution*, users were able to externalize ideas rapidly in the first several minutes of the process. However, this also resulted in a premature exhaustion of the users, thus, resulting in a lower node addition rate towards the end of the study task, specifically for users in the TMM approach (Figure 6.4(a)). On the contrary for *underwater camping*, users were found to be hesitant in generating ideas in the beginning, but observed an upward trend in idea exploration during the later stages of mind-mapping as supported by *QCue* (from 3 to 9 minutes, figure 6.4(b)). This underscores the potential of *QCue* in assisting users to engage in the problem exploration process for topics that are atypical and full of uncertainties.

6.5.2 Direction of Exploration

Our qualitative assessment also looked into the type of ideas/concepts added categorically by the users during different phases of mind-mapping. To this end, we discuss how this categorization affects the final quality of the mind-map across the two topics — *pollution* and *underwater camping*.

During the mind-mapping process on *pollution*, we observed one set of users began by adding nodes that classified the central topic (pollution) into categories such as *air, noise, water, soil, land*, etc.; which is common knowledge to most people. These users further spent the the remainder of their time in expanding on each pollution-type and solution-oriented ideas (eg. regulations, ways to reduce it, etc). In contrast, there were a second set of users who began with the nodes such as *challenges, effects, types, solution*, etc. and were able to explore more concrete ideas on *pollution* than their counterparts. This type of exploratory approach was mainly observed in the *QCue* workflow (Figure 6.3, **exploratory** T1: TMM-2.14, *QCue*-3.03), thus, indicating that computer generated relation-oriented questions stimulated the users' associative thinking capabilities and encouraged them to develop a fundamental understanding of the central topic.

In *underwater camping* maps, the initial set of nodes as added by the users varied across users. As a commonly observed approach, the users started by adding nodes on basic camping requirements such as *fire, food, water, oxygen*, etc (Figure 6.6). Few users also added nodes directly on the central node that alluded to various pros and cons of underwater camping (for example *Research on marine life, scuba diving, lack of sunlight, no fresh air*, etc). In fact, the exploration strategies were more direction-oriented in *underwater camping* as compared with *pollution*, in the sense that the user followed a depth-first exploration. Interestingly, one user who was working in *QCue*, spent 3 minutes exploring what a typical camping actually is (by adding a separate node *Typical* *camping* to the central topic) and then shifted focus onto the *challenges, logistics and possibilities* of underwater camping in the following minutes.

6.5.3 Idea Expansion Strategies: QCue vs TMM

Generally, the users started building on their initial ideas by elaborating on the primary nodes emanating directly from the central topic. However, we observed that the overall structure of the map was consequential to the type of exploration strategy followed by every user. While most of the users tried to balance the distribution of the nodes around the central topic, there were a few who followed a depth-oriented exploration approach by giving less importance to the overall structure. While detailed, the depth-oriented exploration approach narrowed the scope of the central topic, thus, making the long branched ideas less relevant. For example, a user working with the TMM workflow started from *air pollution* and went all the way to *fresh air*, *greenery*, *parks*, *exercise* and *running*, thus, limiting the general notion of *pollution* to *air pollution*.

Further, highlighting the exploratory strategies adopted between *QCue* and TMM users, we observed some interesting differences. In the TMM workflow, users working on *underwater camping* began by directly generating specific solutions to the topic rather than broadly exploring different aspects of the problem itself. For instance, one user added three main branches to the central topic (*oxygen supply*, *Food supply*, and *Need for light*, Figure 6.6(a)) which could be better placed under a separate parent node *requirements to make underwater camping possible*. This further affected the users' ability to categorize their ideas and develop new lines of thoughts. Whereas, in case of *QCue*, cues and queries provided users with general directions to explore around the topic of *underwater camping* before going into details of the same. Consequently, the resulting mind-maps from *QCue* users contained a balanced breadth and depth (Figure 6.3, **structure:** TMM-2.42, *QCue*-2.67), which aligns with our expectation of supporting with cues and queries. This strategy adopted by *QCue* users also helped them in spanning their thoughts about atypical problems and hence exploring ideas comprehensively (Figure 6.3, **communication** T2: TMM-2.06, *QCue*-2.64; **extent of coverage** T2: TMM-2.25, *QCue*-2.44).

6.5.4 Stages of Idea Exploration: QCue vs TMM

Our systematic analysis of the mind-mapping process helped us identify and categorize key stages as observed across all mind-map user activities. We discuss them in the following.

6.5.4.1 Barrier to Entry

We characterize *barrier to entry* by measuring the duration of time in the early stages of the mind-map evolution where the user either hovers over the central topic or opens the idea dialogue box to add nodes and thinks for a significant time. The intent here is to understand if either mind-mapping topics had an effect on the initiation of the process, and how each of the provided workflows (*QCue* or TMM) helped facilitate an easy start for the users.

For the topic *pollution*, we observed a majority of the users add nodes to the central idea soon after the mind-mapping session started. Such behavior is likely to be the case in *QCue*, as well as, TMM workflows owing to the commonplace nature of *pollution* as a topic.

On the other hand for *underwater camping*, users took some time to contextualize the problem and were hesitant in generating ideas initially. We observed that most users were either hovering around the central topic or took a significant amount of time (> 15 seconds) to add their first node to the central topic (Figure 6.6). As a case in point, few *QCue* workflow users queried for suggestions in the beginning itself. One user immediately queried suggestions for *underwater camping* and added the nodes *boat* and *swim* to the central topic so as to give them a head start. Moreover for some users, the cues also assisted them in thinking along various directions and broaden their understanding of the central idea. For example, one user answered *entertainment* to the query, *"What purpose is camping used for?"*, in relation to the central topic. This encouraged the users to think in a completely new direction, thereby, re-scoping the user's thoughts on the topic that is atypical.

6.5.4.2 Brief Moratoriums

We looked for user behavior indicating that the user was thinking and pondering over the nodes in the existing mind-maps during the creation process. This includes the time duration for which the user was inactive for a brief period of time (< 15 seconds) while hovering around the mind-map interface, also, the time during which the user typed something in the idea dialogue box and erased it or modified it to a new idea. These key findings on user behavior helped us highlight the differences between *QCue* and TMM workflows.

Unexpectedly, We found these brief moments of pause often in TMM as compared to the *QCue* approach. Also, TMM users were more hesitant to add node thinking whether it could make their mind-map go in different directions. More often than not, majority of these observations were made during *underwater camping* mind-mapping than *pollution*. *QCue* users on the other hand, were found to be relatively more confident and focused on the problem, potentially with an understanding that they could utilize cues and queries for idea expansion. This indicates that *QCue* kept the users engaged in a continuous thought process over TMM (that relies truely on the user cognitive abilities). Such engagement could be important in creative processes [193].

6.5.4.3 Exhaustion

We identify exhaustion as the portion of the mind-mapping activity where the user just hovers over the existing mind-map for more than 30 seconds indicating that the user might have ran out of ideas during the process. We found this happen often in TMM workflow than *QCue*. Typically, such situations occur when the user explores all nodes they added to the central topic. For instance, a user working on *underwater camping* in TMM added at least one node to each of the primary nodes, following which the user did not add another node for the nearly 45 seconds. During this time, the user hovered over the various nodes he added and the central topic several times, indicating that the user wanted to explore new directions, but is unable to do so or limited by their thoughts. This behavior can also be implied from the node addition rate over time — the rate decreased over time in the TMM workflow regardless of the topics. For *QCue*, the rate was comparatively steady indicating that cues and queries helped sustain user engagement for exploration and line of thoughts even during later stages of mind-mapping (Figure 6.4).

6.6 QCue: Analysis of Queries and Cues as Stimulants

Our purpose for developing QCue is to reinstate the importance of "*reflection in design*" for computer supported idea generation processes. The prior sections discuss how *QCue* as an approach in digital mind-mapping has motivated the creation of balanced and well thought out map structures corroborated with evaluations using established metrics. In this section, we present a categorical and brief account on the usage of *queries* and *cues* as stimulants for design reflection while working with *QCue*.

6.6.1 Query as a Stimulant

The fundamental approach behind queries is to maintain the rate of idea addition during mind-mapping. This mechanism is always triggered by the user when they need any form of inspiration to further explore a given idea. Most users shared their feedback saying that *suggestions* played a positive role in exploring fine-grained ideas in specific directions. When the suggestions are generated upon a query, the user can choose to (1) use it directly by adding it to the map, or (2) not perform any explicit actions on the suggestions displayed. Note that in the second scenario, the user may get inspired and add other relevant ideas to the map. Surprisingly, we found five mind-mapping sessions where the users did not query for any suggestions (3 for *pollution*, 2 for *underwater camping*). Interesting use cases are revealed in the following.

6.6.1.1 Direct Stimulation

Queries were often used by the users to explore a specific aspect of the central idea in further detail (or depth). For example, at around the 8.30 minutes mark, one user queried for suggestions on the node *air* and added *breathing*, queried further and added *hyperventilation* and *artificial respiration* that were more depth-oriented and relevant to the central topic of *pollution*. Across topics, it was generally found that the users queried for suggestions more for the topic on *pollution* than *underwater camping*. Also, in *underwater camping*, query based suggestions were found to be used often in the early to middle phases of mind-mapping in contrast to *pollution*, where suggestions are mostly used in the early and later stages (Figure 6.5) of the mind-mapping process.

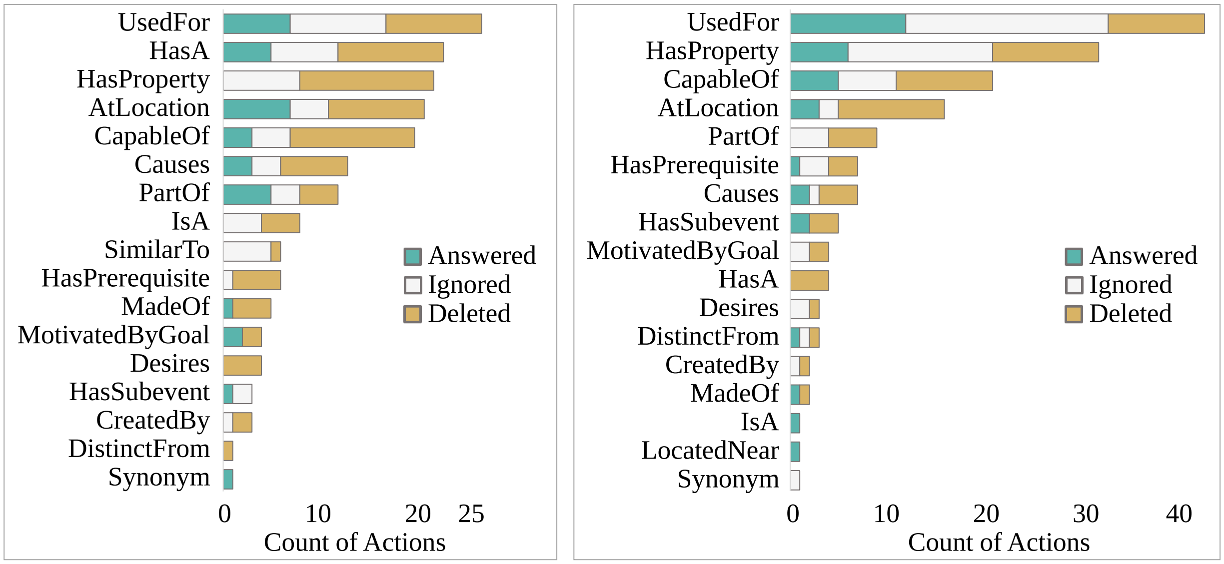
For instance, one user working on *pollution* found the suggestion on *noise pollution* important after 7.30 minutes of brainstorming on his own. He immediately added that as a new main branch and further brainstormed on ideas such as *loud music*, *migranes*, etc. Whereas during *underwater camping*, one user started to look at suggestions in the beginning of mind-mapping process (around 1.30 minutes mark) and added ideas such as *swimming*, *refreshing*, *fitness*, etc. as a starting point. This suggests that the user needed some direct support in the beginning of the activity to augment their thinking on the topic of *underwater camping*.

6.6.1.2 Indirect Stimulation

In this scenario, we observed several instances (20 for *pollution*, 11 for *underwater camping*) where users felt indirect stimulation by looking at the suggestions. For example, one user queried suggestions for the node *food* which had the suggestion *chicken*. The user then added the node *fish* indicating that the suggestion had inspired the user to think about the variety of food options available underwater. Such observations indicate that queries are perceived not just as a concept that could be added to the queried node, but also as a stimulant that helps users abstract some general ideas out of the list of queries. However, few users felt they could generate idea themselves and did not query for any suggestions.

6.6.2 Cue as a Stimulant

Mixed responses were observed from the users after cue nodes were generated in their mind-map. The position of the generated cues was based on the values of the two penalties (Time and Lineage). Most users were comfortable with the default value of thresholds for the time penalty (T) and lineage penalty (L). Whenever a cue node is generated, the user has three types of actions to interact with it: *answering, ignorance, and deletion. Answering* and *deletion* are explicit actions which can be identified by clicking events. *Ignorance* is inferred from the following three usage scenarios: (1) when the user explicitly clicks the 'Ignore' button on the cue node dialogue, (2) when the user opens the cue node dialogue and closes it without performing any explicit actions, and (3) when the previous two scenarios did not happen and the user keeps the cue node until the



(a) Pollution (b) Underwater camping

Figure 6.7: Counts of types of actions the users performed to the types of cue nodes generated by QCue with pollution (T1) and underwater camping (T2). This is across all users.

end of the mind-mapping session. Note that in scenario (3), the user may hover over the cue node several times during mind-mapping. Our statistics show that for *pollution*, out of 179 generated total cue nodes, about 19% were directly answered by the users, 29% were ignored, and 52% were deleted. For the topic that is more open-ended such as *underwater camping*, about 22% of the 161 generated cue nodes were directly answered, 37% were ignored, and 41% were deleted (Figure 6.7). It is noteworthy that, generally cues were extensively used by the users regardless of the topics. In few cases where the users were so involved in externalizing their own thoughts that they mostly did not interact with the cues. Nevertheless, the cues facilitated effective stimulation of the underlying cognitive processes during mind-mapping as follows:

6.6.2.1 Answered the Cues (Direct Stimulation)

The users directly answered some cues that were pertinent to their train of thought. These were often important and impacted the directions in which the users explored. For instance, one user added *global warming* when presented with the suggestion, *“what does air pollution cause?”* on the node *air pollution*. This resulted in one of the main directions the users explored in the

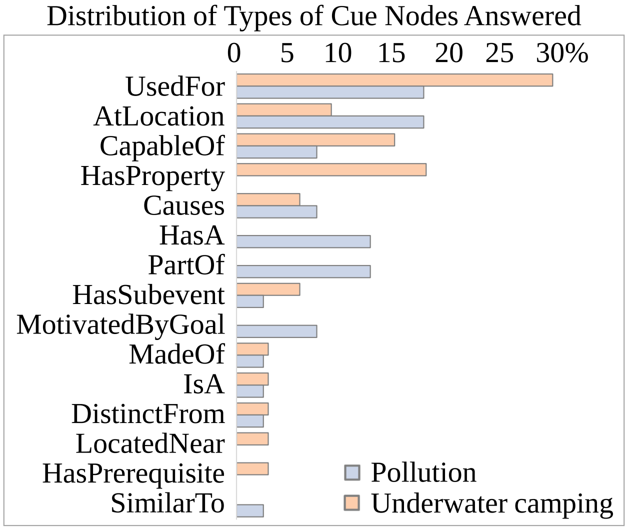


Figure 6.8: Distribution of types of cues answered with respect to underwater camping (T2) and pollution (T1). This is across all users.

remaining duration. Another user extensively used cue nodes throughout the process; and added several interesting ideas such as *fluid* and *higher resistance than air* from the question *"what is something that belongs to the category of water?"*, and *rehabilitation*, *whole body motion* from *"where does swimming find usage?"* (Figure 6.6(b)). We noticed that while the same amount of cue nodes were directly answered with respect to the two central topics, they were used in different mind-mapping phases. For *pollution*, the users were inclined to look for cues in the middle stage of mind-mapping when they reached an impasse and needed further help to reflect on existing concepts. For *underwater camping*, cues were found to be more helpful in the beginning and later phases where the users were trying to (1) understand an idea and explore along different directions from the central topic, and (2) further expand on those directions. This is likely due to the nature of the central topic of *underwater camping* being relatively more indirect (not something people could usually think of). It is also worth noting that users appreciated cues that were constructed using ConceptNet relations and found it more conceptual. This helped users in questioning fundamental aspects for *underwater camping* (Figure 6.7). For example, around 30% of the answered cues were generated based on *UsedFor*, 18% were based on *HasProperty*, and another 15% were based on *CapableOf*. Whereas for *pollution*, the users were more interested in answering cues that were constructed using more detail-oriented relations, such as *AtLocation* (18%), *UsedFor* (18%), *HasA* (13%), *PartOf* (13%), etc (Figure 6.8). This suggests the two important usages of cues: (1) even though *QCue* offers query results for quick idea addition, cues still help mind-map creators in exploring fine-grained ideas, and (2) cues guide users to conceptualize open-ended problems during the mind-mapping process. The latter is critical in design activities, as design problem statements are likely to be atypical and open-ended.

6.6.2.2 No Action

Interestingly, we found that sometimes users looked up at a cue node originating at a one part of the mind-map structure and got inspired to add ideas to other regions. We refer to such instances of node addition as an indirect inspiration to expand on a different (not necessarily related) line of thought than the original target of the cue nodes. For instance, the question *"What purpose is water used for?"* was generated for a user initially in *QCue* for *underwater camping*. The user added a node *supporting life*, and successively added *food, fire, breathing, research into marine wildlife, emergency situations* to the central topic without responding to the cue. One of the users who had prior experience in mind-mapping, seems to also utilized the cues as a non-local guidance to his thought process — got inspired by the cues, added some ideas, kept the cue nodes in the mind-map for potentially future reference, and further expanded on other idea branches. We also noticed that such behaviors mostly happened with *underwater camping* (overall Ignorance: T1-29%, T2-37%, Figure 6.7). This is likely due to the open-ended nature of the central problem, as any question can hardly be fully resolved owing to multiple possible answers.

6.6.2.3 Deleted the Cue Node

The users deleted the existing cue nodes for two primary reasons. First, because they did not find the cues to be helpful to the existing context. Second, they had already explored responses for the cues that popped in other places of their current mind-map. In our cue generation algorithm, we had set a limit on the maximum number of cue nodes that can be present in the mind-map at any

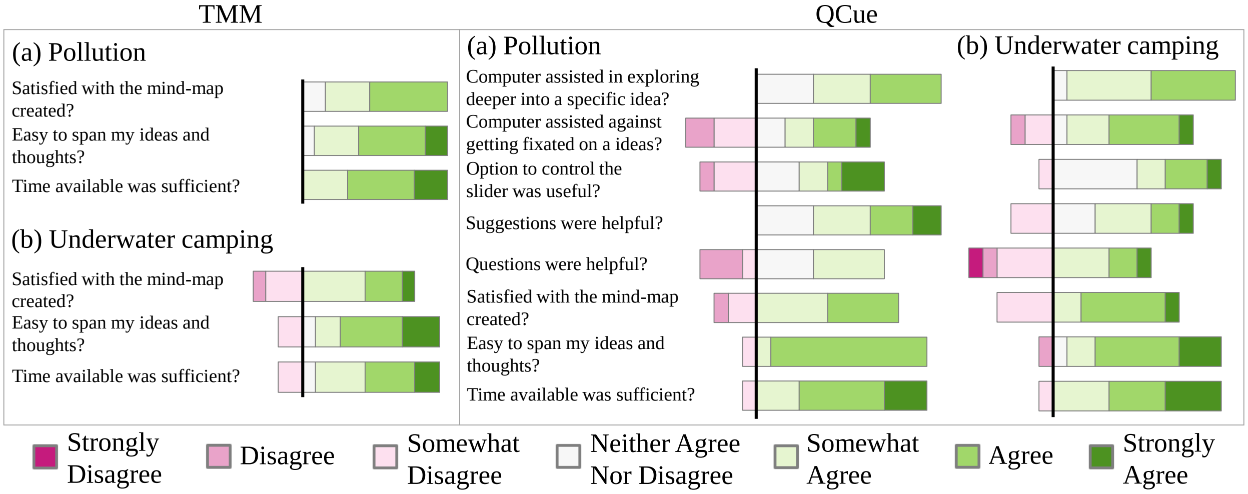


Figure 6.9: 7-Point Likert scale user feedback for TMM and QCue. Bars at the right hand side of the central line (green) indicate positive responses, while those on the left hand side (pink) indicate negative responses.

given instant of time to be 5 for the following reasons: (1) keep generating new questions in the process may make the user feel stressful, and (2) we want to allow room for the user to externalize their own thoughts. Therefore, the deletion of a cue node, in turn, triggers our cue generation mechanism and gives the users a different set of cues in various aspects. This also helped the user to be actively involved in the interface.

6.7 User Feedback

To help us evaluate the effectiveness of our algorithm, the participants filled out a questionnaire after creation of each mind-map (Figure 6.9). We also encouraged the participants to give open-ended feedback to support their rating.

6.7.1 Cue vs Query

There was a mixed response from the users for asking *whether the cues were useful in the process of mind-mapping*. Around 60% of the users agreed that the cues helped them to develop new lines of thoughts at the right time. One user stated, *“Questions (or cues) were helpful at the point when you get fixated. They give you other dimensions/ideas to expand your thought”*. The remaining stated that they do not find the cues helpful because they already had ideas on how to develop the mind-map. *"I felt like the questions (or cues) would make me lose my train of thought"*. Users who found it difficult to add to existing ideas in the mind-map, used the cues and queries extensively to build and visualize new dimensions to the central idea. These users felt that the cues helped them to reach unexplored avenues: *"I started with a particular topic, and ended at a completely unrelated topic. It enabled me to push my creativity limits further"* .

For the usage of queries, above 80% of users agreed that queries were useful regardless of the topics. For *underwater camping*, 20% of the users who disagreed, suggested that the system should include queries that were more closely linked to the context of the central idea. Specifically, a user stated: *"Some suggestions (or queries) under certain context might not be straight forward"*.

What is interesting to note here is that while we received mixed responses in the cues and overly positive responses on queries, we also recorded higher number of user interactions with cues than queries. The likely explanation for this seeming contradiction is that it is easy to answer a cue than looking for a suggestion that fits the user's need at a given instance. Second, querying a suggestion also would mean that the user was clear in what they wanted to add. However, this clarity ultimately resulted in users directly adding the node manually. Therefore, we believe that the users tacitly inclined toward answering to the cues generated by our system.

6.7.2 QCue as a Workflow

In comparison to TMM, the performance for uses working with *QCue* was more consistent during mind-mapping — the frequency of generating new nodes was comparatively steady throughout the process. As one user stated: *"the questions helped me to create new chain of thoughts. I might not have the answer for the question (or cues) directly, but it provided new aspects to the given idea. Especially for underwater camping"*. One user with negligible experience in brainstorming, shared her excitement: *"I was fully engaged in the creation process. I was expecting questions from all different angles"*. On the other hand, we also found that *QCue* users kept generating new directions of ideas with respect to the central topic even after the initial creation phase, where TMM users tended to focus on fixed number of directions (Figure 6.6). This indicates the capability of *QCue* — problems co-evolved with the development of the idea space during the mind-mapping process.

6.8 Discussion

6.8.1 Limitations

There are three main limitations in this work. First, a majority of the recruited users had little to no experience in mind-mapping. While this allowed us to demonstrate the capability of *QCue* in guiding novices to explore problem spaces, we believe that including expert users in our future studies can help us (1) understand how differently they perform using this workflow and (2) lead to a richer discussion on how expertise can be transferred to our system toward better facilitation. Second, one of the key challenges we faced was the lack of robust methodology for determining the effect of cue-based stimulus during mind-mapping (how users may have used cues and queries without performing explicit user interface actions). While we characterize it on the basis of the usage of cues/queries, in conjunction with a detailed qualitative analysis on the mind-mapping process, there is scope for automated methods for robust statistical process analysis. Third, users frequently suggested for context-dependent cues and queries. While the use of ConceptNet provides us with the ability to create relation-oriented cues and show common-sense knowledge that is in the neighborhood, the lack of domain specificity could be an issue [168]. In this regard, there is scope for further investigation of natural language processing methods as well as new databases for doing real-time synthesis of ideas and constructing textual stimulation in specific domains.

6.8.2 Cue Representation

The rationale behind providing cues comes from being able to stimulate the user to generate and add ideas. We believe there is a richer space of representations, both textual and graphical, that can potentially enhance cognitive stimulation particularly for open-ended problems. For instance, textual stimuli can be produced through simple *unsolicited* suggestions from ConceptNet (example: "*concept?*") or advanced mechanisms based on higher level contextual interpretation (e.g. questioning based on second-order neighbors in the ConceptNet graph). From a graphical perspective, the use of visual content databases such as ShapeNet [194] and ImageNet [195] may lead to novel ways for providing stimuli to users. There are several avenues that need to be investigated in terms of colors, images, arrows, and dimension to reflect personal interest and individuality [65].

6.8.3 Reflection-in-Design for Digital Mind-Mapping

Based on the notion of reflection-in-design, we demonstrate a digital workflow that leverages a cue-query mechanism to support the cognitive processes underlying an exploratory task such as mind-mapping. Specifically, among the metrics used for quantitative assessment, the high score for the **structure** metric for the *QCue* maps indicates that our topological and temporal rules were able to assist the users to keep a balance between the breadth and the depth of idea exploration. Additionally, the good scores for the **exploratory**, **extent of coverage**, and **variety** metrics showcase *QCue*'s capability to encourage the users to contextualize different directions of a problem and develop relevant instances.

The main purpose of providing cues during mind-mapping is to see how using an almost Socratic approach can help users reason about the problem space and expand their thoughts for even atypical problems. Our statistics on the usage of cues indicate that users were highly involved in the process of inquiry and reflection. For example, around 70% of the cue nodes were either answered or deleted during mind-mapping — actions that result in the generation of new cues. The collected user feedback further complements such analysis by showing that most users felt easy to span their ideas using *QCue*, and over half of the *QCue* users found cues to be helpful in stimulating new dimensions to the central topic (Figure 6.9). Having said that, we believe this work can be pushed further by incorporating more human-centered designs as stated below:

1. When constructing mind-maps, some nodes might not be relevant or worthwhile proceeding further with for two primary reasons. First, the relevance between the nodes and the central problem might be minimal in an apparent way. Second, the user has chosen to ignore it. In these scenarios, new mechanisms are needed to facilitate communication between the user and the computer. These mechanisms could either be automated or even interactive. For

example, including semantic assessment of the content of each node (eg. distance, relevance, etc.) can help prioritize the needs of exploration. In the front-end, a potential solution would be to include interactions for the user to mark a subtree as *ignorance*. This way, the user can better control their flow of thoughts and idea expansion strategies.

2. While one of our intentions of generating cues is to keep the user engaged in the mind-mapping process, there's a possibility that the users may feel stressed if they are fully involved in externalizing their own thoughts and do not find the assistance to be necessary. One possible solution of this could be to consider an on-demand workflow — the support only comes if the user asks for it. For example, whenever a user gets stuck, he/she may press a button and ask the computer *"Hey, where should I work now?"*. Another potential workaround could be to add a *STOP* button on the interface. Whenever the user starts to feel overwhelming, they can stop the computer assistance explicitly. This can also lead to an interesting discussion on *"STOP — do they really mean it?"*.

3. The strategy of *reflective thinking* adopted in *QCue* may be similar to how teachers support mind-mapping activities among students. Therefore, another way to improve the algorithm is to see how teachers decide when and what to prompt students when they are stuck in their mind-mapping activities and establish the "teacher model". This dynamic can also be studied if we make one user as "student" and another user as "teacher" in a collaborative setup. This may, in turn, be an interesting workflow to study in collaboration dynamics.

6.9 Conclusion

Our intention in this research was to augment users' capability to discover more about a given problem during mind-mapping. For this, we introduced and investigated a new digital workflow (*QCue*) that provides cues to users based on the current state of the mind-map and also allows them to query suggestions. While our experiments demonstrated the potential of such mechanisms in stimulating idea exploration, the fundamental take-away is that such stimulation requires a balancing act between intervening the user's own line of thought with computer-generated cues and providing suggestions to the user's queries. Our work shows the impact of computer-generated textual stimuli particularly for those with little practice in brainstorming-type tasks. We believe that *QCue* is only a step toward a much richer set of research directions in the domain of intelligent cognitive assistants.

7. CONCLUSIONS AND FUTURE DIRECTIONS

This dissertation studied mind-mapping as tool for problem exploration. For this, as a first step, we conducted an experiment to substantially investigate the effects of information organization offered by mind-maps on the identification of design opportunities and needs (Chapter 3). Specifically, we compared mind-mapping with free writing to emphasize how it guides novices in organizing their thoughts and explore concepts around a given central theme in a systematic way, leading to a comprehensive exploration of both known and latent solution possibilities around the theme. We further drew from the findings and designed two human-computer collaborative workflows, namely *Mini-Map* (Chapter 5) and *QCue* (Chapter 6), to provide cognitive supports during exploratory and ideation tasks. *Mini-Map* was successful in providing meaningful contributions as an active collaborator, helping the users to think about fundamental directions using relation-dependent nodes and perform a balanced exploration on the central problem. *QCue*, on the other hand, is a more challenging system. It demonstrated an adaptive approach in finding *where should the user expand on*, and used cue-based stimulation to help users reason about the problem space and expand their thoughts for even atypical problems. While these systems and experiments demonstrated the efficacy of textual-stimulation mechanisms in promoting learning and engagement with problem exploration, there are several interesting and important open-ended questions that should be explored in future research:

1. Currently, little study is devoted to devise evaluation metrics to assess the design opportunities discovered in the initial phase of design, regardless of its influences on the subsequent design outcomes. Also, the connection between the quality of the initial ideas and the final outcomes is not clear. In our work, we proposed a new metrics to assess key elements in a typical design opportunity statement. However, deeper analysis is needed to test these metrics so that they encapsulate the underlying cognitive processes during problem exploration, opportunity identification, and concept generation.

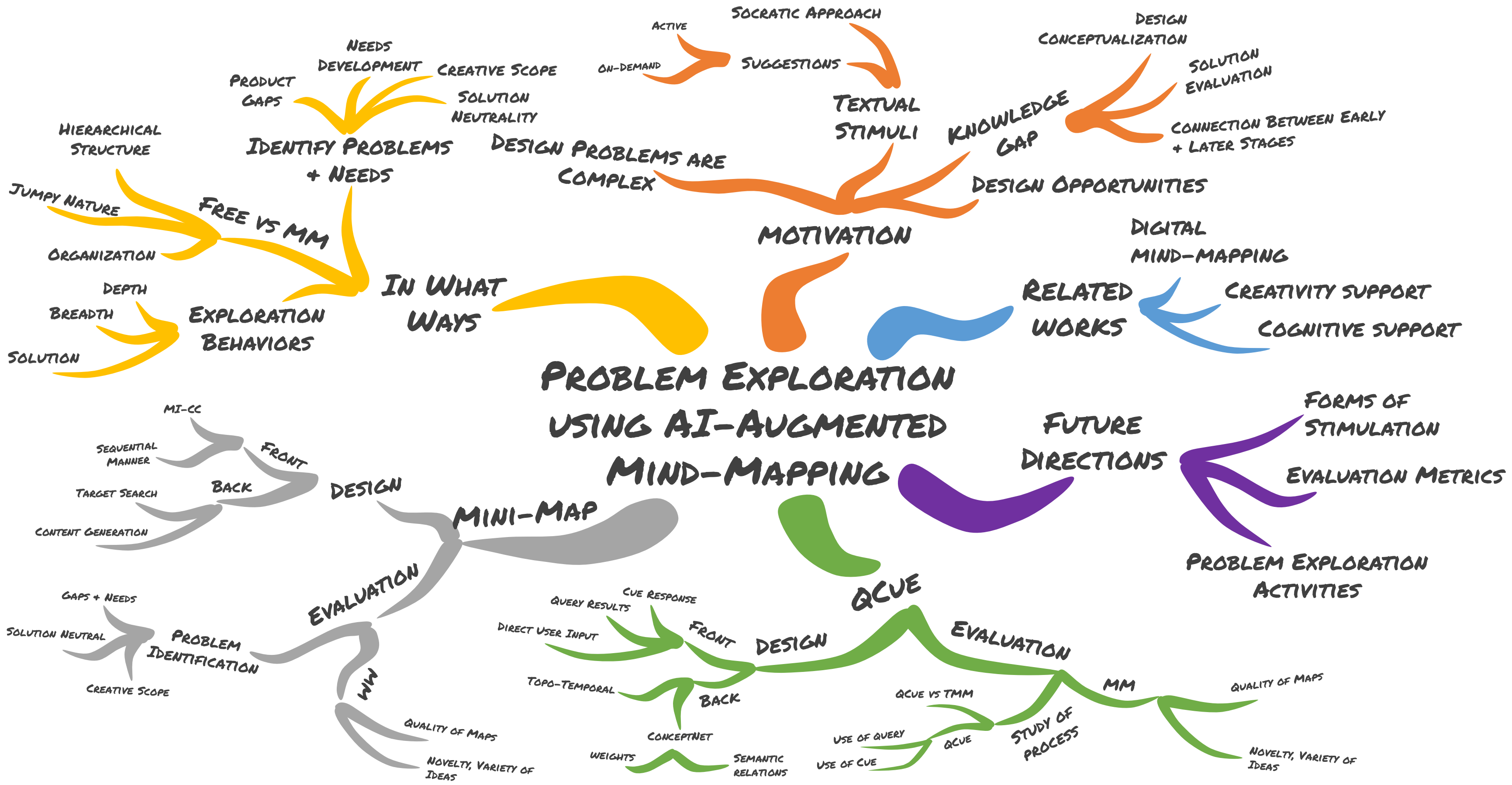


Figure 7.1: Mind-map of this dissertation.

2. While there are many studies devoted to design conceptualization and solution-space exploration, problem exploration techniques are less investigated in-depth in the community. We believe there is a vast unexplored domain for inventing, implementing, and investigating new techniques and computer-supported workflows for improving problem exploration and clarification. The hope is that doing so will ultimately enhance the quality of the resulting design outcome.

3. During early design, keeping the idea solution neutral is important for allowing consideration of different perspectives and opportunities. We noticed that the workflows we designed did not necessarily promote solution-neutrality when exploring the problem space. In fact, even experienced designers may find it difficult in developing solution neutral design statements hence require several iterations to do it properly. Therefore, it would be interesting to investigate designers' behaviors during the process of re-formulating design statements in the context of design scope framing. Also, some effort needs to be made in determining how to improve design practices such that designers can relate to solution-oriented ideas while keeping their minds open-ended in the same time.

4. Asking questions to mind-mapping users encourages them to challenge the fundamental assumptions of the central problem and develop new perspectives. However, how to ask the questions such that the users feel intriguing leading to meaningful learning needs further investigation. In the case of *QCue*, relation-dependent questions helped the users build continuous thoughts and associate concepts effectively. Future works could focus on discussing what types of relations are suitable in what user scenarios such that the users could maintain a continuous flow of thoughts throughout the process without feeling distracted.

5. Both *Mini-Map* and *QCue* demonstrate successful human-computer collaborative workflows for digital mind-mapping. Specifically, *Mini-Map* modelled computer as an active collaborator during mind-map co-creation tasks, while *QCue* positioned computer as a facilitator who provides suggestions and concrete ideas upon user query. That being said, "*what would be a*

useful persona for a collaborator during exploratory tasks?” is still an open question. Users with different personalities may need different collaborative models so that they are not inhibited by computer being either too aggressive or too passive (persona-based customization) to leverage the best out of problem exploration activities.

6. In our works, the external information (e.g. data from ConceptNet) was provided in designed forms to the users (e.g. top 10 weighted concepts, questions, etc.) while exploring the problem space. This was intentional to test the assumptions we made. To have a comprehensive understanding on how big data could affect humans’ exploratory behaviors, another interesting research direction could be the study of information search during similar mind-mapping tasks. This could, in turn, lead to discussion on searching dynamics [141], and how computer models can promote balanced user behavior when making big semantic transitions between the two modes (i.e. active suggestions and on-demand search results).

Problem exploration activities are often promoted in design literature, but limited works have been devoted to validating its benefits. This dissertation took an important step towards a richer discussion on how to make problem exploration and understanding effective. In fact, problem exploration activities could be carried out at any stage of the design process and might even be performed multiple times as the design progresses. Therefore, while our works showcase the impacts of mind-maps, and subsequently the computational models in facilitating such activities, we believe more research questions can be posed to investigate the effects of mind-maps with other techniques, and their (cumulative) effects during other stages of the design process.

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