Queries and Cues: Textual Stimuli for Reflective Thinking in Digital Mind-Mapping

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*Mind-mapping is useful for externalizing ideas and their relationships surrounding a central problem. However, balancing between the exploration of different aspects (breadth) of the problem with respect to the detailed exploration of each of its aspects (depth) can be challenging, especially for novices. The goal of this paper is to investigate the notion of "reflection-in-design" through a novel interactive digital mind-mapping workflow that we call "QCue." The idea behind this workflow is to incorporate the notion of reflective thinking through two mechanisms: (1) offering suggestions to promote depth exploration through user's queries (**Q**) and (2) asking questions (**Cue**) to promote reflection for breadth exploration. This paper is an extension of our prior work (Chen et al., 2020, "Qcue: Queries and Cues for Computer-Facilitated Mind-Mapping," Proceedings of Graphics Interface 2020, GI 2020, Canadian Human-Computer Communications Society/Société canadienne du Dialogue Human-Machine, pp. 125–136) where our focus was mainly on the algorithmic development and implementation of a cognitive support mechanism behind QCue enabled by ConceptNet (a graph-based rich ontology with "commonsense" knowledge). In this extended work, we first present a detailed summary of how QCue facilitated the breadth-depth balance in a mind-mapping task. Second, we present a comparison between QCue and conventional digital mind-mapping, i.e., without our algorithm through a between-subjects user study. Third, we present new detailed analysis on the usage of different cognitive mechanisms provided by QCue. We further consolidate our prior quantitative analysis and build a connection with our observational analysis. Finally, we discuss in detail the different cognitive mechanisms provided by QCue to stimulate reflection in design.* [DOI: 10.1115/1.4052297]

Keywords: mind-mapping, computer-supported creativity tools, conceptual design, ConceptNet, concept generation, reflection in design, design process

1 Introduction

Mind-maps are widely used for quick visual externalization of one's mental model around a central idea or problem. The underlying principle behind mind-mapping is to provide a means for associative thinking so as to foster the development of concepts that explore different aspects around a given problem (breadth), also, explore each of those aspects in a detail-oriented manner (depth) [1]. Generally, nodes in a mind-map are spread out in a hierarchical/tree-like manner [2]. These nodes may typically containing textual or pictorial descriptions of general concepts, topics and subtopics, or ideas related to the central topic of concern in the mind-map. This allows for the integration of diverse knowledge elements into a coherent pattern [3] in order to enable critical thinking and learning through the formations of synaptic connections and divergent exploration [4–7]. As a result, mind-maps are uniquely suitable for *problem understanding/exploration* prior to design conceptualization [3].

Problem exploration is critical in helping designers develop new perspectives and also drive the search for solutions within the iterative process of identifying features/needs and re-framing the scope [8]. 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 [9]. Most current efforts in computer-facilitated exploratory tasks focus exclusively on one of these aforementioned 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 often be challenging, especially for first-time users. This issue is further pronounced. For atypical and open-ended problem statements (that are commonplace in design problems), leading to creative inhibition and lack of engagement.

Effective and quick thinking are closely tied to an individual's imagination and their ability to create associations between various *information chunks* [10]. Incidentally, this is also a skill that takes time to develop and manifest in novices. We draw from existing works [11–15] that emphasize on stimulating reflection during exploration tasks. Quayle and Paterson [11] and Wetzstein and Hacker [12] indicate that the act of responding to questions can create several avenues for designers to reflect on their assumptions and expand their field of view about a given idea. On similar lines, Adler and Davis [16] found that asking questions during a sketching activity keeps the participants engaged and helps reflect on ambiguities. In fact, asking one question in turn raises a variety of other questions, thereby bringing out more thoughts from the user's mind [13]. That being said, Goldschmidt and Sever [14] demonstrated that simply exposing designers to text can lead to higher originality during idea generation. Recent studies conducted by Goucher-Lambert and Cagan [17,18] further indicate that inspirational textual stimuli with varying *semantic* and *analogical* distances from the central problem space activate different regions of the human brain, hence improve the fluency of idea generation during design problem-solving.

Informed by the notion of *reflection-in-design* [11,12], our approach is based on the premise that cognitive processes

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underlying mind-mapping can be enriched by enabling an iterative cycle between exploration, inquiry, and reflection. We apply this reasoning in a digital setting where the user has access to vast knowledge databases. 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 digital 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*).

This paper presents a comprehensive extended account of our previously published work *QCue* [19]—a digital mind-mapping workflow leveraging a novel question-query mechanism to stimulate users' thinking and enhance engagement toward exploring different aspects of a central problem. *QCue* strives to position computers as facilitators to support the underlying cognitive processes during exploratory tasks. In this work, we systematically study how our proposed workflow affects user behavior, also, how different kinds of textual stimulation plays a key role during digital mind-mapping.

1.1 Contributions and Extended Works. In our prior work, we showcase a cue-query based strategy (*QCue*) for computer-facilitated mind-mapping. We collect data through a between-subject study with 24 participants and conduct quantitative analysis to compare how they responded to *QCue* in contrast to individual mind-mapping (referred to as TMM in this paper). In this extended work, we consolidate and systematically describe *QCue* workflow and algorithm. Further, we conduct a comprehensive analysis to demonstrate the efficacy of our approach and discuss new directions for future digital mind-mapping tools. Specifically, the main contributions beyond the prior work are as follows:

(1) We significantly expand on the literature survey on computer-supported mind-mapping, textual stimulation in design, and strengthening our methodology (Sec. 2)
(2) We consolidate our prior quantitative analysis by strengthening our assessment of the mind-maps (Sec. 5) and further complement it with a qualitative observational analysis of the mind-mapping process (Sec. 6). This new qualitative analysis highlights user behavior during different phases of digital mind-mapping with and without *QCue*.
(3) We present a new detailed analysis on the usage of different *QCue* mechanisms (cues and queries) and share insights on how it affects the participants' exploration strategies (Sec. 7).
(4) We summarize our discussion on how the qualitative observation relates to the expert ratings and conclude by highlighting how the *exploration-inquiry-reflection* cycle in a digital mind-mapping setup can be further improved using human-centered approaches (Sec. 9.3).

2 Related Works

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 [20]. Hmelo-Silver [21] underscores 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 [22–24]. There are other popular techniques such as SCAMPER [25], C-Sketch [26], and morphological matrix [27], which 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 [28,29]. The structure of mind-maps thus facilitates a wide-range of activities ranging from note-taking to information integration [30] by highlighting the relationships between various concepts and the organization of topic-oriented flow of thoughts [31,32]. In design ideation, studies have also shown that there are positive correlations between the total quantity of generated nodes and the depth of nodes versus idea uniqueness in a mind-map [33].

2.2 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. [34] 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 (e.g., design keywords, semantic relations, randomness level) 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. [35] 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 [36] 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 and Sever [14] 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 Ref. [37]. For example, Sun et al. [38] 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. [39] demonstrated the idea of design-by-analogy using *WordTree* and showed its power on design problem re-representation. Further, He et al. [40] 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.

2.3 Computer-Based Cognitive Support Workflows. 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 [34,41,42], heuristic-based feedback generation [43], text-mining [44–47], and speech-based interfaces [48–50]. Few works [51,52] 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 [53–56].

Recently, human-computer hybrid platforms further draw design researchers' attention to study how humans and intelligent computational agents can interact, inspire, and impact each other throughout the design cycle [57]. However, most of these works are targeted toward highly technical and domain-specific contexts and are limited in tackling with more open-ended exploratory tasks using interactive and conversational workflows.

While there are works [58–60] 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 [61,62] 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, and nature of collaboration. As a case in point, works by Kerne's group on curation [63–65] and web-semantics [66,67] 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. Similarly, works from Luo's group on data-driven design [46,47,68,69] share our intention of using knowledge bases to inspire human ideation. They demonstrated advanced expert systems that collect and map multi-level inspirational stimuli based on analogical, semantic, and knowledge distance to stimulate the generation of new ideas during design ideation. These works focus primarily on network-based information navigation and retrieval that could be highly useful for facilitating creative design ideation. As a complement to these works, our work seeks to investigate algorithmic mechanisms for providing cognitive support for stimulating associative thinking ability that is especially important for mind-mapping.

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. [70] 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. [71] study mind-mapping for problem exploration in design from the point of collaboration. Their work puts forth some key findings (e.g., idea expansion strategies, team dynamics) and insight on how mind-maps evolve in collaborative design tasks. Following on the same, they propose a *computer as a partner approach* [52], 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. [72] 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 specifically on the associative thinking capability, brought forth by questions formed out of semantic relations with the ideas being explored.

2.4 Digital Mind-Mapping. Several digital tools [73] have been proposed to facilitate mind-mapping activities. However, to the best of our knowledge, these tools provide little computer-supported cognitive assistance for idea generation during thinking and learning (such as brainstorming) processes. The primary focus of these tools is to make mind-map construction easier by providing features such as quickly expanding the conceptual domain through web-search, link concepts to online resources via URLs (uniform resource locators), and interactive map construction. While these digital tools have demonstrated advantages over traditional mind-mapping tasks [62], mind-map creators can still find it challenging due to several reasons: inability to recall concepts related to a given problem, inherent ambiguity in the central problem, and difficulty in building relationships between different concepts [74,75]. These difficulties often result in an unbalanced idea exploration further resulting in mind-maps that are either too broad or too detail-oriented. Our aim in this paper is to investigate computational mechanisms that address the issue of breadth-depth balance through *reflection in design*.

3 QCue: Overview and Algorithm

Our overarching goal in *QCue* is to understand how cognitive support in a textual form (word, phrase, question, etc.) facilitates associative reflection during mind-mapping. As such, mind-maps are inherently multi-modal—they may involve words, phrases, images, and sketches. Each of these modes potentially affects design cognition in different ways thereby making is intractable to support and study the process systematically. Furthermore, the representation of data for each modality is significantly different (for instance, sketch data can be very difficult to parse and segment in comparison to words and phrases). We therefore constrained *QCue* to be a text-based mind-mapping workflow. This helped us study textual stimulation in a controlled systematic manner and also helped maintain consistency in terms of recording and analyzing data consistently across users. Throughout this paper, we use the following terms to denote different elements of a mind-map:

(1) *Node*: This is a basic unit of information without reference to the content it contains.
(2) *Central Topic*: This is the content carried by the central (root) node of the mind-map.
(3) *Concept*: This refers to general or abstract notions that may describe the aspects, features, needs/requirements of the design problem underlying the central topic.
(4) *Idea*: This refers to concrete notions that may be instances, functional elements, or inspirations that may lead to formulating and/or potentially addressing the design problem underlying the central topic.

3.1 QCue Workflow Overview. 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. To this end, the design of our workflow is based on the following guiding principles:

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

The algorithm of generating computer support in *QCue* (i.e., cues and suggestions) was developed based on the evolution of the structure of the user-generated map over time to balance the breadth and depth of exploration. Specifically, the cues were automatically generated based on the temporal and topological evolution of the current mind-map, and the suggestions were offered to the users based on on-demand query using explicit user interactions. Here, the suggestions were retrieved from ConceptNet linked concepts with respect to the queried node's content. The *QCue* interface was designed such that it allows for simple yet fast interactions for idea expansion using the aforementioned computer support (please see Supplementary Materials on the ASME digital collection for a detailed explanation on the design of the *QCue* interface and user interactions). In the following subsections, we will discuss the automatic cue generation algorithm in detail.

a Choice of knowledge-graph. In principle, our algorithms for generating cues and queries require a knowledge-graph that contains (1) the type of semantic relationship between two connected nodes and (2) the weight of the relationship between two connected nodes. As such, any database with these two features can be plugged into our proposed algorithm. In this work, we chose ConceptNet as our knowledge-graph since it is currently the only comprehensive dataset that caters to our requirement. We further note that ConceptNet is also a commonsense semantic network rather than a technology-driven dataset that might be suitable for domain-specific design conceptualization [76]. Our goal in this work is not focused toward solution conceptualization but rather on supporting associative thinking and reflective exploration specifically for novices and to enable them to maintain a breadth-depth balance in mind-mapping. In this regard, a commonsense network such as ConceptNet may help our target users make associations and explore a wider range of topics related to a central problem. That being said, there are emerging efforts in the community in constructing large-scale relational engineering knowledge graph using US Patent Database for a wide range of engineering design applications [77,78]. These discussions are in line with our discussions on future directions.

3.2 QCue Algorithm: Cue Formulation. Given the current state of a mind-maps, there are three aspects that we considered during the design of our cue-generation mechanism. We faced the challenge of determining (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) *what* to ask the user (in terms of the actual content of cue). We designed our cue-generation algorithm to utilize the topological and temporal evolution of a given mind-map in order to determine the potential nodes (the target) where we want the user to explore further. For this, we use two penalty terms based on (a) the time elapsed since a node was added to the mind-map and (b) its relative topological position (or lineage) concerning the central problem.

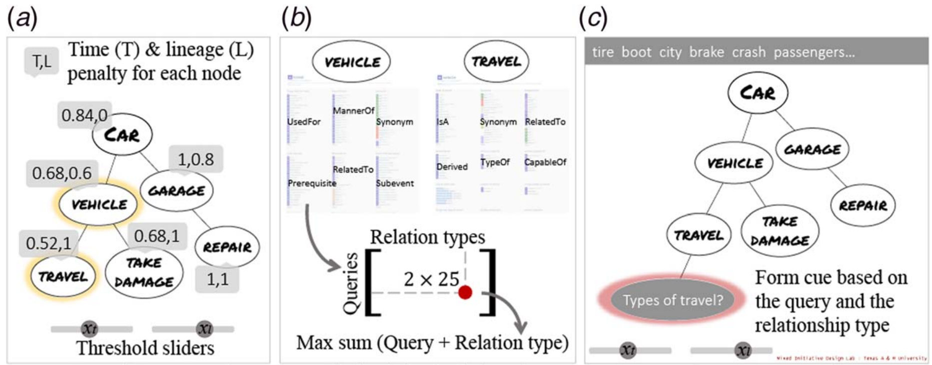
Tesnière [80] note that *continuous thoughts can only be expressed with built connections*. This is our driving guideline for composing cue-based content. Specifically, we observe that the fundamental issue faced by users is not the inability to create individual concepts, but the difficulty in contextualizing broad categories or topics that link specific concepts. Here, we draw inspiration from works that identify semantic relations/connections between concepts to build human-like computer systems [81] and perform design synthesis [82]. 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 formulating contextual cues 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. 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.

3.2.1 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 2 s. The value of c was determined experimentally (Sec. 3.3). 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 nodes 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 $T(n_i) \rightarrow \max\ (T(n_i) - c,\ 0)$.

3.2.2 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 the addition of every child 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 ($L(n_i) = 1 - (x_i/\max\ (x_i))$). 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*. Note that we give equal importance to all nodes at a given depth of the mind-map. The goal is to determine *where* to generate a cue based on the evolving topology of the maps.

3.2.3 Cue Generation Using ConceptNet. Given any state of a mind-map, there are three primary algorithmic steps for generating cues in the form of questions using the 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-mapping.

(1) *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 $N_E \leftarrow N_E \cup \{n_i\}$ (Fig. 1(*a*)). If no node is within the thresholds, all nodes in the current mind-map are considered as potential nodes.
(2) *Content determination:* We further query the spotted nodes (N_E) from ConceptNet. A list of query results containing weighted relations is retrieved for each potential node (Fig. 1(*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 (Fig. 1(*b*)). Note that if a subdivision has been used to generate a cue node, it will be removed from future selection pool. For example, *TypeOf* cannot be selected again for generating a cue node for *travel* (Fig. 1(*c*)).
(3) *Cue generation:* Using the selected subdivision from *content determination*, *QCue* formulates a new cue based on fixed templates (Fig. 1(*c*)). To avoid repetition of cues generated during mind-map creation, we specifically construct at least two to 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 a knife do?"*, *"What is the knife capable of doing?"* and *"Which task is the knife capable of performing?"*. All the templates we constructed can be



Scout ($T < x_t$, $L < x_l$) Find weighted relations from ConceptNet & categorize them Generate a cue node. Shown in the full UI of QCue

Fig. 1 Illustration of the cue generation algorithm using retrieved weighted relations through ConceptNet Open Data API [79]. The two highlighted nodes in (*a*) (Travel and Vehicle) represent computer selected potential node; the highlighted question node in (c) represent computer generated cue. This algorithm is executed at regular intervals of 2 s. The user interface of QCue is illustrated in (c). (*a*) Scout ($T < x_t$, $L < X_l$), (*b*) find weighted relations from ConceptNet and categorize them, and (c) generate a cue node, shown in the full UI of QCue

found in the Supplementary Materials on the ASME Digital Collection.

3.3 Implementation. Our *QCue* interface is a Javascript web application that runs entirely on the browser using NodeJS and D3JS. We incorporated the JSON-LD API (Linked Data structure) offered by ConceptNet to our interface (refer to the Supplementary Materials on the ASME Digital Collection for a detailed explanation of the interface).

a 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 (Sec. 4.1) to observe how people mind-map in a regular setting (TMM) and how people get acquainted with *QCue*. The final assignments are as follows: c = 0.08, x_t and $x_l = 0.6$ when $t = 0$. These values were tuned iteratively with two main intentions in mind. First of all, we wanted the two penalties to have equal importance at the start of mind-mapping. This is because the threshold values are the direct indicators of locations of cues generated by *QCue*. For example, a large x_l results in cues generated toward leaf nodes, hence encourages depth-first exploration (Sec. 3.2.2). Second, to study the effects of providing questions during mind-mapping, we wanted the cue generation algorithm to be triggered if the user is inactive for a long time, which can be calculated by the Time Penalty (x_t). Usually, this indicates that the user might be out of ideas, and *QCue* can start to play a role in guiding and stimulating. During the study, the user is also allowed to adjust the threshold values based on their preference to shape the exploratory directions guided by the cues (Fig. 1(*a*)). In sum, the choices of the penalty and threshold values are subjective to serve our research purposes in this paper. Different approaches on tuning these values are further discussed to inspire future works on the behavior of intelligent assistant for digital mind-mapping (Sec. 9).

4 Evaluation Methodology

We systematically designed our study based on observations made during the pilot study and came up with an evaluation approach as discussed in the following sections.

4.1 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) identify ideas and problem statements that could serve as our evaluation tasks, and (3) determine appropriate initial parameters (such as lineage and time thresholds). 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 concept, cause, effect and potential solutions of the given problem statement.

Participants were both surprised as well as interested in the latter two topics. Specifically for atypical topics, they indicated a need for additional time to prepare themselves before beginning the mind-mapping task. For the former two topics, they showed immediate inclination towards getting started with the mind-mapping session. Since we wanted to test the robustness of our algorithm with respect to a given topic, we decided to conduct the study with two topics of opposite extremes. Namely, *pollution* (**T1**)—a seemingly familiar topic and *underwater camping* (**T2**)—a more open-ended topic that is uncommon to think about. The participants were encouraged to explore the space of the given central topic as fulfill as possible. Specifically, the problem statements are described as follows:

- T1 *Pollution*: Create a mind-map to explore the concepts around the topic *pollution*. For example, the participants can explore the types, causes, effects, and challenges. They can also explore the current technological progress which helps to alleviate such phenomena, or potential solutions.
- T2 *Underwater Camping*: Create a mind-map to explore the concepts around the topic *underwater camping*. The participants can explore the characteristics, needs, potential challenges, or impacts if underwater camping becomes pervasive in daily life. Also, they can think about the current technological progress which helps enabling such activity, or potential solutions.

4.2 Participants. We recruited 24 undergraduate and graduate students from the engineering, architecture, and social sciences majors. The typical participant age group was between 19 and 30 years. Six participants had introductory experience with mind-maps. For those with no prior mind-mapping experience, we prepared a short presentation discussing the general spirit and principles of the technique and provided them with an additional 5 to 10 min to practice before the actual study. We conducted a between-subjects study to minimize learning effects across the two conditions, where 12 participants created mind-maps for a given topic using TMM, and other 12 using *QCue*.

4.3 Participant 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 min and the order of 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 the mind-mapping task, we recorded a video of the task, the completion time, and the time-stamped nodes generated by the users for each mind-map. Each participant performed the following tasks:

(1) *Practice*: In order to help participants familiarize with the study interface, they were given a brief demonstration of the software and its function. They were allowed to practice the interface for 5 to 10 min, with guidance from the study investigator when required.
(2) *Mind-mapping with **T1** & **T2***: Participants were asked to create mind-maps using the assigned interface. The duration of each mind-mapping session was 10 min for a given central topic. They were also encouraged to explore each central topic to their best potential. The workspace was cleared after completion of each mind-map.
(3) *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.

4.4 Qualitative Analysis on the Process. In order to understand the mind-mapping process performed by the users, we carefully and systematically studied the video recordings collected from the user studies ($N = 48$). We analyzed the videos with our primary emphasis on key process factors such as adding a node, user apprehension in adding a node, breadth versus 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 [72,83]. 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 in Sec. 6.

4.5 Quantitative Metrics. Mind-maps recorded during the study were de-identified before evaluation. Our primary goal was to evaluate the structure of the mind-maps generated, the variety of ideas and topics covered by the user around the central problem, and, to some extent, the novelty of ideas for a given user with respect to other users. Specifically, our goal was ***not*** to position *QCue* (and mind-mapping in general) as a tool in competition with other design conceptualization tools and methods. Therefore, instead of directly using typical creativity support metrics [84,85], we adapted the mind-map assessment rubric [52,86,71]. Based on this, the raters evaluated the mind-maps based on the four major criteria each has a scale of 1–4: *structure, exploratory, communication and extent of coverage*. *Structure* measures whether the given mind-map is well-explored in both breadth and depth. The *exploratory* score is measured based on the flow of concepts from the center to the periphery. The *communication* score of each mind-map evaluates whether appropriate keywords were used to help better convey the intent of the mind-map, and the *extent of coverage* score is a measure of effort made by the participant to connect primary concepts together in the given mind-map.

In addition to the mind-map assessment rubric, we also customized three of the well-known design conceptualization metrics, namely, *quantity, novelty, and variety* [84,85] as a supplement to the range of topics and extent of coverage. The *quantity* metric is the total number of nodes in a given mind-map. The *variety* of a mind-map is measured by the number of concept categories that raters find in the mind-map, and the *novelty* score of a mind-map is measured by the average *novelty* scores of all nodes in the given map [71]. Here, each node has its *novelty* score from 0 to 1, and the calculation is based on the frequency of similar nodes in the entire set of the generated mind-maps.

5 Results: Ratings for User-Generated Mind-Maps

5.1 Rater Agreement. In our study, three raters independently performed subjective ratings of every concept for each mind-map. After the independent evaluations by the three raters, they met virtually to discuss and come to a consensus on their ratings. 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. The raters evaluated each mind-map based on the aforementioned metrics (Sec. 4.5). For the structure, exploratory, communication, and extent of coverage metrics, the Fleiss's kappa value was found to be between 0.79 and 0.85 showing a substantial inter-rater agreement [87,88]. For variety and novelty (scalar), the Pearson's correlation coefficient was found to be close to 0.8 indicating a high correlation of agreement between raters [89].

5.2 Rating Results. To draw conclusion from the rating results (see Supplementary Materials on the ASME Digital Collection for example mind-maps with ratings; Table 1), 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

Table 1 Table of average ratings for each metric by four user conditions: TMM, QCue with T1 and T2

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

Note: On a scale of 1 to 4, higher score means the map performs better for that criteria.

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, especially for the topic *pollution* where mean structure value increases to 3.11 from 2.11. These observations indicate that the cue-query mechanism potentially encouraged the users to (1) make connections across a variety of concepts of the given topics and (2) keep the structure of the mind-map in a balanced manner by exploring in both breadth and depth directions throughout the creation process.

6 Results: Assessment of the Process

The analysis was carried out manually by studying (1) the JSON file that contains the metadata of nodes and links for each mind-map (Sec. 3.3) and (2) the videos of the screen recordings for each mind-map created during the study. We mainly used the exported JSON data to study the progression of a mind-map and noted down observations by going through the video. In the following, we explain the overall observation across all users and expose some specific examples of interest.

6.1 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, users were relatively consistent in performing breadth-first exploration while maintaining the overall structure (Table 1, **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 concepts where users were familiar with the central topic. For topics such as *pollution*, users were able to externalize ideas/concepts 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 toward the end of the study task, specifically for users in the TMM approach (Fig. 2(*a*)). On the contrary for *underwater camping*, users were found to be hesitant in generating ideas/concepts 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 min, Fig. 2(*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.

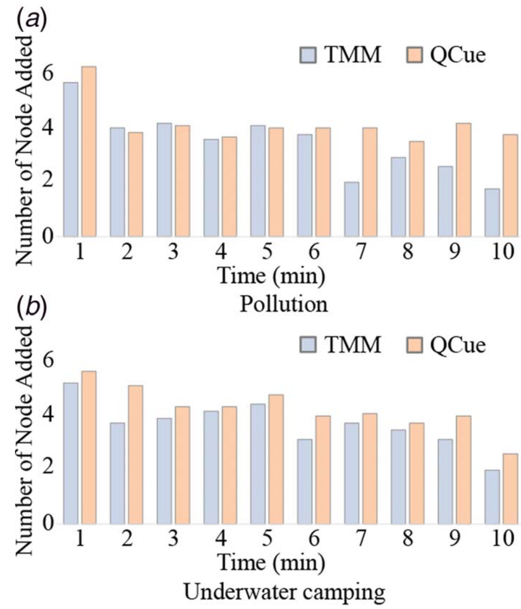


Fig. 2 General trends on how users generating concepts toward different topics (T1 and T2) during TMM and QCue. Each bar represents an average count of the total nodes in the given time frame (per 1 min): (*a*) pollution and (*b*) underwater camping.

6.2 Direction of Exploration. In the following discussion, we focus on the different trends of idea exploration, and how users usually began their mind-mapping processes by adding different types of nodes. To this end, we discuss how such exploration behavior 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 remainder of their time in expanding on each type of pollution and solution-oriented concepts (e.g., regulations, ways to reduce it). 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 concepts on *pollution* than their counterparts. This type of exploratory approach was mainly observed in the *QCue* workflow (Table 1, **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. (for complete mind-map see Supplementary Materials on the ASME Digital Collection). Few users also added nodes directly on the central node that alluded to various pros and cons of underwater camping (e.g., *Research on marine life, scuba diving, lack of sunlight, no fresh air*). In fact, the exploration strategies were more direction-oriented in *underwater camping* as compared with *pollution*, in the sense that the users mostly followed a depth-first exploration. Interestingly, one user who was working in *QCue*, spent 3 min exploring what a typical camping actually is (by adding a separate node *Typical camping* to the central topic) and shifted focus onto the *challenges, logistics and possibilities* of underwater camping in following minutes.

6.3 Idea Expansion Strategies: QCue Versus Individual Mind-Mapping (TMM). Generally, the users started building on their initial thoughts 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 concepts 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, some 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*) 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 (Table 1, **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 concepts or ideas around the central topic comprehensively (Table 1, **communication** T2: TMM-2.06, *QCue*-2.64; **extent of coverage** T2: TMM-2.25, *QCue*-2.44).

6.4 Stages of Idea Exploration: QCue Versus Individual Mind-Mapping (TMM). Our systematic analysis of the mind-mapping process helped us identify and categorize key stages as observed across all mind-map user activities as described later.

6.4.1 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 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 topic 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 adding nodes initially. We observed that most users were either hovering around the central topic or took a significant amount of time (> 15 s) to add their first node to the central topic. 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 assisted them in thinking along various directions and broaden their understanding of the central topic. For example, one user answered *entertainment* to the cue, *"What purpose is camping used for?"*, in relation to the central topic. This encouraged the users to think in a new direction, thereby, re-scoping the user's thoughts on the topic that is atypical.

6.4.2 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 s) while hovering around the mind-map interface, also, the time during which the user typed something in the dialogue box and erased it or modified it to a new concept. These key findings on user behavior helped us highlight the differences between *QCue* and TMM workflows.

Unexpectedly, in general, we found these brief moments of pause often in TMM as compared to the *QCue* approach. TMM users were observed to be 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*, potentially due to the fact that *underwater camping* is a topic that people usually do not think about or know of. During the study, *QCue* users were found to be relatively more confident and focused on contextualizing the problem and organizing their thoughts, potentially with an understanding that they could utilize cues and queries for inspiration and idea expansion. This reveals how *QCue* kept the users engaged in a continuous thought process over TMM (that relies truly on the user cognitive abilities). Such engagement could be important in creative processes [90]. More detailed analysis on how cues and queries guide the users during mind-mapping is provided in the following section (Sec. 7).

6.4.3 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 s indicating that the user might have ran out of ideas during the process. We found this happen often during later stages of mind-mapping, and more frequently 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 s. 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 was 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 (Fig. 2).

7 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*.

7.1 Query as a Stimulant. The fundamental approach behind queries is to maintain the rate of node addition during mind-mapping. This mechanism is always triggered by the user when they need any form of inspiration to further explore a given concept or idea. Most users shared their feedback saying that these *suggestions* played a positive role in exploring fine-grained concepts 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, it is possible that the user may get inspired and add other relevant ideas or concepts 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.

7.1.1 Direct Stimulation. Queries were often used by the users to explore a specific aspect of the central topic in further detail (or depth). For example, at around the 8.30 min 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 (Fig. 3) of the mind-mapping process. For instance, one user working on

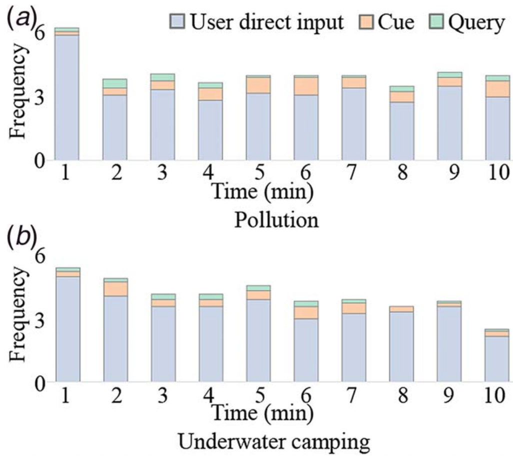


Fig. 3 Comparison of trends on how QCue users adding nodes towards T1 and T2 using the three modes (user direct input, cue node response and query) stacked one above the other. The frequencies are averaged across the 12 users: (*a*) pollution and (*b*) underwater camping.

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

7.1.2 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.

7.2 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 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 (Fig. 4). 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 detailed in the following subsections.

7.2.1 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 remaining duration. Another user extensively used cue nodes throughout the process; and added several interesting concepts 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?"*. We noticed that while the same amount of cue nodes were directly answered with respect to the two central topics, they were used in

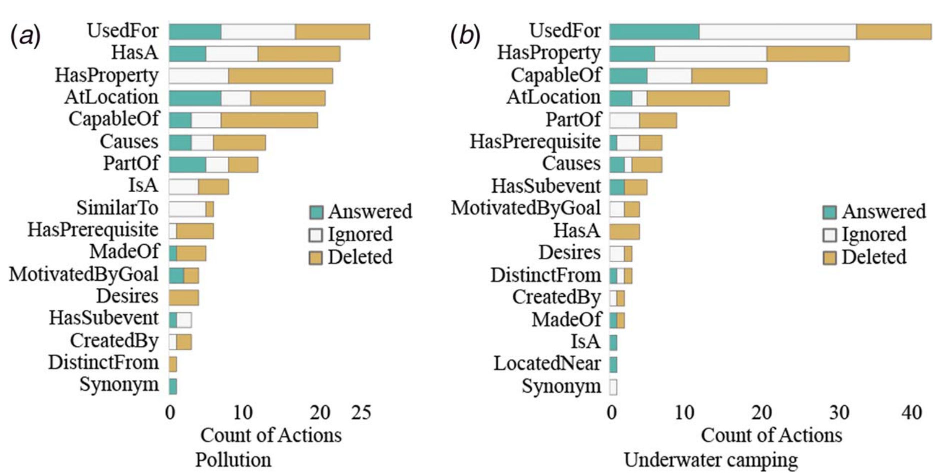


Fig. 4 Counts of types of actions the users performed to the types of cue nodes generated by QCue with pollution (T1) and underwater camping (T2). This is across all users: (*a*) pollution and (*b*) underwater camping.

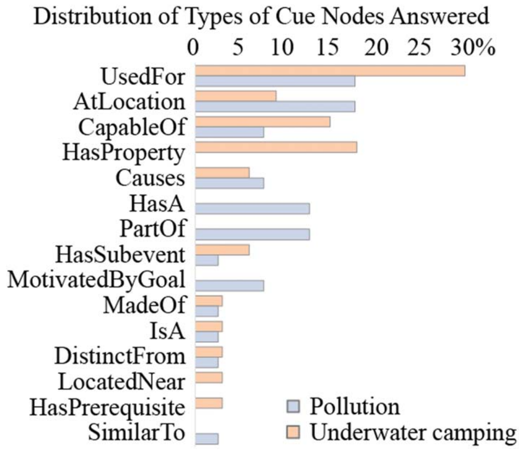


Fig. 5 Distribution of types of cues answered with respect to underwater camping (T2) and pollution (T1). This is across all users.

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 relatively helpful in the beginning and later phases where the users were trying to (1) understand the problem 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. These cues helped users in questioning fundamental aspects for *underwater camping* (Fig. 4). 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%), and *PartOf* (13%) (Fig. 5). On one hand, this suggests the two important usages of cues: (1) even though *QCue* offers query results for quick node addition, cues still help mind-map creators in exploring fine-grained concepts and (2) cues can be helpful in guiding 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. On the other hand, the distribution also tells us that some ConceptNet knowledge that are in the context of existing concepts in the mind-map (and potentially with high edge weights) can be difficult to relate by the users using the corresponding relationship types. For example, a number of cues were generated based on *HasProperty* in the *pollution* map but none of it was answered (Fig. 5). The use cases of *deletion* and *ignorance* of cue nodes are revealed in the following subsections.

7.2.2 No Action. Interestingly, we found that sometimes users looked up at a cue node originating at one part of the mind-map structure and got inspired to add nodes 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. Another user 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 nodes, kept the cue nodes in the mind-map for potentially future reference, and further expanded on other branches. We also noticed that such behaviors happened more frequently with *underwater camping* (overall Ignorance: T1-29%, T2-37%, Fig. 4). 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.

7.2.3 Deleted the Cue Node. The users deleted existing cue nodes for two primary reasons. First, because they did not find the cues to be helpful to the existing context. For example, related to the concept *air*, the cue *"What properties are associated with air?"* was frequently popped up by *QCue* but deleted by the user for considering not relevant to the central topic *pollution*. 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 given instant of time to be five 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.

8 User Feedback

To help us evaluate the effectiveness of our algorithm, the participants filled out a questionnaire after creation of each mind-map (Fig. 6). We also encouraged the participants to give open-ended feedback to support their rating.

8.1 Cue Versus 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 concepts in the mind-map, used the cues and queries extensively to build and visualize new dimensions to the central topic. 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 topic. Specifically, a user stated: "Some suggestions (or queries) under certain context might not be straight forward." In this regard, finding the balance between suggestions/inspirations that are near to and far from the context of the central concept is important to not only cater to user perception but also encourage the creation of non-obvious connections across seemingly unrelated concepts for the *Aha!* moment in design [10,18,68].

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.

8.2 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. This indicates the capability of *QCue*—problems co-evolved with the development of the idea space during the mind-mapping process.

9 Discussion

9.1 Limitations. There are three main limitations in this work. First, a majority of the participants had little to no experience in mind-mapping. While this allowed for 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 developing automated methods for a robust statistical analysis of the mind-mapping process. 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 [91]. To this end, there is scope for further investigation of natural language processing methods and new relational databases (Sec. 3) for doing real-time synthesis of ideas and constructing textual stimuli in specific domains.

9.2 Cue and Query Formulation. One of the key challenges we faced in our implementation was formulating grammatically and semantically effective questions for cue generation. To overcome this, we utilized a fixed-template approach to formulate the cues. However, there is scope for further investigation on natural language processing (NLP) methods as well as new relational databases to improve the flexibility and adaptivity to the cues. Moreover, users frequently suggested for context-dependent queries. For problems such as *underwater camping*, this is a challenging task that may need further technological advancements in artificial intelligence approaches for generating suggestions and cues based on real-time synthesis of ideas from the information retrieved from a knowledge database. We did preliminary exploration in this direction using a Markov chain-based question generation method [92]. However, the cues generated were not well-phrased indicating further studies into other generative language models [93]. In line with the formulation of semantically effective cues, incorporating textual stimuli with varying analogical, semantic, and knowledge distances [68,69,94] from the central problem domain could further inspire ideas of higher novelty and quality. Deeper research is required to integrate the three components—context-dependent cues, varying distances, and grammatically effective sentence formulation—for further enhancing user performance on ideation.

9.3 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 using provided cues and queries.

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

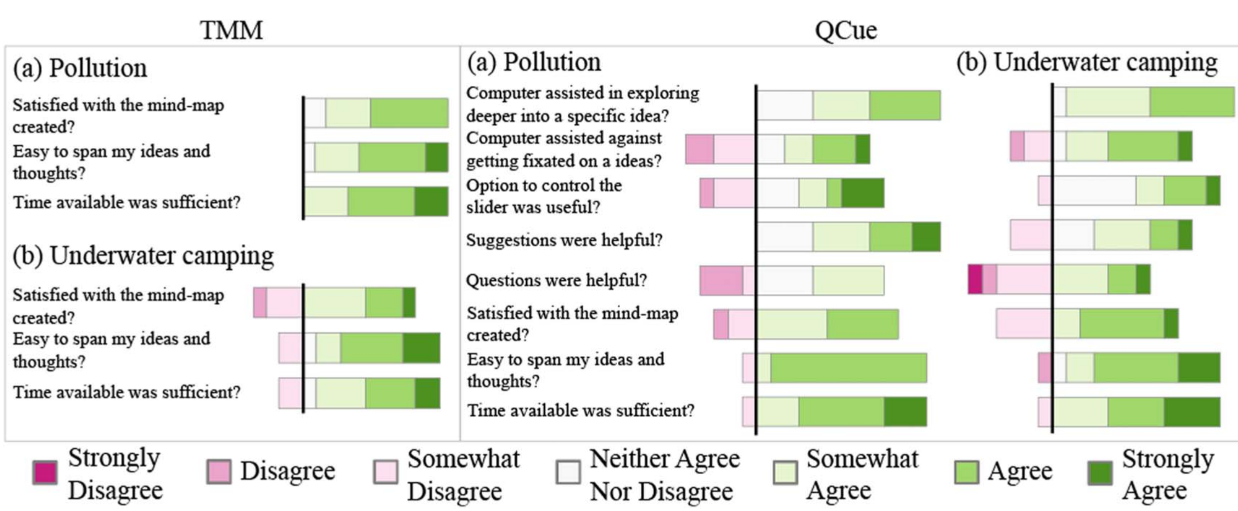


Fig. 6 7-Point Likert scale user feedback for TMM and QCue. Bars at the right-hand side of the central line indicate positive responses, while those on the left-hand side indicate negative responses.

new cues. The collected user feedback further complements this finding by showing that most users felt easy to span their thoughts using *QCue*, and over half of the *QCue* users found cues to be helpful in stimulating new dimensions to the central topic (Fig. 6). Having said that, we believe there is significant scope for improvement 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. For example, including semantic assessment of the content of each node (e.g., distance and relevance) 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 sub-tree as *ignorance*. This way, the user can better control their flow of thoughts and idea expansion strategies.

(2) While we intended for the cues to improve user engagement, there were cases when sudden appearance of a cue could disturb the user's train of thought. 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, a user may explicitly ask the computer tool to suggest locations where the mind-map may need expansion. Alternately, providing the ability to pause cue generation to the user could be useful as well. Alternately, the system may wait before generating cues until the user has had sufficient time to express their own thoughts. More research is needed to better understand when to start cue generation based on user's level of expertise.

(3) Continuing on the previous point, the time and location of cues are largely dependent on the threshold values we assigned in *QCue* (Sec. 3.3). While this helps us build an initial foundation on question generation during mind-mapping, new mechanisms can be included in the future to make the choice of parameters more flexible and customizable based on different user personalities. For example, an automatic parameter tuning step can be ran before the user uses *QCue*. Further research is required to map different threshold values with respect to different user personalities so as to build an adaptive threshold mechanism.

(4) 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.

10 Conclusion

Our broader goal in this research was to explore how text-based stimulation helps novices in associative and reflective thinking during mind-mapping. For this, we introduced and investigated a new digital workflow (*QCue*) that automatically offers cues to users in the form of questions based on the current state of the mind-map and also allows them to request for suggestions through explicit query. Our experiments revealed three behavioral properties of the cue-query mechanism. First, showing cues based on the topological and temporal evolution of the mind-map can have both positive (helping them expand the scope of exploration) as well as negative (diverting user's focus) effects on the user. Therefore, attention should be given toward adaptive methods for producing automatic cues. Second, even when users did not use cues explicitly (by answering them), we found that the cues promote reflection toward other directions of thought in the mind-map. Lastly, cues are also useful in helping users frame better queries for expanding the mind-map. Having said this, our work highlights a broader need for developing a blend of common-sense databases (e.g., WordNet and ConceptNet) with domain-specific knowledge bases [77,78] that allow a wide range of cues and queries at varying levels of technological specificity for a wider range of users on the novice-to-expert spectrum.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

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