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COLLABORATIVE MIND-MAPPING: A STUDY OF PATTERNS, STRATEGIES, AND EVOLUTION OF MAPS CREATED BY PEER-PAIRS

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ABSTRACT

We present a study on collaborative mind-mapping to understand how peers collaborate in pairs to create mind-maps, how the maps evolve over time, and how collaboration changes between the peer-pair across multiple maps. Mind-mapping is an important tool that is studied and taught in design practice and research respectively. While widely used as a brainstorming technique, the collaborative aspects of mind-mapping are little understood in comparison to other ideation methods such as concept sketching etc. In addition to presenting creativity ratings on the outcome (i.e. the mind-map), we extensively report on the patterns of collaborative exploration, strategies that emerge from the collaborators, inhibition, and the overall process of map creation. We discuss the implications of these observations on the development of computer-support for mind-mapping.

1 Introduction

Mind-mapping is a popular tool that is used and taught in early design ideation [1, 2]. It allows for externalization of ideas as a structured network comprised of textual and visual representations of concepts emanating from a central problem, and radiating outward as branches holding relevant information. While design research has often used mind-maps for concept generation (e.g. actionable ideas at the periphery of the map), the main value of mind-mapping comes from being able to "*have a visual overview of a problem at hand that shows the relationship between a central theme and its ramification of important factors or ideas*" [3]. This is because it allows an unconstrained exploration of a variety of ideas [4] before solving a problem. This paper presents a study of collaborative mind-mapping in pairs with an emphasis on the process through which the map evolves during the ideation process. In keeping with the original spirit of mind-mapping, we focus mainly on the *problem exploration* ability afforded by mind-mapping in early design instead of *solution finding* or concept generation. There are two main motivating observations that led to this work.

The first inspiration for this study stems from our recent work [5] wherein we constructed and studied algorithms for enabling human-AI (artificial intelligence) collaboration in a mind-mapping process. The key challenge we faced was in modeling a free-form exploration process by the AI due to which we constrained the mind-mapping interaction to be sequential addition of nodes to the map similar to a game-like scenario (given a pair of designers, each designer adds exactly one node at a time). However, past works [6] have discussed group satisfaction, interest, involvement, and intellectual arousal in a collaborative scenario that allows for group members to freely externalize their thoughts non-sequentially. The purpose of this current paper, therefore, is to go beyond the outcome (what mind-maps were

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created) and develop a richer qualitative understanding of the process (how an "*in-the-wild*" mind-mapping activity would proceed). Developing this understanding will potentially allow for advancements in computational frameworks, tools, and interactive workflows for creativity support afforded by mind-mapping. Specifically, it is important to study (a) human behavior during collaboration, (b) changes due to collaborator presence, and (c) the fundamental issues that may hinder the exploratory nature of mind-mapping tasks.

From a broader perspective, the second inspiration for this study stems from the difference across various ideation techniques and the creative modalities they offer in a creative task. There is no evidence to claim that other free-form ideation techniques such as collaborative sketching [7, 8, 9] would offer the same kind of cognitive support toward creative idea generation that mind-mapping would. In this regard, mind-maps serve as means to explicate one's implicit understanding of a problem by building different perspectives, obtaining clarity, and develop deeper insight [10] for a given central idea. Therefore, mind-mapping (regardless of being individual or collaborative) is first and foremost a means to understand different aspects of a problem rather than a solution finding mechanism. A study of collaboration specific to mind-mapping is therefore much needed to develop a better understanding of its specific capabilities so as to create new metrics that better represent creativity resulting from mind-mapping.

1.1 Contributions

Our work takes a step the direction of understanding how humans collaborate as pairs for an unconstrained problem exploration task using mind-maps. For this, we present a detailed evaluation on the mind-mapping process through an in-depth video protocol analysis, and a qualitative analysis of the structure (topology) of the mind-maps. We further map the qualitative observations with an inter-rater study by adapting currently established metrics. Our study shows some unexpected observations regarding (a) how the central problem of the map can lead to differences in mind-map evolution, idea exploration, and exhaustion in the collaborators, (b) how and when collaboration can have an adversarial impact, and (c) when collaborators take inspiration from each other and add to each other's ideas. Based on our observations we suggest potential guidelines for designing interactive collaboration workflows for digital mind-mapping.

2 Related Works

2.1 Why Mind-mapping?

Of the many ways of ideation that are currently employed and taught in conceptual design, mind-maps serve a special purpose in that they go beyond the scope of merely exploring a solution-space. Mind-maps are basically tools for aiding critical thinking and analysis in active learning set-ups [11, 12]. Its hierarchical structure allows in-depth exploration of ideas [13], making them useful for a variety of applications ranging from document drafting [14], project planning [15], and decision making [16]. Zampetakis et al. discuss utility of mind-maps in learning process of engineering students for creative thinking [17]. Specifically during design ideation [18, 19], they are useful for reflection, note-taking, idea-communication, and idea synthesis while reducing the cognitive load accompanied with retrieval and maintenance of diverse-knowledge elements [20, 21]. In our work, we investigate mind-mapping as a means for problem exploration in conjunction with problem-solving when relevant.

2.2 Digital Brainstorming & Collaboration

Collaboration invokes positive participation experience for any brainstorming task [22, 23, 24, 25]. 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 [26]. These works fall under the broader category of Electronic Brainstorming [6] overcoming *impasse* related shortcomings of the traditional brainstorming process. Digital brainstorming tools are further categorized as Computer Supported Coworking (CSCW) tools [27] discussing multiple technology assisted collaboration scenarios. In relation to mind-maps, we currently focus on asynchronous and co-located aspect of the CSCW matrix [28].

Shneiderman et al. [29] 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. [30] 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 [31, 32, 33, 34]. Further, few works explore interactive modalities in digital collaboration [35, 36]. Although, several aforementioned works focus on digital collaboration, very few have tried understanding the fundamentals involved in the process.

2.3 Knowledge Gaps in Digital Mind-Mapping

In their work *Computer Supported Creativity*, Buisine et al. [37] demonstrate lack of significant improvement in a collaborative digital table top set up compared to traditional pen and paper mind-maps. However, the digital set-up promotes an enhanced, systematic and well-organized environment for people to collaborate. This leads to a balanced contribution from the participating members in a group. Faste and Lin [14] evaluated numerous existing mind-mapping software applications, performed ethnographic studies with a variety of users, and developed a framework of principles to guide future development of digital mind-maps. Largely, mind-mapping in collaboration is studied for a medium to large group interacting on an interactive display with independence [38,39]. Also, mind-maps have been found to enhance teacher-student collaboration while learning fundamental concepts pertaining to a given topic [40].

3 Methodology

3.1 Overview and Rationale

Large brainstorming groups perform similar to small groups in terms of productivity [41, 42]. Bouchar et al. [43] also found that larger the group, larger the potential loss of innovative ideas. Pinsonneault et al. [6] pointed out that working in nominal brainstorming groups could potentially alleviate the phenomenon where the idea generation productivity can be impaired by exposing their thoughts to group members. Gallupe et al. [44] also addressed the comparability of productivity between a group consisting of two and more collaborators. Our prior work [5] puts forth a comparison between computer assisted and human assisted collaboration for mind-mapping tasks. However, this comparison is based on allowing each user paired with a computer or human, to mind-map in a sequential manner. In a typical brainstorming scenario, collaboration is parallel, yet asynchronous [45]. The very purpose of our study was to understand this parallel development of a mind-map.

Leveraging the best of both traditional collaborative approach and electronic brainstorming, we designed a study focusing on understanding the fundamental of human-human collaboration teamed in pairs for a digital setup. The rationale here was to evaluate the collaborative ideation outcomes in terms of quality, variety, and novelty metrics [46, 47], and the mind-mapping process in evolution and interactivity perspectives. We also wanted to constrain our study such that the collaborators express all their ideas in the mind-map without inhibiting their ability to work freely in tandem. For this, we did not allow the collaborators to discuss verbally during our study — instead we encouraged them to put forth their ideas directly on the map.

3.2 Experiment Setup & Preparation

We developed a web-based application which consisted of a shared virtual canvas for participants to expand on a given the central idea. Each participant was provided with their own computer using which they could freely add any node anywhere on the same shared mind-map simultaneously. At the front-end, the application allowed participants to use a simple input interaction to create mind-maps on the canvas. Double-clicking on any node (including the node with the central idea) resulted in a pop-up window where the collaborator could add the content of the new node. We further encoded varying font size and color gradient in a radially outward direction from the central idea. This visual scheme added emphasis to the ideas conveyed in the mind-maps. Also, ideas added by two different participants were assigned different color schemes to avoid any confusion while maintaining an unobstructed flow if thought. At the back-end, we implemented our application using D3JS to maintain a force-directed layout for the created mind-maps. In addition, we used Firebase Database REST API to synchronize data from two computers.

3.3 Experimental Tasks & Procedure

We recruited 20 undergraduate and 4 graduate engineering students (18-30 years old). 14 participants had prior experience using mind-mapping in creative tasks. The participants were divided into pairs for each study and both participants in the pair performed mind-mapping at the same location. In total, we had 12 pairs of participants create 24 mind-maps using the web-based application — two per study session. The participants were allowed to spend a maximum of 10 minutes per mind-map. No verbal discussion was allowed between the participants.

3.3.1 Tasks Each pair was provided with two problem statements (corresponding to two central ideas in the mind-map) and asked to create one mind-map per problem using our web-based application. The problem statements were selected such that they were descriptive enough, and encouraged participants to create multi-level mind-maps. The problem statements are described as follows:

P1 *Solar Energy — Brainstorm the properties and ideas around solar energy. Where can solar energy be utilized and why is it useful. Limitations and potential solutions:* This problem statement was kept generic and can be typically found familiar to the target participants.

P2 *Space Travel — Brainstorm the needs, difficulties, ideas for space travel and corresponding solutions. Also, if space travel comes to reality:* This problem statement was relatively open-ended to encourage participants explore a wide variety of ideas.

3.3.2 Procedure The total experiment duration varied between 30 to 35 minutes. In order to avoid any learning bias, the two problem statements were randomized across the pairs. In addition to demographic survey and study description, we explained the basic features of our designed web-based application and allowed 2 to 5 minutes for the participants to get acquainted with the interface. For each study session, the participants were recorded throughout the mind-mapping process under their consent. The time-stamped data for the created mind-maps (nodes and links) were also recorded using JSON data structure. The procedure of the study is described as follows:

1. *Practice*: Participants were demonstrated on how to operate

the web-based application, using *Safety* as a practice central topic. They were encouraged to ask any questions for their clarity. Also, they were allowed to refer to the problem statement at any time during the study.

2. *Collaborative mind-mapping with* ***P1*** *&* ***P2***: Participants were allowed 10 minutes to mind-map on each central topic and were encouraged to externalize their ideas as much as they can in the given time. The canvas was set to a default blank screen after the completion of each mind-map.
3. *Questionnaire*: Each participant answered a set of questions using an electronic questionnaire. The questions were related to their knowledge level with respect to the central topic before and after the creation of each mind-map. After completion of the two mind-maps, participants responded to another questionnaire regarding individual perception towards their collaborators. We also collected open-ended feedback on the study and conducted informal interviews.

4 Analysis of Outcome: Inter-Rater Evaluation

4.1 Metrics for Evaluation

To evaluate the outcomes from the user study, mind-maps created by participants were assessed by two expert raters possessing sound knowledge about creating mind-maps and their structure in general. They were unaware of study design and tasks, and were not provided with any information related to the general study hypotheses other than the final mind-maps the participants created. Both raters were senior graduate researchers in engineering and product design disciplines. They were asked to rate each mind-map on a scale of 1 to 4 based on well-established metrics. From the mind-map assessment rubric [46, 48], we adapted the following metrics for a comprehensive assessment:

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 paper is not toward solution generation, the existing metrics for novelty and variety in mind-mapping as demonstrated by Linsey et al. [47] need to be adapted for a fair inter-rater evaluation. Specifically, we instructed our raters to 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 used the following metrics as detailed by Linsey et al. [47].

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 $N_j = 1 - {}^{C_i}/_{T}$, 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.

The inter-raters were supplemented with all mind-maps and the specific grading rubric. The two raters 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. The Cohen's Kappa value for the metrics Structure, Exploratory, Communication, Extent of Coverage and Quantity(unique) were found to be in the range of 0.9 - 1, showing strong agreement and reliability between the two raters. Also the Pearson's correlation between raters for Variety and Novelty scores was found to be 1, which is the highest correlation possible [49].

4.2 Evaluation Results

Each study session had participants paired up and stayed close to the allowed time per mind-mapping session. The inter-raters evaluated each mind-map based on aforementioned rubrics in section 4.1. As a part of evaluation, they reported number of raw and unique ideas per mind-map. The Variety and Novelty scores were calculated based on the category list created by the two expert raters. For *Solar Energy*, the raters agreed upon: electricity generation, electricity storage, mobility, utility, natural availability, environmental impact, renewable energy, financial analysis, sustainability, future prospects, legislation, flora and fauna. For *Space Travel*, the categories were: exploration, human factors, transportation, facilitators of space travel, limitations, discovery, technology, financial aspects, sustainable operations, objectives, legislation and governance, physical conditions , speed of travel, relativity (time travel), professionals, movies and fantasy. Their analysis shows a higher mean of raw ideas generated for the *Space Travel*(49) as compared to *Solar*

Problem	Structure (1-4)	Exploratory (1-4)	Communication (1-4)	Extent of Coverage (1-4)	Quantity (raw)	Variety	Novelty (0-1)
Solar Energy	3.08	2.41	2.58	2.63	40.25	54%	0.30
Space Travel	3.41	2.91	3	2.79	49.25	60%	0.20

FIGURE 1: The values of various metrics were averaged across topics. This table summarizes the mean values of various metrics calculated by the expert raters.

Energy(40). Also, *Space Travel* had approximately 98% unique ideas of the total ideas generated compared to 80% uniqueness for *Solar Energy*. Owing to the nature of the study, we evaluated data by performing hypothesis testing to draw conclusions from the results. We initially confirmed normality of our data using Shapiro-Wilk test. Each metric per mind-mapping topic had a non-normally distributed data. Thus, we performed a non-parametric test using the Kruskal-Wallis test for the 24 mind-maps. We make the following hypotheses:

Null Hypothesis(H_0): Average score across each metric is similar across two problems for all generated mind-maps.

Alternate Hypothesis(H_a): Average score across each metric is different across two problems for all generated mind-maps.

The four basic metrics discussing Structure(p = 0.3), Exploratory(p = 0.227), Communication(p = 0.1199), Extent of Coverage(p = 0.1325) failed to demonstrate a significant difference across the two topics. Thus, the null hypothesis H_0 stands true based on our study results. This provides an initial insight on how mind-mapping in pairs is neutral to the problem statements provided for brainstorming. Although, rubric scores highlight the mind-map structure, the Variety and Novelty scores speak a different story. *Solar Energy* mind-maps showcase a mean cluster Variety of 54% and mean Novelty value of 0.3. Whereas, *Space Travel*, owing to its open-ended nature, showcased 60% mean cluster Variety and mean Novelty score of 0.2. This can be attributed to participants' prior knowledge on *Solar Energy* leading to a relatively lower variety as compared to *Space Travel*, which is an open-ended and unfamiliar problem to brain storm. However, unfamiliarity affects Novelty score for *Space Travel* as all ideas do not converge with most categories.

5 Analysis of Process: Video Protocol Analysis

In order to understand the collaborative mind-mapping process better as many of the relevant stimuli and responses are not apparent through analysis of outcome (section 4), we conducted protocol analysis of each study session [50, 51]. This was performed post hoc by manually analyzing screen recordings for creation of each mind-map.

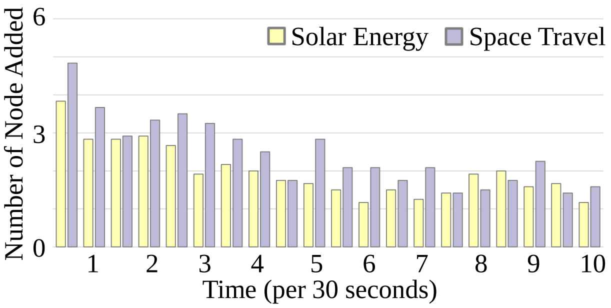


FIGURE 2: General trends on how participants generated ideas towards **P1** and **P2**. Each bar shows an average count of the total nodes added in the given time frame (per 30 secs) across all pairs.

5.1 Mind-map Evolution over Time

The participants were asked to follow basic principles of mind-mapping [10] for the study. During our analysis, we observed multiple strategies applied by participants for creating mind-maps across the assigned central topics. As the topics were randomized for each participant-pair, we believe strategy selection was potentially affected by domain knowledge limitation and personal inhibitions in a collaborative setup. For *Solar Energy*, several participants performed a depth-first exploration in first few minutes of the study (relatively more deeper branches are observed at the initial 2 minutes mark). Whereas, for *Space Travel*, growth was relatively uniform in terms of breadth and depth of the mind-map layout (5 to 8 main branches during initial 2 minutes). Thus, initial exploration of *Space Travel* was relatively quicker in comparison to *Solar Energy*.

We observed three primary layouts for *Solar Energy* mind-maps — bounded (limited ideas), unbounded (extensive idea exploration), and scattered (exploration without a defined structure). Interestingly, we found several maps for *Solar Energy* with either *leaf* nodes (node without a subsequent child node) of depth 1 (directly added to the central topic) or long chains of nodes (e.g. a mind-map with 17 branches, where 11 have only one node). We observed this to happen mainly in two scenarios: (a) when users found it difficult to relate new ideas to existing ones and (b) when users faced lack of domain knowledge. This was less resonant in the mind-maps for *Space Travel*. This was

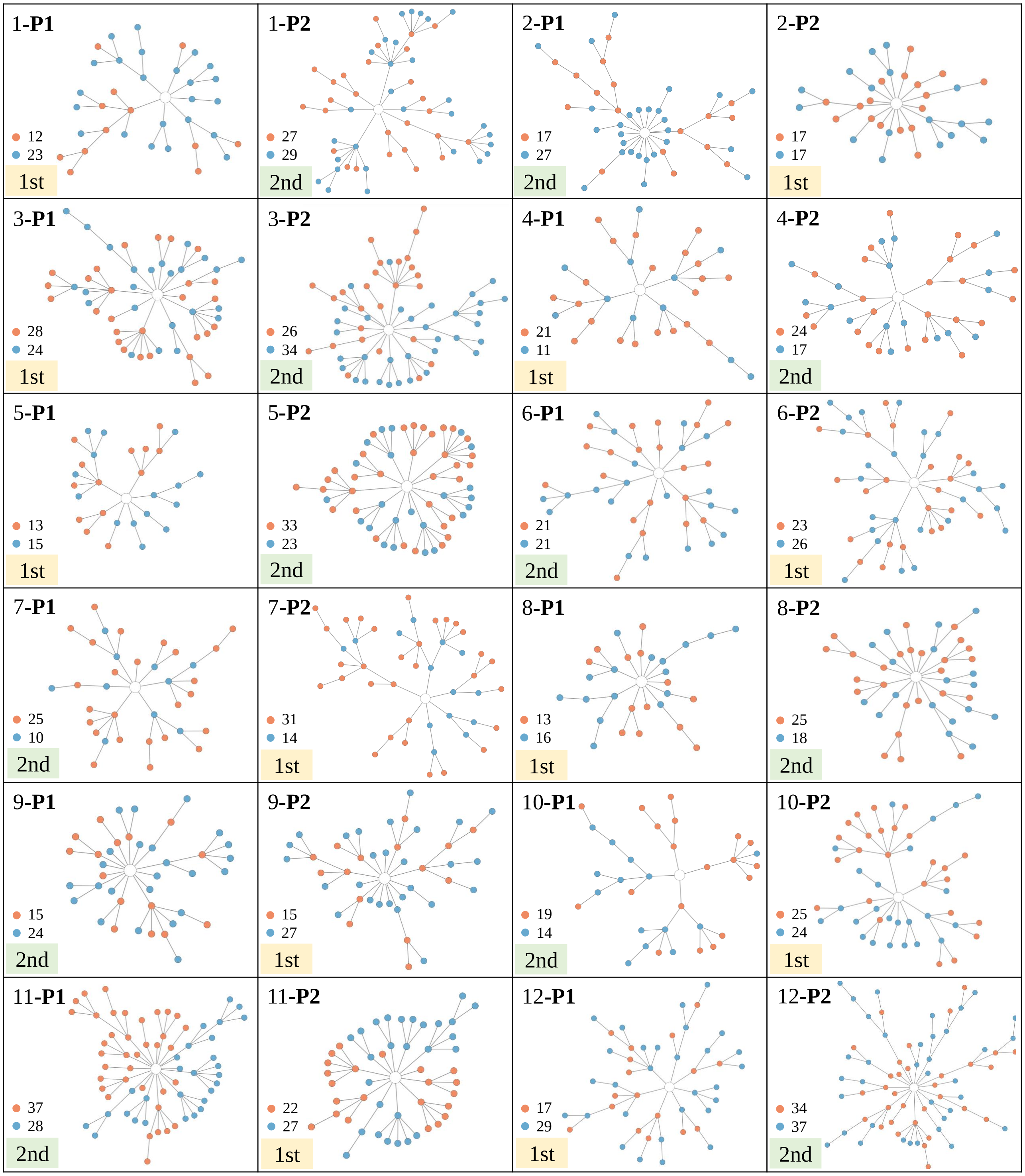


FIGURE 3: Topology of mind-maps created by participants with **P1** (*Solar Energy*) and **P2** (*Space Travel*). Orange and blue colors represent participants in a pair and white node represents the root node (central topic). The colored labels specified the order of mind-maps created by the corresponding pair. The mind-maps were rendered using force-directed layout provided by D3JS.

particularly interesting because we hypothesized that a problem that is reasonably scoped (less open-ended such as in the case of *Solar Energy*) should result in mind-maps that are relatively more balanced in terms of the breadth and depth of exploration when compared to more open-ended central topic (*Space Travel*).

As expected, the rate of idea generation (the frequency of node addition over time, Figure 2) differed across the two topics. With *Space Travel*, the rate of node addition decreased steadily towards the end. In contrast, participants reached an early saturation with ideas for *Solar Energy* (6 to 7 minutes mark) followed by a very short spike in idea generation. This can be attributed to two primary reasons. First, participants utilized all their prior knowledge of *Solar Energy* during the initial phase of mind-mapping. Second, on reaching an impasse, they started brainstorming about the solution-specific ideas related to the topic.

5.2 Pair Participation over Time

Although it is challenging to pin-point the actual contribution among collaborators, we wanted to characterize the intent to either (a) contribute, (b) participate, or even (c) compete. For this, we observed the collaborators' behavior in terms of the relative number nodes added by each collaborator to the maps across the two problem statements. Here, we make two observations. For eight (1, 2, 3, 4, 5, 8, 11, and 12) of twelve the pairs, the number of nodes from each collaborator were high. This strongly indicates increased comfort and engagement between the collaborators over time. Interestingly, for some pairs (1, 4, 9, 12), we noticed that (a) one collaborator added significantly fewer nodes in the first session and (b) the difference between the number of nodes decreased notably for the succeeding problem statement mind-map (Figure 3). This indicates that in these specific examples a collaborator with relatively fewer ideas in the first session seeks to compensate during the next one. In fact, this observation was independent of any specific problem statement. We also observed a stark decrease in participation level for two pairs (e.g. difference of 4 nodes in the first map vs. 12 in the second map, difference of 17 nodes in both maps) and more data is needed to formulate a strong view regarding participation.

5.3 Idea Exploration Directions

Here we discuss the type of ideas explored by the users during their collaborative mind-mapping and how it influenced the final quality of the mind-maps created.

5.3.1 Solar Energy:

The breadth typically included *solar panels, renewable energy, sun, vehicles*. It was observed to be broader likely because of the topic familiarity. Most participants were able to list the environmental benefits, the cost constraints related to Solar Energy. For application uses, popular suggestions were (*vehicles, rooftop solar panels*). The subtopic of *solar panels* was expanded to include the placement (assembly and geographical) in house. For instance, pair 11 (Figure 4(a)) gave the most complete expansion of solar panels, specifying *solar photo-voltaic (PV) solar panels, solar cell design, material*, and even mentioning *semiconductors*.

Typical participant ideas included *renewable energy* in terms of environmental benefits such as *waste reduction, pollution minimization*, and *clean air*. Other additional examples were *wind energy* and *hydro-power*. Few were able to make relations to *environmental impacts*, such as *minimizing greenhouse gases* and decreasing dependency on *fossil fuels*. Initial consideration included benefits of *Solar Energy* for *vehicles* and *rooftop tiles*. The *sun* subtopic was minimally expanded, with only a few users considering *radiation*. We observed that most users did not add any additional nodes to the central idea after initial few minutes suggesting user inclination towards ideas brainstormed in the initial stages of mind-mapping.

5.3.2 Space Travel:

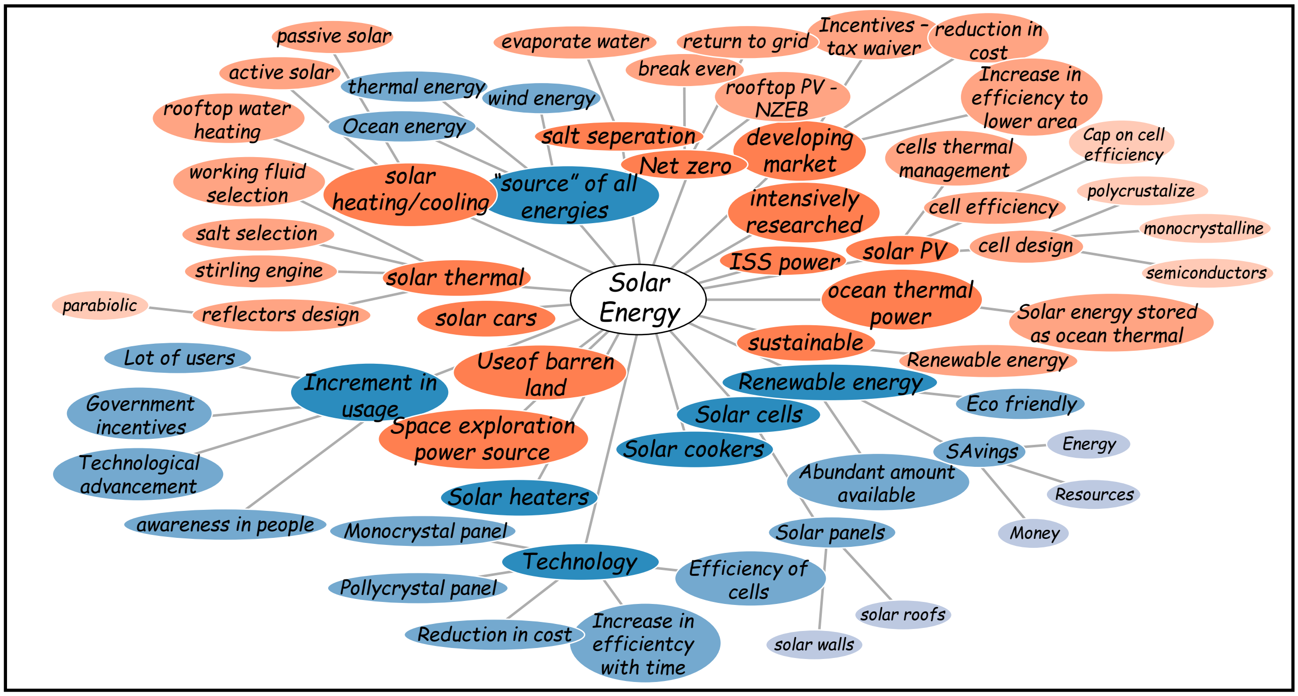
The initial set of nodes added by users for this topic included companies involved with *Space Travel* such as *NASA, Space X*, the types of infrastructure and transportation required for *space Travel* such as *space stations, space ships,* and *rockets*, as well as *astronauts* and *engineers* (Figure 4(b)). Lastly, *high costs* was the most often stated of the *difficulties* associated with *Space Travel*. Some users added nodes directly on the central node alluding to the advantages and potential risks of *Space Travel* such as *research on space life, new technology*, and *loss of human life*). Ideas also included locations where *Space Travel* technologies are being developed (such as *Houston, Florida, California)*. The participants mostly limited the *difficulties* or *disadvantages* of *Space Travel* to its *high cost* and the obstacles found in *obtaining funding* through *private agencies* or *the government*. Only two pairs mentioned the *difficulties* in providing the *necessary resources* humans need to live. However, the subtopic of *astronauts* allowed several of the other pairs to address these requirements, including the identification of *necessary resources* such as *oxygen, food, water* and *living conditions*.

5.4 Pauses in Exploration

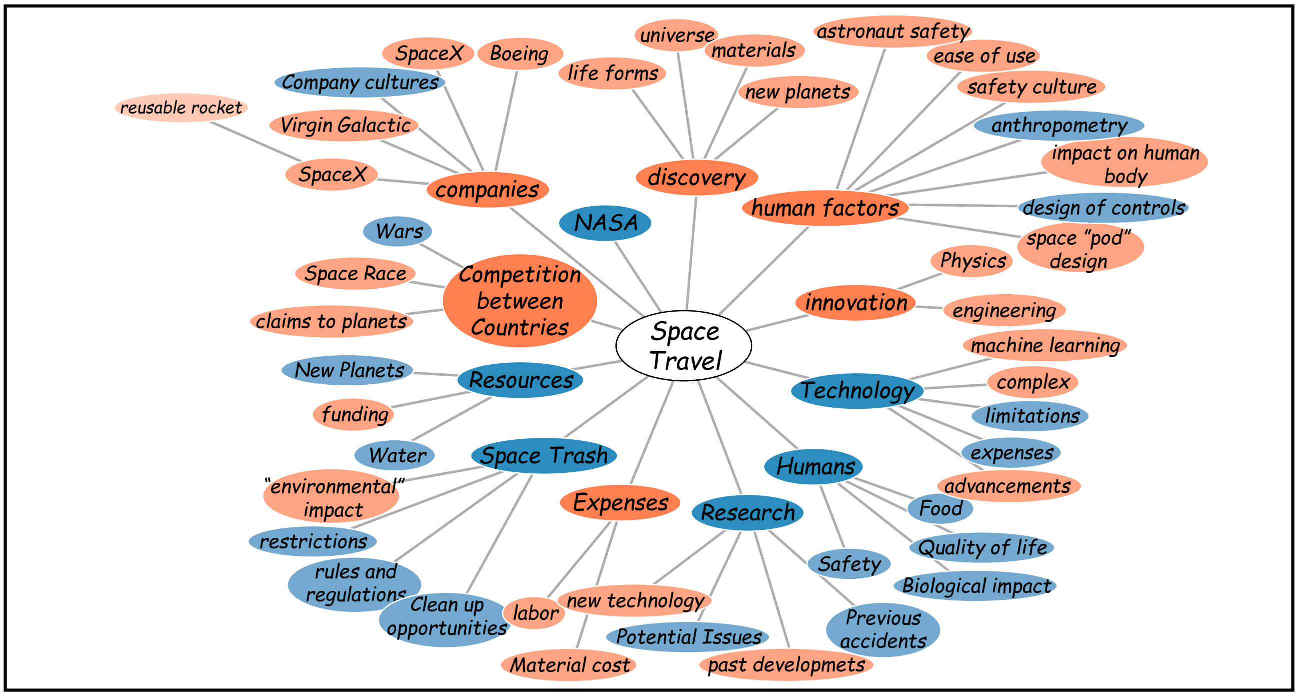
We measured the duration where the participants either hover over existing nodes or open an input dialogue box and do not add a valid idea to the current mind-map for a long time. These pauses could be caused by reasons including reflection, exhaustion, and impasse. Most of these pauses occurred during later stages of mind-mapping when participants needed more time to reflect and add more detail-oriented nodes to the map.

5.4.1 Solar Energy:

Here, most participants could start externalizing ideas in the first several minutes of mind-



(a) *Solar Energy* map created by a pair of participants. (11-**P1**)



(b) *Space Travel* map created by a pair of participants. (5-**P2**)

FIGURE 4: User created mind-maps using our web-based application with (a) *Solar Energy* (**P1**) and (b) *Space Travel* (**P2**). Orange and blue colors represent each participant in a pair. The white node represents the central topic (root node). The color gradient represents level of idea exploration in a radially outward direction.

mapping session. Apart from those who were familiar with central topic, a majority of participants were observed to slow down their pace in generating ideas in the middle and later stages of mind-mapping. Specifically, they were spending time (> 20 seconds) in hovering over ideas externalized by their collaborators and iterating the content of the same idea before adding it to the map. Moreover, 4 pairs of participants almost stopped mind-mapping in the last 2 to 3 minutes of the session indicating early exhaustion of ideas.

5.4.2 Space Travel: Two participant types were observed in the initial phase: (a) those who spent more time initially to think about the problem and hovering over the central topic before adding the first node and (b) those who started adding nodes as soon as the session started. Majority of the participants frequently (> 3 times) referred to the given problem statement during mind-mapping – they were able to generate ideas steadily after doing so. For example, one participant immediately created a branch *Discovery* to the central topic and added the nodes *New life* and *inhabitable planets* to it. Another participant further expanded on an existing branch (*Rockets*) with *Sufficient fueling* and *aerodynamics* to collaborator's idea (*shape*). Compared to *Solar Energy*, participants performed generated ideas more consistently in the given task duration.

5.5 Response to Collaborator's Ideas

Participants were allowed to expand on any existing nodes in a current mind-map. We were interested in the frequency with which they responded to their collaborator's ideas by adding nodes to a previously existing node added by the collaborator.

Most participants responded to their collaborator's ideas to some extent (the mixture of colored nodes in Figure 3). This, however, is not always true during the creation process. With *Solar Energy*, we found 4 pairs where participants exclusively added to their own ideas in the beginning phase of mind-mapping (2 to 4 minutes mark). Similar observations were made with 5 pairs in case of *Space Travel*. Usually in these cases, the participants were able to externalize ideas rapidly in the first several minutes, but got exhausted easily, as they started to take a look at their collaborator's ideas after. One pair who created a mind-map with *Space Travel*, for instance, generated around 20 ideas in the first 3 minutes itself. The rate of node addition, in this case, was significantly decreased in the following 1 minutes, and they hovered over the ideas externalized by their collaborators as well as opened the input dialogue box several times without typing anything. At around the 4 minutes mark, they started to branch out and detail on each other's ideas toward the end.

Interestingly, we found two pairs wherein each collaborator worked exclusively on their own sets of ideas most of the time (Figure 3: 2-**P1**, 2-**P2**, 11-**P1**, 11-**P2**). In this case, as expected, the participants seemed to have equal contribution to the central topics, as the total counts of externalized ideas with respect to the two participants in a pair are comparable. This is probably because of the strong confidence in the knowledge possessed by both of them. However, even though they did not directly respond to their collaborator's nodes, the ideas generated are observed to be affected by their collaborators (Figure 4(a), e.g. *Risky* after *safety*, *Climate predictions* after *climate*, *GPS* after *Destinations*, *Pollycrystal panel* after *cell design*, *developing markets* after *Government incentives*, etc).

6 Limitations

There are three main limitations in our current work. First, our mind-mapping workflow was constrained to addition of nodes. This was necessary to conduct a controlled study. However, allowing for new modalities such as modifying self-created and collaborator's nodes, re-linking existing nodes etc. will lead to several new insights into collaborative behavior. We plan to investigate these modalities in future. Second, we had a relatively low sample size (12 pairs leading to 24 mind-maps). This allowed us to study the process in significant detail and also allowed for a reasonable inter-rater analysis. However, taking the next steps toward intelligent systems for digital mind-mapping will require much larger data-sets that could be used to generate machine learnt models to exhibit human-like collaborative behavior. We intend to collect several hundreds of mind-maps through crowd-sourcing to continue with our work. Finally, this study restricted inter-personal communication between the participant pair. Even though this was an intentional decision on our part to conduct a controlled study [6], we believe there is a rich set of research problems that will investigate multi-modal collaboration. Also, there is much to be learnt regarding how the collaboration between individuals itself evolves over multiple mind-mapping sessions between the same individuals (section 5.2). We currently did not have objective metrics to specifically characterize the contribution by each collaborator in a pair. This is a critical area that we intend to pursue.

7 Discussion

7.1 How do Pairs Collaborate?

Based on the participants' feedback (Figure 5), we see a strong positive agreement on collaboration helping participants explore more ideas. *Space Travel* received relatively higher positive response from participants than *Solar Energy* for their collaborators knowledge. One participant with minimal prior experience in brainstorming tasks and limited knowledge in *Solar Energy*, shared his reliance on collaboration *"I wasn't very comfortable in the solar energy concept, but after seeing his thoughts, I was able to come up with ideas. Not only did he help me come up with ideas, but were able to build longer chains of ideas by* *adding to different aspects"*. Thus, collaborator presence acts as catalyst for idea exploration in mind-mapping process.

Participants with prior knowledge on a given topic tended to expand on their own ideas more than using the collaborator's ideas. One participant stated: *"Collaborator wrote a little too fast. I would have preferred less intervention"*. Another participant, on the other hand, appreciated the assistance from the collaborator, stating:*"I find it helpful when he adds ideas to central topic rather than develop ones previously created"*. We also found that in addition to working on their own sets of ideas throughout the session, they seemed to have an implicit understanding with each other's ideas and the inter-relatedness between them. This brings forward the importance of a positive and balanced experience between collaborators. Also, there is necessity for a healthy reasoning system in human-computer collaborative mind-mapping.

7.2 Design Implications for Digital Mind-mapping

From our previous work [5], there are two key problems in creating an intelligent collaborator in a mind-mapping process: (a) target search (finding where the AI should add a node) and (b) content generation (generating the content for a new node). In this context, the following observations are helpful:

7.2.1 Phase-dependence: Half of the participants did not add to their collaborator's ideas in the first several minutes of mind-mapping. Frequent intervention from an "expert" collaborator (human and computer alike) in early stages can very easily make users lose their chain of thought ultimately leading to reduced engagement. Allowing users to expand and reflect on their own ideas with minimal to zero interruptions is important. On the other hand, as the frequency of new ideas generated per minute decreases steadily towards the end, an increasing contribution on contextual ideas from AI can help complement the impasse faced by the users as well as stimulate their thinking.

7.2.2 Content-dependence: Compared to initial few minutes, most participants did not create as many new main branches in the later stages of mind-mapping. In addition, some relied heavily on the ideas generated previously by their collaborator. Therefore, to overcome this early saturation, computer assistance could play an important role in helping users branch out by generating contextual idea nodes directly to the central topic using knowledge databases.

7.2.3 Stimulation: The types of stimulation from computer remains a rich research area in computer-supported works. In our prior work [5], we demonstrated the efficacy of making AI co-generate ideas with human in a serial manner. In our current work, we found that most of the participants referred to the problem statements at least 2 to 3 times during the study. This helped them generate more ideas in the mind-map. The problem statements we provided were a set of questions querying the basic principles and different aspects to the given central topics. Thus, we think question based stimulation is effective in helping users externalize ideas and potentially alleviate their personal inhibitions. Also, support from computer can be further enriched through the use of visual content retrieved from ShapeNet [52], ImageNet [53], or other graphics databases, thus assisting users with multi-modal contents and allowing utility of mind-maps as engineering, architectural, and industrial design tools.

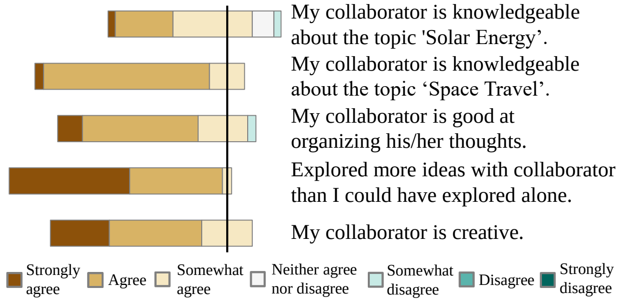


FIGURE 5: 7-point Likert scale user feedback.

8 Conclusion

At its core, this work sought to understand how peers collaborate to create mind-maps, how the maps evolve over time, and how collaboration changes over time. The primary outcome of this work is the wide variety of collaborative behavior that we recorded and coded. This could be useful toward future computer-supported digital mind-mapping tools. For this, we conducted a human-subject study with peer-pairs to find strategies and patterns created in terms of human behavior and graph evolution perspectives, and raised issues that may hinder idea exploration process in mind-mapping tasks. To the best of our knowledge, this study is the first one to discuss and analyze in detail, the process involved in collaborative mind-mapping. We believe that this study is a first critical step toward developing deeper understanding of collaboration in mind-mapping. We hope this work will lead to a richer set of research directions in the context of computational reasoning systems for brainstorming and intelligent assistants for creativity support.

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