Providing Intelligent and Adaptive Support in Concept Map-based Learning Environments

by

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ABSTRACT

Concept maps are commonly used knowledge visualization tools and have been shown to have a positive impact on learning. The main drawbacks of concept mapping are the requirement of training, and lack of feedback support. Thus, prior research has attempted to provide support and feedback in concept mapping, such as by developing computer-based concept mapping tools, offering starting templates and navigational supports, as well as providing automated feedback. Although these approaches have achieved promising results, there are still challenges that remain to be solved. For example, there is a need to create a concept mapping system that reduces the extraneous effort of editing a concept map while encouraging more cognitively beneficial behaviors. Also, there is little understanding of the cognitive process during concept mapping. What's more, current feedback mechanisms in concept mapping only focus on the outcome of the map, instead of the learning process.

This thesis work strives to solve the fundamental research question: How to leverage computer technologies to intelligently support concept mapping to promote meaningful learning? To approach this research question, I first present an intelligent concept mapping system, *MindDot*, that supports concept mapping via innovative integration of two features, hyperlink navigation and expert template. The system reduces the effort of creating and modifying concept maps while encouraging beneficial activities such as comparing related concepts and establishing relationships among them. I then present the comparative strategy metric that modes student learning by evaluating behavioral patterns and learning strategies. Lastly, I develop an adaptive feedback system that provides immediate diagnostic feedback in

response to both the key learning behaviors during concept mapping and the correctness and completeness of the created maps.

Empirical evaluations indicated that the integrated navigational and template support in MindDot fostered effective learning behaviors and facilitating learning achievements. The comparative strategy model was shown to be highly representative of learning characteristics such as motivation, engagement, misconceptions, and predicted learning results. The feedback tutor also demonstrated positive impacts on supporting learning and assisting the development of effective learning strategies that prepare learners for future learning. This dissertation contributes to the field of supporting concept mapping with designs of technological affordances, a process-based student model, an adaptive feedback tutor, empirical evaluations of these proposed innovations, and implications for future support in concept mapping.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Pictures and diagrams are critical to scientific practice. Visualization tools and graphical presentations are able to deliver visual information that is easier to process by our brains. Therefore, graphs are widely used by teachers, instructors, and textbooks to enhance reading comprehension. A survey of more than 2,500 pages from ecology research journals articles revealed that there are 14 graphical representations per 10 journal pages (Roth, Bowen and McGinn, 1999). This work also reported that high school biology textbooks had the same frequency of visual representations with research articles. Among different types of knowledge diagrams, the concept map is one of the most If commonly used diagrams in educational contexts. Concept maps are a type of graphic organizer that illustrates knowledge structures as labeled links (denoting relationships) connecting various labeled nodes (denoting specific concepts in the knowledge domain). Concept maps have been considered to be a meta-cognitive learning tool, which empowers students to control and monitor their learning progress. Research has shown evidence that learning through constructing concept maps had positive impact on critical thinking skills (Lee *et al.*, 2013), as well as self-regulation and self-efficacy (Chularut and DeBacker, 2004).

However, as research in the literature has pointed out, the use of concept mapping comes with drawbacks (Kinchin, 2001). The major disadvantages of concept mapping are the complexity of the task. Creating a concept maps requires a lot of mental effort as it involves a combination of various learning behaviors such as reading the content, summarizing key concepts, compare and contrasting. In order to create a concept map that represents a complex knowledge network, certain training and expertise is required. In addition, when concept maps get more and more complex, editing and maintaining a good structure becomes harder as the learner need to understand not only relationship among concepts, but the overall hierarchy of the content (Daley and Milwaukee, 2004). Therefore, when creating concept maps, ones who lack certain skills are often demotivated and fail to benefit from the task (Beitz, 1998; Kinchin, 2001; Eppler, 2006). Thus, to resolve these limitations and enhance the benefits of concept maps, support and instructions need to be provided.

Research in the literature has proposed various ways of supporting concept mapping. The introduction of personal computers enabled the development of computer-based concept mapping tools (Anderson-Inman and Horney, 1997; Novak and Cañas, 2006a; Hwang, Wu and Ke, 2011a). Some of these tools, like CmapTools, have been extensively studied by researchers, and have demonstrated advantages over pen-and-paper based concept mapping tasks (Cañas *et al.*, 2004). These tools provide features like fast input, easy modification, and map sharing, but do not fully utilize the interactive and intelligent potential of digital platforms to support students. However, as surveyed above, challenges in concept mapping exist not only in the editing level, but also in the cognitive aspects, such as summarizing key concepts in the content, comparing and relating concepts, creating high-quality cross-section relationships, maintaining an hierarchical knowledge structure (Kinchin, 2001). Although concept mapping contains a wide range of learning activities and involves different learning stages, there are two fundamental behaviors that are constantly being performed throughout the concept mapping process: **accessing key information** and **comparing related concepts**. These two behaviors are critically important as they directly mediate the process of relating and incorporating new information into learners' prior knowledge structure, which fosters meaningful learning. In addition, the two behaviors connect different stages of concept mapping, from reading the learning content, to finalizing the concept map.

Therefore, facilitating the process of accessing key information and comparing related concepts is highly desirable. Research in the literature has explored several ways of supporting concept mapping. One of the approaches is offering incomplete templates that serve as foundational scaffolding. Prior research work has explored various methods of template designs, such as expert-skeleton maps, parking lots, kit-build maps, and achieved promising results. Yet, there are still some drawbacks with these approaches. The major one is that learners sometimes struggle to understand the unfamiliar external structure. When learners lack the amount of prior knowledge to process these expert templates, these external structures are more likely to impose cognitive load. As researchers have pointed out, learners confronted with ready-made maps may initially feel overwhelmed or demotivated by the complexity of the map (Kinchin, 2001).

A related way of cognitively supporting concept mapping is providing concept map-based navigation. Concept map-based navigation aims to support the access of related information by using a concept map as navigational anchors. Learners are able to click on a node in the concept map and navigate to the corresponding page, which provides quick and easy access to information in the text, as opposed to reading the text in a fixed linear order (Zeiliger, Reggers and Peeters, 1995; Mendes, Martinez and Sacks, 2002; Puntambekar and Stylianou, 2005). These works showed that concept map-based navigation facilitated the development of metacognition. However, few of them revealed impacts on learning gains. Similar to the template support, learners in these works are presented with a fully constructed concept map before they've started learning. Therefore, the mental effort to process the map remains to be a challenge. Another potential issue with respect to hyperlink navigation design is the disorientation of the navigations. As Puntambekar pointed out (Puntambekar and Stylianou, 2005), map-based navigations might not always be effective. Navigating a hypertext learning systems requires a good understanding of the overall structure of the system, such as knowing where a particular concept falls in the big picture and what other concepts it is related to. Without certain understanding of the content, the flexibility and nonlinearity in hypertext navigation might cause confusion and disorientation, and in term, diminishing the benefit of quick access to information and the ability to develop learner-oriented navigation paths.

Apart from the methods presented above, research in the literature has also attempted to support concept mapping with the use of artificial intelligence, including automatically generating templates from the learning content (Gregorowicz and Kramer, 2006; Chen, Wei and Chen, 2008) and providing diagnostic feedback (Lukasenko and Anohina-naumeca, 2010; Wu *et al.*, 2012). Much of the work on intelligently supporting concept mapping has focused on providing students with tools that evaluate or support the outcome of the activity (i.e., the concept map itself). For example, template-based support facilitates the construction of the final outcome map by prompting learners with a basic structure to expand. The diagnostic feedback approaches focus on the structure and content of the maps the learners create (Hirashima, 2011). Previous research work on outcome-based assessment has provided evidence that maps students create have strong correlations with learning gains, and it is desirable to provide adaptive diagnostic feedback based on the quality of created maps.

However, individual differences vary not only in the learning outcome, that is, the final map students create, but also in the learning process, that is, how these maps are created. We argue that it is just as important to consider the cognitive process of concept constructions. As two identical maps can result from two completely different strategies, and these strategic moves can be highly representative of learner characteristics such as objective, motivation, and misconceptions. Understanding the concept mapping process and providing accurate instructions to foster more effective concept mapping strategies can be highly beneficial. The notion of facilitating the concept mapping process is supported by cognitive theories as well as empirical investigations. Research in reading comprehension strategies have suggested that skilled readers are distinguished by a great deal of effective strategic behaviors (Jenkinson, 1978; Anderson, 1979). Supporting the development of these strategies can be significantly boosted learning outcomes. Ponce and colleagues (Ponce and Mayer, 2014b) evaluated qualitatively different learning processes and strategies specifically in concept mapping and note taking activities. Results indicated that a generative strategy, where learners process the content while actively comparing and connecting concepts in different sections, leads to higher learning gains over a linear strategy, where learners process the text content passively in a linear order. Therefore, proper instructions on fostering these beneficial strategies have great potential to promote learning.

Hattie (Hattie and Timperley, 2007) classified types of feedback into four levels. Feedback about a task (FT); Feedback about the process (FP); Feedback at self-regulation level (FR) and feedback directed to the "self" (FS). The comparison of these types of feedback suggested that in order to support the development of learning behaviors and strategic planning, process-based feedback can be more effective, compared to task or outcome-based feedback. Although several works have attempted to model the learning process in concept mapping (Leelawong, Biswas and Isis, 2008), the evaluation still remains at a fairly high level, which lacks detailed understanding of learning behaviors students perform during concept mapping, as well as the objectives behind each type of behavior and its learning effects. Therefore, in order to provide accurate feedback to foster effective concept mapping strategies, there is a need to develop a comprehensive understanding of the cognitive learning process in concept mapping activities. More specifically, there need to be a clear identification of what types of behaviors students perform during concept mapping; when and why do these behaviors happen, as well as how does each type of behavior affect learning.

To summarize, concept mapping is an activity that has great potential to enhance learning activities. Challenges with concept mapping exist in various aspects of the task, including the editing, access of information, extraction of key concepts, comparison of related concepts, and knowledge organization. Although research in the literature has explored different ways of supporting these challenges in concept mapping, there are still some unsolved limitations within each method. Therefore, there is tremendous possibilities in leveraging computer technologies to deliver effective support to facilitate these processes. To close this gap in research, this thesis work decomposes current challenges with concept mapping into three major categories: concept map construction, student modelling, and diagnostic feedback. The following paragraphs will describe research questions that address the challenges within each category and present the deliverables and contributions of this work.

1.2 Challenges and Research Questions

The fundamental research question for this work is: **"How do we leverage computer technologies to intelligently support concept mapping in ways that promote learning?"** In the paragraph above, we have discussed some of the unsolved challenges in concept mapping, including high demand of effort and training in concept mapping, lack of understanding in the concept mapping process, insufficient support of concept mapping strategies. Therefore, exploring our fundamental research question entails dealing with three major challenges: developing efficient concept mapping tools; comprehensively modeling student behavioral patterns, and providing adaptive diagnostic feedback to support beneficial behaviors. In the next section, I will present these challenges and propose specific research questions that need to be explored in order to address these challenges.

Computer systems need to provide effective cognitive support to concept mapping.

Concept mapping as a learning activity has been widely used and recommended in educational context to support learning. Unfortunately, when concept mapping activities are practiced in a pen-and-paper manner, much of the benefits are diminished, as students often need to spend significant amount of time and effort revising and maintaining concept maps. Computer-based concept mapping tools have great potential in supporting concept mapping. Existing tools tend to provide features like fast input, easy modification, and map sharing, which mainly focus on the editing level. It has been reported that when engaged in concept mapping activities, students need support and guidance not just in editing, but also in spotting key concepts, identifying relationships, and organizing knowledge structures. Therefore, supporting only the editing stage of concept mapping might not be adequate to fully reveal the benefits of learning with concept maps. Affordances should be provided to assist different stages of concept mapping. These different stages in concept mapping mentioned above are connected by two fundamental activities, that are accessing key resources and comparing related information. Therefore, leveraging computer technologies to assist these two activities has great potential to support concept mapping.

Prior work in the literature has explored several ways of cognitively supporting concept mapping and highlighted two critical scaffolding directions. The first one is **template support**, that sets a hierarchical framework that guides the fundamental structure of the map, it usually involves certain level of expert template or structure being presented to the learners as the starting point for the activity. The other is **navigational aid**, that provides quick access to key information. These supports have been proved to have promising impact in enhancing learning with concept maps as they directly intervene the process of accessing to recourses and comparing related information. However, previous work that provides these supports has certain drawbacks. For example, the template support is constrained by the high mental effort required to process the external structure. Similarly, the benefits of navigational support are limited by inadequate guidance and disorientations in the navigation. Hence, providing affordances to ameliorate these limitations has promising potential to amplify the benefits of template and navigational support.

Based on the discussion above, the challenges of developing a computer system that effectively supports concept mapping can be decomposed to three sub challenges. First, we need to explore different ways of designing the expert templates in order to eliminate the high cognitive load. Second, we need to design effective navigational support that yield goal-orientated navigations. Third, we need to explore ways of integrating these two types of support. To solve these challenges, I hereby propose four research questions:

Q_1: Do different template designs affect learning in concept mapping?

Q_2: Is map-based navigation more effective with learner generated maps?

Q_3: What are the effects of an integrated template and navigational support?

In this thesis work, Chapter 3 tackles the first research question by studying the effect of different template designs. Chapter 4 presents an initial design of a concept mapping system, *MindDot*, that enhances the access to related information though a hyperlink navigation feature, which links learners' maps with related resources and allows them to navigate using their own maps. Chapter 5 investigates the effect of the hyperlink navigation feature through an empirical evaluation. Based on the findings about the template and navigational support, Chapter 6 presents a new design iteration of the concept mapping system that integrates the template and navigation support. Details of the designs and evaluations will be presented in these chapters.

There is need to understand how learners create concept maps.

In order to provide accurate and effective instruction to support concept mapping, assessing student learning is critical. Current approaches in evaluating student learning in concept mapping mainly focus on the outcome, that is the maps learners create. Work in the literature has shown evidence that the correctness and the quality of the created maps are predictable to learning outcomes and can be used for diagnostic purposes. However, a major limitation of this approach is the neglect of the learning process as map-based assessments only evaluate *what* is in the map, without considering *how* it's created. In the above section, I have described the need of designing cognitive affordances to support concept mapping. These affordances such as template and navigational support can predominantly change the way learners search, access key information, organize the map structure, as well as compare and contrast relation information.

Thus, apart from assessing the outcome map, student models should also evaluate the use of technological affordances and relevant learning behaviors during the concept mapping process when considering possible forms of intelligent support. For example, in what order are the concept nodes and links created? How does the learner interact with the template? How does the learner process the learning content while building the map? Resolving these questions can be critical to diagnose student learning, as even two identical maps can result from two completely different strategies, and these strategies might influence learning results. However, little research work in the literature has comprehensively evaluated such behavioral characteristics in concept mapping. Thus, I foresee an opportunity to develop a cognitive model to qualitatively evaluate learning behaviors in concept mapping in different granularities. Such model will be critical in predicting student learning, diagnosing misconceptions and providing effective instructions. The research question I propose for this challenge is **Q_4: "Is a process-based learning model more predictive of learning than an outcome-based**

model?". This research question is explored in Chapter 5 and Chapter 6. Chapter 5 took a preliminary peek into certain behavioral characteristics within the concept mapping process and examined their learning effects. Chapter 6 continues the investigation by augmenting the student model in Chapter 5 with positive and negative behavioral patterns that impact learning.

Student need effective instructions in concept mapping.

Feedback is one of the most powerful influences in learning. Prior works in the literature have explored providing feedback in concept mapping to support learning and have achieved promising results. However, existing feedback mechanisms have several drawbacks that need to be addressed. Current feedback approaches mainly focus on maps learners create, while neglecting the cognitive process of the construction. The above sections have highlighted the importance of providing cognitive affordances to facilitate the process of accessing key information and comparing related concepts. With these innovations and affordances being introduced in concept mapping contexts, instructions in concept mapping should also cover how to effectively use these affordances to develop beneficial learning strategies. Thus, feedback in concept mapping can be more effective if the learning behaviors and strategic moves during the construction process are both evaluated and supported.

In addition, the outcome-based diagnosis model requires students to finish the whole concept map or submitting a current version of the map. Instructions in these approaches are usually delayed, which makes it challenging to provide instant step-by-step guidance to support the map construction. Hence, I foresee the need to develop an instant feedback mechanism that incorporate both out-based model and process-based evaluation to offer instructions that corrects errors in the map, as well as fostering beneficial learning strategies. To resolve this challenge, I hereby propose this research question **Q_5: "Does outcome and process combined feedback improve the benefits of concept mapping?"** Chapter 7 explores this research question by evaluating a feedback system that augments existing outcome-based mechanism with process-based diagnostics and personalized instructions.

1.3 Contributions

This thesis work presents the development of *MindDot*, an iPad-based interactive concept mapping learning environment integrated with a digital textbook. The system is designed to tackle the research questions and their associated challenges presented above through different innovative features. One of the core features of *MindDot* is the integration between the learning material and the concept mapping tool. *MindDot* uses a split screen design that displays the textbook content and the concept mapping view at the same time. This integration has several benefits. To begin with, it allows learners to create concept maps directly from the content. *MindDot* offers touch gestures that enables users to quickly select key concepts from the content and add them as nodes without the tedious effort of typing. Second, the integration creates coherent connections between the created map and the content, which leads to the major innovation, that is the integrated template and hyperlink navigation support. All the created nodes in the map can later be used as navigational anchors, that permits quick comparison to related content. Similarly, the expert template can be used as both expandable scaffoldings and navigational guides. Apart from these innovations, *MindDot* allows users to perform all the interactions in concept mapping, including reading content, extracting key concept, creating nodes, comparing related information, all in one place. The centralization of all the learning behaviors enables me to evaluate and model the whole learning process, and later, provide diagnostic feedback to support effective learning behaviors and beneficial strategic moves. The development of the system went through several round of iterations and each modification is based on empirical study results. By exploring the proposed research questions with *MindDot*, this thesis work plans to make the following main contributions:

1. Developing an intelligent concept mapping system that provides cognitive support.
2. Establishing a learner model that evaluates learning strategies in concept mapping and predicts learning results.
3. Designing a feedback tutor that fosters beneficial learning strategies in concept mapping and enhances learning.

The remainder of the thesis is structured as follows. In Chapter 2, I will discuss the background and related work of concept map-based learning. The literature review covers various aspects of concept mapping, including history of concept maps, theatrical and empirical support of concept mapping, different ways of practicing concept mapping, the development of computer-based concept mapping tools, as well as providing feedback and instructions to support concept mapping. I finalized the chapter with a summary of current works and a discussion of remaining challenges. With the goal of creating an intelligent and effective concept mapping system, Chapter 3 begins to explore the effect of adaptive expert templates. The proposed approach furthers existing template support by tailoring the design of the template to fit student prior knowledge. The effect of my approach is tested by a controlled study. The chapter ends with a discussion of the empirical results and suggestions for template designs. In Chapter 4, I present the initial design of *MindDot*, an intelligent and interactive concept map-based learning system. The initial design of the system contains some of the core features designed to support concept mapping, including integration of textbook content and concept mapping tool, interactive gestures and navigational support. *MindDot* is a critical component of this thesis work, as it serves as a centrum for all the learning activities, which allows me to evaluate and model the cognitive process of the map construction. In Chapter 5, I present an empirical investigation that evaluates the innovations of the system. In addition, I propose a student model that traces different behavioral characteristics and strategies during the learning process. The chapter then concludes with suggestions of potential ways of supporting beneficial learning strategies during concept mapping. Chapter 6 furthers the initial design of *MindDot* by incorporating a template-based support. The innovation of this approach is the integration of the hyperlink navigation and the expert template, which facilitates the understanding of the template and enhances navigational capabilities of the system. I then describe a controlled experiment that investigates the effect of the innovation. Based on the study data, I then present a sequential analysis that extracts behavioral patterns and two types of visualizations, which reveals certain behavioral characteristics. I finalize the chapter by refining the process-based student model presented in Chapter 5 with more fined-grained evaluation of the learning process. Chapter 6 approaches the theme of providing feedback to support concept mapping. I will start by describing different types of feedbacks in the system, the goal of each type of feedback and how they are triggered. The system is evaluated through a controlled lab study, from which I draw insights related to the learning effect of different types of feedback mechanisms as well as how they influence learning. Finally, in Chapter 7, I conclude with an overall discussion of how the contributions in this thesis work addresses the three proposed major research questions, as well as their implication for the advancement of feedback designs in supporting concept map-based learning.

CHAPTER 2

BACKGROUND AND RELATED WORK

This section provides background on the main research areas employed by this research—affordances in concept mapping, student modeling, and adaptive feedback. I begin by describing different aspects of concept mapping, including different types of knowledge organizers, advantages and drawbacks of concept mapping, and empirical evaluation of concept mapping activities. I then present current research work on supporting concept map construction. These research works include computer-based concept mapping tools, concept map-based navigation, template-based support, and diagnostic feedback. Afterward, I will survey how research in the literature has modeled and evaluated the concept mapping process, including evaluations on the reading strategies, self-regulated learning, and sequential pattern analysis in concept mapping. From there, I describe the use of feedback in intelligent tutoring systems and current approaches to providing feedback in concept map-based learning environments. Finally, I conclude the section with a discussion of existing challenges in using concept mapping as a learning tool and how this proposed thesis work builds on prior research work to cope with these challenges.

2.1 Concept Mapping and Learning

Graphic organizers are two-dimensional visual knowledge representations that illustrate relationships among concepts or processes by means of spatial position, connecting lines, and intersecting figures (Ives and Hoy, 2003; Taylor and Alvermann, 2013). Some commonly used diagrams like scatterplots, flow charts, and timelines can all be considered as graphic organizers.

Proper use of graphic organizers allows visualization and displays of complex information and relationships that are hard to be explicitly presented in text format. This information has great potential to promote learning, as it facilitates the process of activating prior knowledge and illustrating its relationship with new concepts (Hawk, 1986). Different types of graphic organizers have been developed and evolved in the past to visualize ideas, concepts, and complex relationships. For example, the flow chart was developed in 1973 to describe the structure and workflow of computer programs (Nassi and Shneiderman, 2005). Its ability to summarize and visualize software workflows yields a wide adoption in logical analyses of programs and program verification, optimization, and debugging. More recently, with the help of vastly developed computer technologies, a variety of mapping tools including concept mapping (Novak and Cañas, 2008), mind mapping (Mento, Martinelli and Jones, 1999), and argument mapping (Bell, 1995; Gelder, 2002) have become more popularly adopted in educational settings. These mapping tools share a similar objective, that is, supporting the understanding of knowledge relationships by explicitly connecting them or manipulating them in a diagram. The process of constructing these relationships and completing an inter-connected cognitive network supports the understanding of complex knowledge structures and the process of relating new information to the learner's existing knowledge structure. These benefits would yield meaningful learning (Mayer, 2002) compared to traditional learning methods such as reading and note taking (González *et al.*, 2008; Ponce and Mayer, 2014a).

This work focuses on exploring learning with concept maps. A concept map can be regarded as a type of graphic organizer, in which key concepts are denoted as labeled nodes and relationships among them are illustrated as labeled links connecting related nodes. There is a lot of flexibility in how a concept map can be created. For example, the links in a concept map can be labeled or unlabeled, directional, or non-directional. Compared to other types of mapping tools, such as mind mapping, concept mapping is more structured and less pictorial in nature. The goal of concept mapping is to outline relationships between ideas in a hierarchical manner. Concept maps can be used in different ways in educational contexts. It can be used as a learning tool, allowing the learner to actively select key concepts and establish relationships among them to enhance learning. It can also be used as a teaching tool, highlighting some of the key concepts and relationships while preparing for a class. In addition, it can also be used as an assessment tool to evaluate conceptual knowledge. Some of these scoring methods overcome some shortcomings in traditional assessment methods like multiple-choice questions and standard tests. In the following paragraphs, I will describe some major usages of concept mapping and its current challenges.

2.1.1 Concept map as a learning tool

Concept mapping is an effective way of learning because it requires explication and reflection and may help students to develop auto-monitoring techniques and so to enhance their critical thinking (Hammond, 1994). Evidence from the cognitive sciences shows that visual displays and mapping tools facilitate learning (Vekiri, 2002). The learning effect of concept mapping is supported by various cognitive theories and empirical studies. For example, its impact on recall, retention, and long-term memory can be explained by the dual coding theory, and the influence in cognitive engagement is grounded by the active learning theory. The rest of the paragraph describes psychological foundations of concept mapping as well as empirical evidence of concept mapping.

Dual coding theory

Paivio (1990) proposed a dual coding theory claiming that there are two distinct and independent but also interlinked cognitive systems for processing information: an imagery system for nonverbal information and a verbal system for linguistic information. The two cognitive systems are functionally distinct as they process visual and verbal information separately and independently of each other. They are also structurally distinct because they store information in different representation units, the logogens and the imagens. Although these two cognitive systems are functionally and structurally different, they are interconnected. Associative connections can form between the verbal and visual representations, enabling the transformation of each type of information into the other. For example, when hearing the word "car", people can easily relate to an image of an actual car in their mind.

Links between verbal and visual codes provide additional retrieval paths for both types of information. Thus, visualization and mapping tools contribute to the effectiveness of instruction by enabling learners to store the same material in two forms of memory representations, linguistic and visual. When presented with verbal and visual information at the same time, learners are more likely to form associations between visual and verbal material during encoding. This may increase the number of paths that learners can take to retrieve information by activating both verbal and visual representations (Clark and Paivio, 1991). Empirical investigations in the literature have shown evidence that presenting illustrations and maps along with verbal information presented as text increases recall of information referenced in both the map and the verbal presentations (Diana and Webb, 1997). Later, Kulhavy introduced a conjoint retention theory that interprets dual coding theory applied specifically to map-based learning (Kulhavy, Stock and Kealy, 1993;). Therefore, concept map can be an effective tool to promote learning as it requires learners to construct a spatial frame for indexing and efficiently retrieving concepts and their relationships, which facilitates the association between visual and verbal information.

Active Learning Theory

Active learning theory has been proposed by various research works (Bonwell and Eison, 1991; Sonnleitner, 2017). The idea of active learning is simple. Meaningful learning is more likely to occurs when students are encouraged to engage in productive learning activities. Activities such as note-taking, text highlighting, concept map construction are considered a productive learning activity because the learner is cognitively engaged in activities that are related to the instructional objective. Later, Chi and Wylie proposed an ICAP framework that further categories learning into four modes based on different levels of cognitive engagement and learning behaviors (Chi and Wylie, 2014). The ICAP framework states that *Interactive* engagement achieves the greatest level of learning, followed by the *Constructive* mode, which is greater than the *Active* mode, which in turn is greater than the *Passive* mode (I>C>A>P). The constructive mode in the ICAP framework are behaviors in which learners generate or produce additional externalized outputs or products beyond what was provided in the learning materials. Concept mapping is highly beneficial to learning as it can be considered as a constructive mode of engagement. When constructing concept maps, learners are not just manipulating content presented the given learning material, but are constantly generating outputs, such as cross-section relationships and hierarchical knowledge structures beyond what is provided. Research work has shown that compared to *active* modes of engagement such as note-taking, concept mapping yields significantly better learning outcomes (Ponce and Mayer, 2014b).

Empirical Evidence

The effect of concept mapping as a learning tool has been evaluated by various research in the literature. Horton et al. (1993) conducted a meta-analysis of 18 classroom-based concept map studies. In 15 of the reviewed studies, students created the concept maps and 3 studies in the review used teacher-prepared concept maps for learning. They reported (over 14 studies) that concept mapping by students raised posttest achievement scores by a mean of 0.42 standard deviation. The mean effect size reached 0.88. A more comprehensive meta-review was reported by Nesbit and Adesope (Nesbit and Adesope, 2006), in which they extracted 55 studies from the literature, involving 5,818 participants. The review suggested that learning with concept maps are more effective for attaining knowledge retention and transfer, compared to activities such as reading text passages, attending lectures, and participating in class discussions. The benefit was found on learners across a large range of educational levels, subject areas, and classroom settings. This report showed evidence that compared with constructive learning activities according to the ICAP framework (Chi and Wylie, 2014), such as writing summaries and outline, concept mapping was slightly more effective.

Research works in recent years have focused on exploring the effect of concept mapping on more specific aspects of learning. For example, concept mapping has been shown to have promising impacts on students' problem-solving skills (Okebukola, 1992) and aid in collaborative learning (Sizmur & Osbourne, 1997, Martínez 2010). Similarly, other research has shown evidence that learning through constructing concept maps had a positive impact on critical thinking skills (Lee, 2013), as well as self-regulation and self-efficacy (Chularut, 2004).

2.2 Computer Based Concept Mapping

For many years, concept maps were drawn by hand. While concept mapping has been shown to be a beneficial learning activity, the traditional pen-and-paper approach has limitations. Anderson-Inman and colleagues (Anderson-Inman and Zeitz, 1993) have claimed that the greatest obstacle to practicing concept mapping in classroom settings is the process of making a concept map. Reader and Hammond (Reader and Hammond, 1994) found that even college students had difficulty in constructing and revising a concept map. A study conducted by Chang (Chang, Sung and Chen, 2001) suggested that the pen-and-paper concept mapping approach revealed limited leaning improvements. Similarly, Anderson-Inman et al. (Anderson-Inman and Horney, 1997) observed that concept mapping was rarely used spontaneously by students, because it was difficult and that the process of map modification was messy and cumbersome. When creating concept maps, students need to write down all the concept names and draw links to connect them. The writing and drawing process is time-consuming. What's more, as the concept map gets larger, expanding and editing the existing map would be much more challenging. Although these repetitive writing and drawing actions might assist students in memorizing key concepts, the real benefit of concept mapping lies in the process of extracting key concepts from the content and establishing relationships among concepts. The high demand of time and effort in making concept maps leaves students less time to focus on germane learning processes (Hwang, 2013). In addition, pen-and-paper concept mapping is time-consuming to evaluate, and it can be difficult for instructors to provide appropriate feedback to students during the task (Chang, 2001).

The introduction of personal computers enabled the development of computer-based concept mapping tools such as CmapTools[1], Mindmaple[2], and Mind Vector[3]. These computer-based concept mapping tools provide features like fast input, easy modification, and map sharing. Computer-based concept mapping systems significantly reduced the tedious process of writing, copying, and editing, and enabled learners to spend more time on cognitively beneficial behaviors such as extracting important concepts from the content and identifying relationships among them. Anderson-Inman and Zeitz (Anderson-Inman and Zeitz, 1993) described the benefits of concept mapping using computer software over traditional pencil and paper methods of organizing information. They found that classroom use of Inspiration, a concept map-based learning environment encouraged users to revise and manipulate their concept maps.

Plenty of research works have demonstrated that computer-based concept mapping tools have demonstrated significant advantages over traditional concept mapping tasks (Cañas, 2004), just by focusing on the mechanics of constructing the concept maps. However, these tools only provide physical level support such as fast input, easy editing, and modifying. These tools assist concept mapping in the same way that a text editor helps writing. Granted that some of these tools have demonstrated positive effects on concept mapping, challenges in

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[1] https://cmap.ihmc.us
[2] https://www.mindmaple.com
[3] https://www.mindvectorweb.com

creating good concept maps exit not only physically, but also cognitively. Few research works have supported concept mapping, both physically and cognitively. One of the major challenges of doing so is the integration of concept mapping and the whole learning experience. Many of the existing computer-based concept mapping systems are independent of other learning resources such as textbooks, web pages and notes. The system only contributes to a small portion of the entire learning experience, which involves a variety of learning activities such as reading, note-taking, critical reasoning, and concept mapping. Therefore, it's challenging for the computer system to model the whole learning process and provide effect cognitive support. This thesis work tackles this problem by proposing a computer-based concept mapping system that integrates the learning content and the concept mapping tool. My system serves as a platform for all the learning activities, which creates tremendous possibilities for modeling student learning and providing effective affordances to support different stages of concept mapping. In the next section, I will be discussing current research work that explored cognitively supporting concept mapping. I will describe three major types of affordances, template-based support, navigational aid, and strategic instructions. I will also present the advantages and disadvantages of each method as well as potential ways of improvements.

2.3 Template support in concept mapping.

An approach that both makes concept mapping more efficient and provides cognitive support is a template approach, where students are presented with an incomplete concept map, prepared by the instructor, and asked to extend it or fill in missing nodes (Chang, 2001). These templates are also referred to as "expert skeleton" concept maps (Novak, 2008). "Expert skeleton" concept maps serve as a guide or scaffold or aid to learning in a way analogous to the use of scaffolding in constructing or refurbishing a building. Research in the literature has proposed various ways of supporting concept mapping with templates. In the following paragraphs, I will present different types of template-based support and discuss the strength and limitations of each method.

2.3.1 Select to fill in

Schau et al. (2001) are some of the first researchers who attempted to support concept mapping with fill-in templates. In their work, instead of having students generate concept map from scratch, they provided students with an incomplete concept map template to fill in. The template was modified from an expert-drawn concept map. Some or all of the concept words and/or linking words were omitted. Students filled in these blanks either by generating the words to use (called "generate and fill in") or by selecting them from a set that may or may not include distractors (called "select and fill in" or SAFI). After students completed the select-and-fill-in task, the system evaluated the correctness of the filled-in concepts names and provided an assessment score.

The select-and-fill-in approach was designed to solve three main challenges students encounter when creating concept maps from scratch. First, students must learn how to draw concept maps and then actually draw them, processes that are time-consuming and can be tedious and frustrating. Indeed, some students (and instructors) do not like to and so will not draw concept maps (e.g., T. H. Anderson& Huang, 1989; Barenholz & Tamir, 1992). Second, there is no universally accepted and simple scoring system for generated concept maps (see Shavelson et al., 1994). Third, the quality of student-generated maps depends heavily on the individual's communication skills (Schau 1997).

A study was conducted to evaluate the correlation between SAFI score and test scores. Results indicated that SAFI concept map scores from middle school science and undergraduate astronomy students showed high internal consistency. The SAFI map scores were strongly related to scores from a standardized achievement measure for middle school students, regardless of grade level, gender, or ethnicity. Schau's work provided evidence that students' interactions during the select-and-fill-in process are highly correlated with learning and can be used as an effective way of measuring learning comprehension. However, the author didn't compare the select-and-fill-in approach with traditional concept mapping methods, and the effect of template-based support still remains to be explored.

A work that compared template-based support with a construct from scratch approach is presented by Chang (2001). The template that Chang used in their system was similar to the ones presented in Schau's work. However, there are still certain differences in terms of how the template is modified. In Schau's templates, only certain concept names are omitted. In Chang's system, apart from certain concept nodes, several links are also left blank. The omitted node and link names were then listed on the side for students to select and fill in. In Chang's work, they compared the learning outcomes between the experimental condition (construct-on-scaffold) with a controlled condition (paper-and-pencil). Results showed that the post-test score of the 'construct-on-scaffold' group was significantly better than the 'paper-and-pencil' group ($p < 0.05$).

2.3.2 Focus Question, Parking Lot and Expert Skeleton Map

In recent years, Novak has proposed a template-based concept mapping approach that enhances traditional expert templates with two types of additional scaffoldings, focus question and parking lot.

Focus Question

Focus question is a question that is given at the beginning of a concept map session. It's designed to provide insights for the concept mapping task and help students to get more focused. For example, "How do we measure time?" can be given to the students as the question to answer before the construction of the concept map. The type of focus question makes a difference in the type of concept maps that the student builds. A question like "What are plants?" will lead to a declarative, more classificatory concept map than the question "Why do we need plants?" Experiments show that not only the focus question, but also the root concept of a concept map have a strong influence on the quality of the resulting concept map (Derbentseva et al., 2004, 2006). It is important that a question be given and not just a topic (e.g. "make a concept map about plants"), since answering the question helps the students focus on their maps

Parking Lot

In Novak's work, a list of concepts waiting to be added to a concept map is considered as the parking lot of concepts. The starting point for the construction of the concept map can be a list of concepts that the teacher wants to make sure all students include in their map. Experienced concept mappers agree with researchers that the most challenging and difficult aspect of constructing a concept map is constructing the propositions; that is, determining what linking phrases will clearly depict the relationship between concepts. So, giving the student some of the concepts does not take away from the difficulty in the map construction, although it may somewhat limit the creativity of the student in selecting the concepts to include.

Combination of the three methods

In Novak's approach, Focus questions, parking lots, and expert skeleton maps are usually used in conjunction with each other. In this case, students will start by thinking about the focus question. Then, students will spend some time reviewing the given template, with the goal of understanding the key concepts and relationships provided in the given structure. After processing the template, students will think about missing concepts and relations. Students will then choose the concepts in the parking lot and connect them with the template to complete the concept map. The method provided by Novak brings promising insights into supporting students with incomplete templates. However, the effect of each method, as well as the combination of these methods, are still yet to be evaluated by empirical investigations.

2.3.3 Limitations in template-based support

While the research presented above suggested that supporting concept mapping with a template-based scaffold produced positive effects on student learning, a few concerns have been raised by researchers. Firstly, the flexibility of map construction in computer-based concept mapping requires further investigation. Heeren & Kommers (1992) recommended that the flexibility of map construction is a major principle in concept mapping. A flexible method for students to construct maps may benefit a greater number of students with different learning styles or skills. In a template-based concept mapping task, students are usually presented with a concept map structure that already contains a certain number of concept nodes and links. The existing structure largely limits the flexibility of concept mapping, as Chang (2001) pointed out in their work. While the students using the 'construct-on scaffold' version outperformed the students using the 'construct-by-self' version, a post-study survey revealed that the 'construct-by-self' version evoked the highest percentage of students who wanted to use concept mapping in their future studies.

Another potential limitation of template-based support is the additional effort needed to process the given template. Kinchin (2001) theorized that learners who are confronted with ready-made complex maps might initially feel overwhelmed by the unfamiliar structure and connections, and the benefit of promoting learning with a ready-template might be diminished by the extraneous effort to process it. Therefore, when designing template-based concept mapping scaffolding tools, the effort to process and understand the given templates needs to be taken into consideration. In this thesis work, we present two ways of enhancing traditional template-based support. The first approach is providing personalized templates based on students' prior knowledge. The template presented to students shows some key concepts and links that exist in students' prior knowledge structure. Concepts to be added are listed on the side. This method reduces the amount of effort to process and understand the external template as it contains only the concepts that learners know. The second approach is augmenting the template approach with a hyperlink feature, where students can use each hyperlinked concept to navigate to the page where the concept was created. Thus, this approach may help students process the template by connecting each template node to relevant textual information. Design details and evaluation of these two methods will be presented in later chapters.

2.4 Concept map-based navigation

Another way research has attempted to support concept mapping is by providing concept map-based navigation. Carnot (Carnot *et al.*, 2013) compared learners' searching capabilities between browsers based on a concept map-based interface and on a web page-based interface. It was reported that most participants searched out more information and searched it more accurately when using a concept map-based browser than when using a web page-based browser. Other researchers such as Zeiliger et al. (1996) offered students concept maps for navigation in a hypermedia learning system, with the goal of assisting learners in constructing their own visions of the domain and establish better connections between concepts. Nonetheless, the experiment showed that students with the concept map-based navigation performed the same as those without support in the learning assessments. Similarly, Puntambekar (2005) gave students a pre-made concept map that was used as a navigational guide to the hypertext learning content. Results showed that students with navigational support visited more concepts that were relevant to the learning goal. However, no significant learning difference was found between the support condition and no support condition.

A major drawback of the hyperlink navigation design is the disorientation of the navigations. As Puntambekar pointed out (Puntambekar and Stylianou, 2005), map-based navigations might not always be effective. Learners involved in hypertext learning systems not only have to understand the content, but they also need to understand the structure of the system, knowing where a particular concept falls in the big picture and what other concepts it is related to. Consequently, the flexibility and nonlinearity in hypertext navigation might cause confusion and disorientation, and in turn, diminishing the benefit of quick access to information and the ability to develop learner-oriented navigation paths.

Research in the literature has proposed several ways of facilitating learning with hypertext systems. For example, Shapiro (Shapiro, 2000) examined the effect of support hypertext-based learning with interactive overview maps. Empirical data showed that the influence of an overview guided the development of learners' internal knowledge structures. The effect is especially strong with low prior knowledge students. Similarly, Dee-lucas (Dee-lucas, 1996) tested the effect of hierarchical overviews in hypertext learning environments and found that hierarchical overviews can enhance learners' ability to locate and organize the required information in ways that are more appropriate to their learning goals. Other works furthered overview with support such as indices, search capabilities, and hot text (words in the text that can be sleeted to view additional content). Research on these methods suggested that these facilities can aid learners in developing effective study strategies (Halasz & Conklin, 1989, Heller, 1990). Therefore, the hyperlink navigation needs to be enhanced by additional support that can serve as navigational guidance. Without such support, learners are likely to randomly tapping nodes in the map and navigate to different sections in the content without specific purposes.

This thesis furthers prior research work on concept map-based navigation with several key innovations. Chapter 4 presents a hyperlink navigation feature that allows learners to navigate with concept maps created by themselves. This approach eliminates the existence of an unfamiliar expert-generated map, which reduces the cognitive effort to process the map and the disorientation caused by the unfamiliar structure. In addition, the navigational capability is developed gradually as the learner goes through the learning material. All the navigational anchor point to content that the learner has reviewed. Therefore, this approach has the potential to improve the effect of concept map-based navigation. Another innovation is described in Chapter 5, in which I integrated the hyperlink feature with the template-based support. When students first load the application, the system provides students with an incomplete expert template as a support for their concept mapping activity. All the nodes in the template are hyperlinked to relevant pages. With the navigational support provided by the hyperlink feature, students can tap on the nodes in the template and read related content. This feature has the potential to reduce the effort to process and understand the template structure. At the same time, the template serves as a navigational framework, guiding students to pay attention to where those key concepts are mentioned in the content. In this way, students can use the hyperlink feature right from the beginning of the activity to help them interpret the template, make comparisons between key concepts, and figure out what concepts to add themselves.

So far, I have surveyed two major types of support in concept mapping, template-based support, and concept map-based navigation. Although these methods have demonstrated the impact of proper support in concept mapping, these two types of support mainly focus on the early stages of concept mapping. The expert templates can be highly beneficial when learners construct their maps from scratch, but the effect is gradually diminished as the template gets filled-in, and learners are manipulating with their own nodes. Similarly, the navigational aid facilitated the access of related information during concept map construction. However, when learners' maps get more complicated, it becomes limited in supporting challenges learners are likely to encounter, such as identifying miss concepts and relations, improving completeness and correctness. Another constraint with these affordances is the lack of expert intervenes. Although these tools provide support in organizing map structures, compare and relate concepts, it is still likely that some learners might experience problems using these affordances correctly and effectively. For example, some learners might have trouble understanding the given template and decided to ignore the template and construct a map from scratch. Similarly, students without the objective or intention of comparing and connecting concepts might not use the navigational aid to search related information. Addressing these challenges can be critical in promoting learning with concept maps. Therefore, there is a need to deliver instructional support, such as hints, and feedbacks, that guides the use of provided affordances and facilitates the concept mapping process.

2.5 Feedback in Concept Mapping

Feedback has been considered as one of the most critical expert influences in learning. It is information provided by an agent (e.g., teacher, peer, book, parent, experience) regarding aspects of one's performance or understandings. The benefit of feedback comes in its ability to reduce the discrepancy between current and desired or targeted understanding (Hattie, 2007). The effect of providing feedback to support learning has been well investigated by prior research. Hattie (2007) reported a synthesis of 12 meta-analyses evaluating the effect of providing feedback in classrooms, including 196 studies and 6.972 effect sizes. The average effect size was 0.79. These meta-analyses revealed that proper use of feedback has great potential to enhance learning results. However, there was considerable variability in the reported effect sizes. Feedback directly targeted to the task and how to do it was more effective, whereas praises or punishments for task performance appears to be ineffective. Hattie (2007) further classified various types of feedback into four levels. Feedback about a task or a product (FT); Feedback about the process of completing the task (FP); Feedback at self-regulation level (FR) and feedback about the person, directed to the "self" (FS). Among the four levels of feedback, FS is the least effective, as it carries little information that provides answers to any of the three questions and too often deflects attention from the task. FP is most beneficial when it helps students reject erroneous hypotheses and provides cues to directions for searching and strategizing. FR is powerful to the degree that it leads to further engagement. FT is powerful when it results from faulty interpretations, and it provides cues to improve strategy processing or enhancing self-regulation.

The power of feedback in concept mapping context has been demonstrated by research in the literature. For example, Hirashima (2011) proposed the Kit-Build concept map framework where a learner builds a concept map by using only a set of provided components and automatic assessment of a learner-build concept map is given based on how student use these components. Similarly, Wu (2012) presented a concept mapping environment that provides feedback based on the similarity between a student map and an expert map. In this work, the feedback given to students is tailored to their final product, that is, the concept map created. Other researchers have attempted to provide diagnostic feedback by automatically scoring students' concept maps (Taricani, 2006). But no significant difference was found in the learning results.

The work presented above has shown promising results in providing feedback to facilitate concept mapping. Nonetheless, feedback in much of the current mechanisms is only triggered when students finish the whole concept map (Sugihara *et al.*, 2012; Hirashima *et al.*, 2015) or submit a current version of the map to the system (Wu *et al.*, 2012). There are several drawbacks in current approaches. First of all, feedback in these works is usually delayed. Students are not able to get immediate feedback during the concept map construction process in order to correct misconceptions or misbehaviors. Several research works have pointed out that in a lot of scenarios, delayed feedback can be less effective as immediate feedback. Opitiz and colleagues compared the effect of immediate and delayed feedback on language learning (Opitz, Ferdinand and Mecklinger, 2011) an suggested that delayed feedback resulted in a substantially reduced proportion of correct answers as compared to immediate feedback. Other work in the literature presented similar results that revealed reduced learning when feedback was delayed by a few seconds (Todd Maddox, Gregory Ashby and Bohil, 2003). Therefore, I foresee potential benefits of providing immediate feedback in concept mapping. For example, when learners just started the concept mapping activity, there could be instructions about the overview of the topic and what concepts to focus on. Or when a learner is stuck at a certain point during concept mapping, there could be hints about potential improvements of the concept maps. However, current outcome-based methods are limited in offering such support.

Another drawback of current work in providing feedback in concept mapping is the neglect of different types of learning behaviors during the concept mapping process. Current feedback mechanisms mainly focus on the final map students created. Few have evaluated the learning process and provide feedback to support it. We argue that it is just as important to consider the cognitive process of concept constructions. As two identical maps can result from two completely different strategies, and these strategic moves can be highly representative of learning characters such as objectives, motivations, and misconceptions. Unfortunately, prior research misses the opportunity to offer feedback based on learning strategies and patterns students perform during concept mapping. Granted that providing feedback based on the outcome has been shown to have significant impacts on learning, feedback could be more accurate and effective when different types of behaviors in the concept mapping process are taken into consideration. For example, when a student is reading the content continuously without actively adding concept nodes to the map, feedback such as "Hey, we notice you have been reading the book for a while. Are there any important concepts you would like to add to your concept map?" could be highly beneficial. Or, if the learner connects two nodes without spending enough time reading them in the content, feedback that reminds the learner to review and compare these two concepts in the learning material could yield a more consolidated understanding of the relationship between the two concepts. In order to provide such support, a prerequisite step is to establish an understanding of the learning process. In the following paragraphs, I will discuss current research works that evaluate the learning process, such as reading behaviors, cognitive engagement, learning strategies, and metacognition.

2.6 Reading Strategies

While concept map has been practiced in educational research in different contexts (McClure, Sonak and Suen, 1999; Novak and Cañas, 2006a; Liu and Lee, 2013), this thesis work focus on using concept map as a learning tool. In this scenario, learners are given some reading content and are asked to build a concept map based on the material. The concept mapping task involves the process of reading the material, extracting key concepts, establishing relationships, and organizing knowledge structures. All these behaviors require the acquisition of new information related to the learning goal. Reading is a central element of the entire concept mapping process, as it connects and assists the transitions of different cognitive behaviors. Thus, understanding the reading comprehension process is critical in order to provide support and instructions in concept mapping. Research reports have suggested that skilled readers are distinguished by a great deal of strategic behavior carried out while reading (Jenkinson, 1978; Anderson, 1979). Research in the literature has proposed various types of beneficial learning strategies in reading compression. However, Bereiter and Bird (Bereiter and Bird, 1985) proposed four effective reading strategies that models the process of problem solving, information seeking, comparing and relating concepts. I have discussed earlier that these processes are critical elements in concept mapping. Therefore, I describe these strategies and some potential use in modeling concept mapping activities in the following paragraphs.

1. **Restatement**. The development of another form of restatement in which material is rephrased in simpler or more familiar terms. This could be indicated as an "adding" node behavior in concept mapping context, as students choose or input a word to summarize a certain concept.
2. **Backtracking**. Looking back and resuming reading at some point previously passed could arise either from failure to comprehend the last segment read or from loss of connection with previous sections. In concept mapping activities, this could be represented as revisiting previous read pages or sections in the text to compare concepts and create relationships.

3. **Demanding relationships**. The development of relationships between concepts permits readers to generate knowledge beyond what's presented in the content. This is a response to missing information that the reader expected later portions of the text to supply. In the concept mapping context, this could be indicated as actively creating concept links among concepts to demonstrated learns' own understandings in the text.
4. **Problem formulation**. Formulating some difficulty as a problem was itself a strategic move, which enables the reader to bring into play general problem-solving procedures that are not normally activated during reading.

Empirical data from previous work suggested that instructions on developing these learning strategies had significant impacts on learning. Students who gained more on these learning strategies also gained more on reading comprehension outcomes. Similarly, Olshavsky (Olshavsky, 1976) classified reading strategies into 10 categories, such as synonym the substitution strategy, the inference strategy, and story-related strategy. Results indicated high learning students and low learning students are differentiated by the usage of certain strategies.

More recently, research on hypertext comprehension has also explored the relationship between reading strategies and comprehension. Salmerón *et al.* claimed that reading strategies in hypertext could be considered as the decision rule that a reader follows to navigate through the different nodes of a hypertext (Salmeron, Canas and Kintsch, 2010). Two empirical studies were presented to assess the effects of reading strategies such as reading orders, reading habits, on reading comprehension. Empirical results indicated that low-knowledge participants learned more by following a high coherent reading order, whereas high-knowledge participants learned more by reading the hypertext in a low-coherence order. Similar research works in the literature further reinforced that reading comprehension results are significantly determined by how learners process the text and what reading strategies learners use.

Research works presented above have highlighted the importance of supporting effective strategies to promote reading comprehension. Granted that reading comprehension is a critical element in concept mapping activities, students are involved in other types of cognitive engagement, such as goal setting, summarization, building relationships, and identify missing concepts, when constructing concept maps. Understanding reading strategies is inadequate to model the entire learning process in concept mapping. Hence, to provide accurate and effective support in concept mapping, there is a need to develop a more comprehensive model that incorporates a larger variety of behaviors and strategies.

2.7 Self-Regulated Learning

There are plenty of cognitive frameworks and pedagogical theories that model students' individual differences in the learning process. One of the major approaches in this field research is to evaluate the process of goal setting, strategic planning, self-monitoring, and verbal elaboration during learning. The learning process that constantly involves the use of these behaviors and strategies are known as self-regulated learning. Self-regulated learning is defined as a metacognition guided learning process, in which learners independently and proactively engage in self-motivating and behavioral processes that increase goal attainment. The effect of self-regulated learning has been investigated and reported by numerous research works. Zimmerman and Martinez-Pons (Zimmerman. B and Martinez-Pons, 1986) assessed students' use of self-regulated learning strategies in both classroom and non-classroom settings via a structured interview procedure. They designed 14 categories of strategies to model self-regulated learning and found that the high learning group reported significantly greater use than the low learning group for 13 of these categories. High achievers also reported significantly less single category of non-self-regulated strategy than low achievers. In addition, the data analyses revealed that student use of self-regulated learning strategies yielded a substantial increase in the prediction of standardized achievement test scores.

A similar study was conducted by Azevedo, Guthrie, and Seibert (2004) on college students' ability to learn about complex science topics. The study investigated how students use self-regulated learning strategies when using a hypermedia environment to learn about the circulatory system. The results revealed individual differences in learners' ability to regulate their learning. Students with higher learning gains were much better at regulating their learning during knowledge construction activities. In contrast, low learning students demonstrated less capabilities in leveraging self-regulated strategies to monitor their own learning. Other empirical investigations and cognitive theories in the literature have provided additional evidence for the impact of self-regulated learning (Pintrich and de Groot, 1990; Zimmerman, 1990; Pintrich, 1999; Paris and Paris, 2001).

It was further reported that proper instructions on fostering the development of self-regulated learning could be highly beneficial. Hattie et al. (Hattie, Biggs and Purdie, 1996) analyzed the impact of diverse training characteristics of interventions to foster study skills based on a meta-review involving 270 effect sizes from 51 interventions that aimed at improving learners' use of various types of study skills. The results indicated that interventions were most effective when fostering a high amount of student activity and metacognitive awareness. The effect on teaching students self-regulated learning strategies was further highlighted by Azevedo and Cromley (Azevedo and Cromley, 2004), who presented empirical evidence that training learners to self-regulate their learning on the basis of a 30-min training period on the use of specific empirically-based self-regulated strategies and variables led to significant increases in their understanding of the circulatory system. What's more, verbal protocol data suggested a correlation between training learners received and the use of the self-regulated variables. Students who received instructions on self-regulated learning can effectively deploy the key self-regulated learning processes and mechanisms that led to significant shifts in their mental models.

Apart from exploring the learning effect of self-regulated learning, several research works have specifically investigated the use of self-regulated learning in the concept mapping domain. Corno and Mandinach (1983) argued that using a concept-mapping strategy can be a powerful means to promote self-regulated learning skills, which would support learners experiencing meaningful learning. Correspondingly, Chularut and DeBacker (2003) stated, with empirical data, that concept mapping activities promoted not only learning results, but also the use of self-regulated learning strategies. Subsequently, Novak and Gowin found that concept maps could help students learn how to learn (Novak & Gowin, 1984).

To amplify the benefit of self-regulated learning in concept mapping, researchers have attempted to provide computed-based intelligent support to foster self-regulated learning skills. One example is Betty's Brain, a teachable agent system, in which students teach a computer agent through the construction of a concept map. The system monitors users' teaching behaviors and provides metacognitive feedback to support self-regulated learning. Feedback in the system is triggered by tracing students' teaching behaviors and qualitatively reasoning through the concept maps. For example, during the goal setting phase, the mentor in the system gives advice on what to study and how to study; during the knowledge monitoring phase, TA and Mentor ask students to reflect on the questions not answered correctly to determine what to learn. Compared to traditional outcome-based feedback that directly informs the students about errors and misconceptions, feedback in Betty's Brain target more on teaching students how to be a better learner. An empirical study was conducted to compare student learning from Betty's Brain while getting direct outcome-based feedback and self-regulated feedback. Results suggested that directed feedback enhanced student learning performance in the early sessions of the main study. The effect of metacognitive feedback in their learning and self-monitoring tasks stated to appear in later sessions as students gradually learned to use self-regulated strategies. The transfer test revealed more visible positive impacts of the metacognitive feedback as students received metacognitive feedback were able to transfer their self-regulated strategies to a new learning environment, where most of the scaffolds to aid the learning task were removed.

Betty's Brain highlighted the importance of supporting beneficial learning strategies and behaviors. However, there are some challenges applying this approach in scenarios where students learn by constructing their own maps. First, the self-regulation features used for tracing learners' teaching behaviors in Betty's Brain contains a very specific action. For example, "goal setting" refers to the action when learners ask the mentor about what to study;

"Seeking Information" refers to the action when the learner looks up online resources. Betty's Brain does not keep track of the sequences of how these actions are performed. A "seek information" action can happen after a student finishes asking the mentor about the learning goal. Or, it can happen after a student finishes taking a quiz. The same action might have different implications of student learning in different scenarios and contexts. In addition, the self-regulation features presented in Betty's Brain are fairly high level. It lacks fine-grained information about the thinking and reasoning process that learners go through when constructing the map As Zhou et al., (Zhou *et al.*, 2011) argued, analyzing frequencies of singular learning behaviors are limited in capturing either patterns of an individual's study tactics or navigation in a hypermedia environment. To fully understand and capture the cognitive dynamics of the learning process, tracing methodologies such as sequential pattern analysis or transition matrix need to be applied.

Recently, Winne (Winne and Hadwin, 2013; Marzouk, Rakovic and Winne, 2016) developed a multi-media learning system nStudy, which supported learning with tools such as concept maps (referred as TermNet in the paper), notes, and tagging tools. The system traced students' learning processes through sequential pattern mining algorithms. This modeling method extracted frequently occurred behavioral patterns, such as "browse, make term, browse, update term" that indicated certain learning objectives. Combinations of different behavioral patterns then accumulated to form certain learning strategies. A limitation of Winne's evaluation is the lack of understanding of the learning impacts on each behavioral pattern. It remains unclear what type of behavioral patterns are more beneficial and worth supporting.

Nonetheless, Winne's work advances prior research in evaluating process data and broadens views about learning and other processes that relate to learning. Understanding the learning process and identifying patterns of activities have great potential to elaborate descriptions of learning processes by generating a more accurate picture of what is "going on" during learning and offer meaningful insights into students' learning strategies and motivation, and how their strategies and motivation change within a session or across sessions.

Hence, in Chapter 4 of the thesis work, I continue the exploration of the learning process by developing a comparative strategy model that detects and extracts positive and negative behavioral patterns in an action-by-action manner. This model furthers Winne's work by investigating the learning effects of different behavioral patterns, which enabled the development of a feedback mechanism that provides instructions on fostering beneficial behavioral patterns. This feedback method furthers traditional outcome-based approaches by incorporating behavioral characteristics in the cognitive learning process.

2.8 Summary of Related Work

Research reviewed in this section highlights the need for providing effective support to facilitate students in concept mapping. Prior research has explored various ways of leveraging computer technology to assist concept mapping. Some of the previous work mainly focus on supporting the mechanics of constructing concept map, without directly scaffolding the cognitive processes involved in concept mapping. For instance, developing efficient concept mapping software, using concept mapping as navigation tools, and offering incomplete templates. Some are able to provide diagnostic feedback to correct misunderstandings or suggest missing concepts. However, these works only evaluate the outcome of the concept mapping activity, while neglecting the cognitive process in concept mapping. While research has explored providing metacognitive feedback to support self-regulated learning skills, the student modeling lacked sequential contexts, and instructions given to the learner were too high level. In order to provide step-by-step guidance to foster effective learning strategies, there is a need to develop a comprehensive learner model that evaluates different behavioral patterns and strategic moves, as well as their learning impact from a fine-grained level.

To address these challenges, this thesis work presents *MindDot*, a concept map-based learning environment that supports concept mapping through interactive gestures, hyperlink and template support, process-based diagnosis, and adaptive feedback. The system integrates the learning content with the concept mapping tool, which not only provides easy concept map construction but also serves as the centrum for all the learning activities, such as reading, comparing, summarizing, and reviewing. This integration allows me to record and evaluate different types of learning behaviors students perform in the system and provide feedback to support these effective learning strategies. The development of *MindDot* involves four design and evaluation iterations. In the following chapters, we will specify each iteration of *MindDot*, including objectives, system features, empirical evaluations, and implications for future designs.

CHAPTER 3

EXPLORING TEMPLATE-BASED AFFORDANCES IN CONCEPT MAPPING

The fundamental objective of thesis work is to leverage computer technologies to support concept mapping intelligently. Addressing this problem entails dealing with three major challenges, that are designing effective concept mapping systems, modeling student learning, and providing accurate feedback. This chapter starts the research by tackling the first challenge, designing a computer system that provides effective cognitive support in concept mapping. Based on the results and implications from previous work in supporting concept mapping, I have described a 3-step research agenda to resolve this challenge, that is: 1. Design template-based scaffolding that is easy to understand and expand. 2. Design navigational support that facilitates the access to key information and the comparison among related concepts. 3. Integrate the template and navigational support in a complete computer system.

This chapter begins the research by tackling challenges in the template-based support with the following reasons. First, template-based support is one of the most impactful influences in concept mapping as it directly scaffolds the structure and the quality of the maps. Supporting the quality of the map can be highly effective, as research has pointed out that qualitatively different concept maps lead to different learning gains. Kinchin (Kinchin, 2001) classified concept map structures into three categories: spoke, chain, and net, and found that only the net structure, in which nodes in the map are highly interconnected and has a complete knowledge structure, lead to meaningful learning. The net structure is also more cognitively demanding, requiring students to identify key concepts in the content and generate relationships and connections beyond what's presented in the learning materials. Therefore, template-based support has great potential to improve the quality of the maps and promote learning with concept mapping. Another reason that I started with this approach is that exploring template-based support does not require a specifically designed system. In fact, there are a large variety of existing concept mapping tools that I can use to manipulate different designs of the template. The system I used for this work was the CmapTools. CmapTools is a software program developed at the Institute for Human and Machine Cognition (IHMC) that empowers users, individually or collaboratively, to represent their knowledge using concept maps (Cañas *et al.*, 2004). It is a free software program that has been widely adopted by educational researchers (Novak, 1971; Basso and Margarita, 2004; Dumestre, 2004; Eskridge, Granados and Cañas, 2006). This chapter begins to explore different types of template design and how they affect learning results. In the following paragraphs, I will summarize current challenges in template-based support and propose the research questions. Then, I will describe my methods and potentials contributions. After that, I will present an experimental investigation that evaluates the learning effect of my approach. I then finalize the chapter with results from the study and implications from template designs.

3.1 Research Questions and Contributions

It has been discussed in Chapter 2 that a major challenge in current template-based support is the extraneous mental effort to process the external template. Reducing the effort to understand the template has great potential to enhance the benefits of template-based support. Thus, this chapter focuses on tackling the research question Q_1 proposed in the introduction. To explore this research question, we need to understand the required mental effort to process the template. When presented with a ready-made template, learners are likely to get overwhelmed by the complex structure, especially when the concepts in the template are not familiar to learners. The challenge lies in the gap between what knowledge the students are familiar with and what information is presented in the given template. This gap can be considered as cognitive load, which refers to the total amount of mental activity imposed on working memory in any one instant. The cognitive theory was developed by Sweller (Sweller, 1988), who differentiated cognitive load into three types, intrinsic, extraneous, and germane. The cognitive load imposed by the expert template can be considered as an extraneous cognitive load, which refers to learners' mental effort to process information that is presented to them during learning activities. Research in the literature has argued that instructional procedures are likely to impose high cognitive load when developed without full consideration or understanding of learners' own knowledge structure. (Amadieu *et al.*, 2009). Therefore, when presented with an unfamiliar external template, learners' working memory is incapable to process a large amount of new information. The transition between working memory and long-term memory, which indicates the grasping and understanding the knowledge represented in the template (Novak and Cañas, 2008), is largely hindered.

Therefore, additional resources and materials given to the learners must be designed to fit learners' prior cognitive structures. Prior knowledge is a critical element in concept mapping, as knowledge construction occurs when students actively seek to integrate new knowledge with their prior knowledge. In a concept mapping context, the integration between prior knowledge can be represented as actions such as adding a new concept node to the existing map structure or connecting a concept node that learners have mastered with an unfamiliar concept node. Understanding learners' prior knowledge and providing relevant guidance could be a critical factor for scaffolding concept mapping (Amadieu *et al.*, 2009). By determining what knowledge students have already mastered and what concepts are new to the learner, we are able to provide guidance when the integrations occur.

We hereby propose a method of reducing the effort to process external templates by adapting the given template to leaners' prior knowledge. In our approach, the templates given to the students are personalized based on their prior knowledge. As the expert template contains concepts and relationships for which the student has demonstrated prior knowledge, it is much easier for students to understand and process the template. In addition, we list the to-be-added concepts, which represent unknown or to-be-learned knowledge, on the side, encouraging students to fill in these nodes to complete the template. Based on the discussion above, we hypothesize that students will both spend more time on unknown concepts and be better supported in connecting new knowledge to prior knowledge, thus improve learning.

3.2 Study Design

To examine our hypothesis proposed above and investigate how adaptive template-based support affects learning, we conducted a study with three conditions: adaptive scaffolding, fixed scaffolding, and unscaffolded. In the adaptive scaffolding condition, the expert skeleton map was personalized to include concepts that students had already acquired. Students in the fixed scaffolding condition also received an expert skeleton map. However, instead of aligning the map to the student prior knowledge, students in this condition received one of the personalized maps from the adaptive scaffolding condition. In this way, the two conditions were yoked, and we were able to control for content across conditions. Finally, in the unscaffolded condition, students constructed a map from scratch. In all three conditions, students were given a list of "suggested concepts," which included all the concepts in the original expert map, but not currently in the students' concept map. The system used in this study was the CmapTools described above, and the expert skeleton maps were also edited using this tool.

We conducted a study with 38 non-biology major students (22 undergraduate students and 16 graduate students). First, students were given a 10-minute online pretest to assess prior knowledge of plant reproduction. Next, students were given the chapter in an e-book format, and had 10 minutes to read. Students then received a 4-minute tutorial about what concept maps are and how to use the CmapTools to construct one. Then, they were asked to construct a simple concept map from an example text. After the tutorial and practice, students were randomly assigned to conditions and received either an adaptive map, a fixed map, or a blank (no-scaffolding) map and were given 20 minutes to construct or complete the map based on the template. Finally, a posttest (counterbalanced with the pretest) was given. To create the adaptive expert skeleton map, we first created an expert map with 72 nodes to represent the key concepts and the knowledge structure from the chapter. In order to determine which concepts to remove from the map, we mapped each question on the pretests to a portion of the expert map. This allowed us to modify the expert skeleton map based on students' pretest scores. For example, if a student incorrectly answers question 4 in Figure 3.1, the correct concept ("flower") is removed from the map and left for the student to complete.

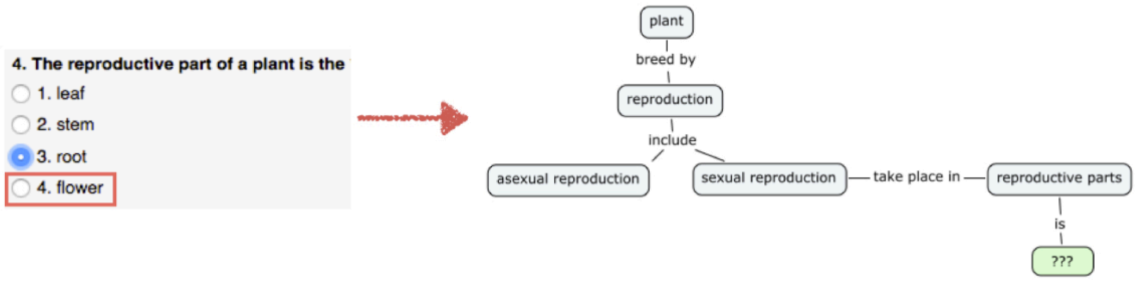


Figure 3. 1 Modifying the expert skeleton map based on test questions

3.3 Results and Implications

Our first step was to investigate the hypothesis that adaptive scaffolding is better than both fixed scaffolding and unscaffolded concept mapping. We conducted a two-way repeated-measures ANOVA with condition as a between-subjects variable and test- time as a within-subjects variable. Table 3.1 shows the mean and standard deviation of the overall scores on the 9 key ideas evaluated. Students got 1 point when they got a concept correct and 0 points when they got it wrong. All conditions had significant pre to post learning ($F[1,35]=39.60$, $p < 0.001$, $\eta 2 = 0.531$), but there were no significant differences between conditions ($F[2,35] = 1.16$, $p = 0.33$).

	Pretest		**Posttest**	
	M	SD	M	SD
Adaptive	3.21	1.31	4.64	2.13
Fixed	2.67	1.07	5.17	2.04
No support	3.00	1.60	5.50	2.02

Table 3. 1. Test Results between groups

As there was no significant difference between conditions, we were interested in exploring further how student interaction with the map influenced learning. We coded the 9 key ideas in the expert map as being: (1) added to the map by the student, (2) already existing in the expert skeleton maps, or (3) not added. For the already existing concepts in the expert map, we further categorized the concepts that were adjacent to the newly added concepts as "exist close" and the ones which were more than one hop away as "exist far". For instance, concepts "seed" and "water" are both presented in the expert template. A learner adds a node "sunlight" and links it with the node "seed". However, the learner did not link the node "water" with any nodes he adds. Then the concept "seed" is considered as "exist close" and "water" is considered as "exist far". For each type of concept, we computed the learning gain for each user by subtracting the pretest score from the posttest score. As only students in the adaptive and fixed conditions experienced all types of concepts, we only analyzed results from this subset. Means and standard deviations of leaning gains and the number of concepts in each interaction type are presented in Table 3.2.

	Gain per Student		**#Concepts per Student**	
	M	SD	M	SD
Exist close	0.59	1.18	1.59	0.51
Exist far	-0.15	1.08	2.04	0.92
Added	1.50	1.58	4.57	1.30
Not added	0.25	0.64	1.75	0.79

Table 3. 5. Gains and number of concepts for each activity

It is not meaningful to make a statistical comparison between the types of interaction due to challenges with our data set (a small number of key ideas and each key idea maps to different numbers of concepts in the expert map). However, looking at the means, it appears that adding concepts to the map was the most beneficial, followed by interacting with close existing concepts. "Exist far" concepts, which were not adjacent to concepts added, were not learned effectively.

3.4 Discussion

We conducted a study where we compared adaptive scaffolding to fixed scaffolding and no scaffolding in concept map construction. While all students learned from the concept mapping activity, we found no significant differences between conditions. Exploratory results suggest that students may learn from concepts that are added to the map compared to ones that were not added, and, for the provided concepts in the template, students may benefit more from ones that are close to the interacted region. There are several limitations in the data collection in this study that indicate caution in interpreting the results. The number of graduate students and undergraduates were not balanced throughout the conditions. Another potential problem was that the expert skeleton maps we gave to students might have been too large. While we assessed students on 9 key ideas, these ideas spanned more than 70 nodes in our expert map. The complexity of the given template might have imposed a high cognitive load on students, reducing the benefits of the expert skeleton maps. However, the tentative learning difference in the existing concepts that are close or far from the area of the map where students interacted is worth investigating. While adding concepts to the template, students may benefit most from relating existing concepts directly with the new knowledge that is being added, as they did for the close concepts. Students did not interact with the far concepts directly, and thus may not have fully mastered those concepts at posttest. Thus, even though the template is tailored to students' prior knowledge, students still struggle to fully process and interact with the template. To reveal the benefits of expert templates, more support is needed to enhance the interaction between the students and the given template. In addition, expert skeleton maps should be designed in a way that is easy to fill-in and expand, which may lead to more interactions with newly added concepts.

3.5 Conclusions

The work in this chapter took a preliminary step in designing support to facilitate learning with concept maps. The study took the template-based support as a trajectory to explore the first research question, which is exploring the effect of different template designs. The personalized scaffolding design in this work did not yield significant learning impact due to some limitations in the study. However, it did point out some interesting implications for future scaffolding designs in concept mapping. First, the study highlights the importance of supporting interactions between the students' nodes and template nodes. My empirical data suggested that meaningful learning was likely to happen during the integration between students' maps and the template structure. Therefore, instructions on how to integrate learners' maps with the template maps can be critical to promote learning results. For example, there could be some support in assisting learners in comparing and relating their own nodes with the template. Equivalently, guidance or instructions that explain or walk students through the expert template could also be promising.

Another potential implication from this work is that quick access to related information and resources is essential to learning. In this study, students benefited less from the "far" concepts, that are nodes they didn't directly interact within the template. Part of the reason that these "far" concepts existed was the inconvenient access to related resources in the system. Filling in the incomplete template required learners to review concepts in the template and then search for related missing concepts in the content. In this process, learners were constantly comparing and relating the template with the learning material. However, the CmapTools used in the study was independent of the learning content, and there was no navigational support between the concept map template and the learning content. The comparison between the template and the content could be cumbersome as learners might struggle to pinpoint the all concepts from the template to the learning content, even when the concepts contained in the template were familiar to them. Therefore, I foresee design opportunities to integrate the learning content with the concept mapping and provide affordances that connect related parts in between the two segments. Based on these implications and design suggestions, I continue the thesis work by exploring navigational support in concept mapping. The next chapter will present a first design iteration of *MindDot*, an intelligent learning system that integrates the learning content with the concept mapping tool and supports concept mapping with navigational aids.

CHAPTER 4

DESIGNING AN INTERACTIVE CONCEPT MAPPING SYSTEM

Chapter 3 described preliminary work that explored the effect of adaptive affordances in concept mapping. The work reinforced the importance of quick access to related information and pointed out future directions in supporting concept mapping, such has integrating the textbook content with the concept mapping tool and offering navigational aid. The work in Chapter 3 was based on the CmapTools, which is a widely used concept mapping tool that allowed learners to construct concept maps conveniently. Although the CmapTools is capable of offering certain cognitive support such as expert-made templates, it is largely limited in providing more complex affordances such as navigational aid or real-time feedback. In order to further explore the research questions proposed for this work, there is a need to develop a concept map-based learning system that is able to provide advanced affordances and instructions. In the next paragraph, I will discuss some drawbacks of existing concept mapping tools and present some guidelines of future concept mapping systems that address these limitations.

I have presented in the introduction that two fundamental behaviors in concept mapping are accessing key information and comparing related concepts. Computed-based concept mapping systems should be designed to support these fundamental behaviors. A major limitation with current concept mapping systems is the gap between the concept mapping system and the learning content. A lot of the existing concept mapping systems are independent with the learning content, and concept mapping activities based on these tools are often used as after class or additional tasks. Students using these tools might encounter challenges relating the concept map with the content, especially when revisiting the map after it's created. Therefore, the learning content should be closely integrated with the concept mapping tools to support the relationship between the summarized map and its detailed explanation. Such integration also enhances the capability of navigating the content using the concept maps. Another constraint with current concept mapping tools, especially for those that are independent of the learning content, is the limitation in tracking and modeling different types of learning activities. Concept map-based learning involves combinations of different learning behaviors, such as reading the content, identifying key concepts, taking notes, and making comparisons. Although lots of the current concept mapping system do record the actions learners perform within the system, it is uncapable of modeling the reading and comparing behaviors learners engage in with the learning content. Understanding the learning behaviors and interactions with the content is highly important as they can be highly reflective of the meaningful learning process. Consequently, concept mapping systems should record and model the interaction with the learning material in order to provide accurate and effective feedback.

Thus, to further explore the design of advance affordances and answer the research questions proposed in the introduction, there is a need to develop a concept map-based learning environment that meet the requirements presented above. Although this chapter does not directly tackle the proposed research questions, it takes a critical step in designing an intelligent concept mapping system, *MindDot*, which serves as a foundation for exploring these research questions. The development of the system follows a design and iterate process. In the following sections, I will describe the design details of the system and a preliminary evaluation of the system.

4.1 System Design

MindDot incorporates the implications found in the previous chapter and aims to serve as an infrastructure that provides fundamental requirements for developing advanced affordances to support concept mapping. I have discussed that one of the most important capabilities of concept mapping systems is a coherent integration of the learning content. In this work, *MindDot* integrates the learning material with the concept mapping tool via a dual window design. This integration leads to several benefits. First, *MindDot* facilitates the construction of concept maps by enabling students to create concept maps directly from the textbook content via touch gestures. This feature eliminates the tedious process of typing and editing while encouraging learners to focus on the cognitively beneficial behaviors such as comparing and reasoning. Second, this integration permits quick access to related information by allowing learners to navigate the content using the concept map. This navigational aid facilitates the processing of expert templates and the comparison of related concepts. Another critical benefit of the integration is that *MindDot* serves as a centrum for all the learning activities, including reading the content, building the map, and navigating the content and recourses. This allows the system to trace student learning by recording and monitoring all the learning activities, which further enables me to construct a learner model and provide accurate feedback accordingly.

The system was written in Objective-C and ran on the iPad platform. The content displayed in the book is in .epub format to facilitate importing new materials as necessary. The system described in this Chapter is the first design iteration. The following 2 chapters will present several design iterations of the system. Although this version of the system does not contain all the innovations, it serves as a basic framework that contains all the fundamental infrastructures. The following are the key features of the system:

1. Integrated text and concept map view. Our system has both a textbook view and a concept map view. When students hold the tablet in portrait mode, the system works as a traditional digital textbook. However, when the tablet is in landscape mode, the screen splits into two, with the left side displaying the textbook view and the right side showing the concept map view (see Figure 4.1). The dual-window alignment provides quick access to both views for easy comparison between the text and the concept map. The students navigate within the textbook view by swiping right to go forward and left to go back. One potential drawback of the dual-window design is that with the relatively small iPad screen, especially divided in half. The amount of content that can be displayed on each page is largely limited. Therefore, when users rotate the iPad to vertical mode, we hide the concept map view and display the textbook full screen to provide an easier reading experience.

2. Easy concept map construction. We have presented some limitations of concept mapping, and one of them is the tedious effort to build the map structure. A major reason that building a concept map is cumbersome is that students need to repletely write down or copy the keywords from the content to use as nodes in the map. Therefore, it is promising to reduce the effort of copying and writing and encourage learners to focus on activities that have more impact on meaningful learning, such as comparing and relating concepts. In *MindDot*, students can create concept maps through a "click-to-add" gesture. When learners long-press on a keyword or phrase in the content, a concept node with the selected word is added to the map. If students want to customize their concept maps by creating nodes that do not come directly from the text, they can add concept nodes by clicking on the "+" icon in the concept map view and using the iPad keyboard to label their nodes. To link concepts, the student first long-press on a concept node, choose the linking option and then tap the second node they want to link. Students can then choose a word from a suggested list or type their own words to specify the relationship between the two concepts. Students can delete concepts or the whole map as necessary.

3. Hyperlink Navigation. When a concept is added to the textbook, it is hyperlinked to the page in the textbook that was active when it was created. To navigate back to that page, the student can click on the concept. In addition, if the student is navigating using the textbook view (swiping left or right), when the student arrives on a page, the concepts that were created on that page will be highlighted both in the concept map view and in the textbook view. We expect that this hyperlink navigation feature would better support students in pursuing comparative strategies by helping them to compare concepts from different segments of text.

4. Map of View. I encourage learners to create complex concept maps. Therefore, the concept map canvas can be expanded to a scroll view in order to create more space for additional map structures. As the concept map gets large, it is likely that the map will not fit within the iPad screen, and the concept map view will only display a portion of the entire map. Thus, I designed a map of view feature to assist the navigation of the concept map canvas. The map of view feature is a map that displays the preview of the entire map and what portions of the map is currently being displayed. The map of view is displayed at the bottom right corner by default, and users can drag the view to other positions to avoid overlaying the concept map content.

5. Note Taking. While a concept map can be a great tool to summarize and outline the knowledge structure, one constraint about concept mapping is that the map structure contains limited information about each specific concept. When learning from an external concept map or reviewing a concept map created a while ago, learners might have trouble explain the map or relate the map with relevant information. Thus, we created a node-taking feature that allows learners to attach notes to each node. When users long-press a concept node and select the "note" button, a note-taking view will pop up for free input. Once the user finishes inputting the note, the note view will be hidden and the concept node will display a note badge, indicating that a note is attached to the node. Learners can long press the node to review or edit the notes at any time.

6. Web Resource. To further enhance the system with additional resources, I created a web resource that enables students to quickly access relevant information on the Internet and use the Internet resources to enrich their maps. To search for relevant information about a specific concept node, learners can tap on the node and select the "web" option. By doing this, the textbook view on the left will switch to a web browser that automatically returns with additional information about the concept, such as Google search results, Wikipedia search results, and relevant Khan Academy resources. If learners want to do a free web search or access other related resources, they can click the "Web" icon on the bottom toolbar to go to visit the Google home page. The web browser integrates the "click-to-add" and the navigation features. When learners are reading web resources, they can long-press important words and add then as nodes to the map and later use these nodes to visit related web pages.

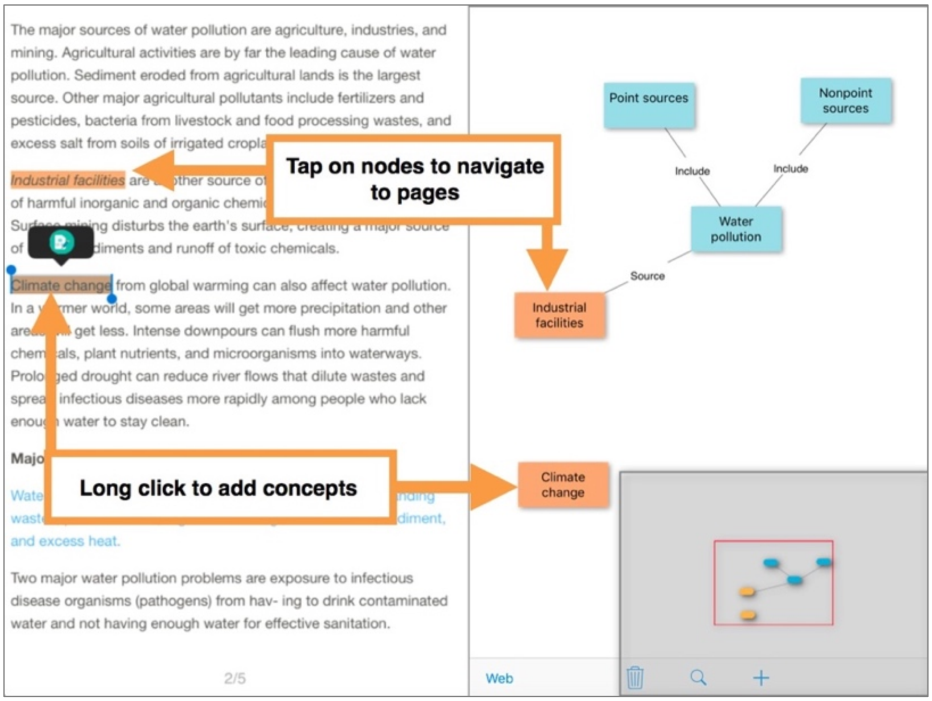


Figure 4. 1. Screenshot of *MindDot*. Students can create concept maps directly from the textbook and use the created maps for navigation.

4.2 Usage

We hypothesize that these proposed features can work with each other to offer a highly effective learning experience. An example of leveraging all the described features in the application would be as follows. A student, Sam, reads the textbook and finds the concept "seed" on page 5. He uses the "click-to-add" feature to add a node named "seed" to the concept map view, with no typing needed. He then writes a note to explain why he thinks this concept is important and attaches to the node. He continues to read the textbook. On page 30, where it talks about water pollution, he creates a node "water quality." Sam then realizes water quality might have something to do with the growth of the seed. He taps on the concept map node "seed", and the system navigates back to page 5. He reads the textbook content about the concept "seed" together with his notes attached to the node "seed" and finds out that the growth of seeds largely depends on the oxygen level and mineral composition of underground water. He then taps on the node "water quality" and, jumping back to page 30,he finds that the water quality would affect the oxygen level and mineral composition. With this information, he links the concept map nodes "seed" and "water quality" and names the relationship as "depends on". Sam then wonders whether the water quality in his hometown is affected by industrial pollution. As this information is not provided in the textbook, Sam uses the integrated web view to quickly search for water quality on Google. Sam reads the webpage about recent pollution reports and further adds several concept nodes from the webpage to the map using the "click-to-add" feature.

The example above demonstrated a scenario in which the learner leveraged all the key features in the system to access various types of information and extracted several important concepts and established relationships among them. According to Novak's theory, meaningful learning is likely to happen in scenarios like this. However, there are some unanswered questions about how learners use the system. For example, do students use all the features in the system while learning? What features are more frequently used? What are the obstacles to using the system? In the next section, I will present a think-aloud that qualitatively evaluates how learners use MindDot in a real-world practice.

4.3 Think-Aloud Study

4.3.1 Study Design

To evaluate how students use each feature and how combinations and interactions of different features affect the learning process, I conducted a think-aloud study with 7 college students. *MindDot* was installed on an iPad 2 Air, with a 9.7-inch display and a multi-touch interface. The learning material consisted of a 10-page online reading material about Energy on Earth. The reading content displayed in the application was manually edited to fit the screen of the iPad. The study session lasted about an hour. The study started with a brief training section that walked the participants through all the features in the system and how to use them to build concept maps. Students are then asked to read the content and construct a concept map while reading. During the study, students are asked to verbalize their thoughts, feelings, and opinions while interacting with the system.

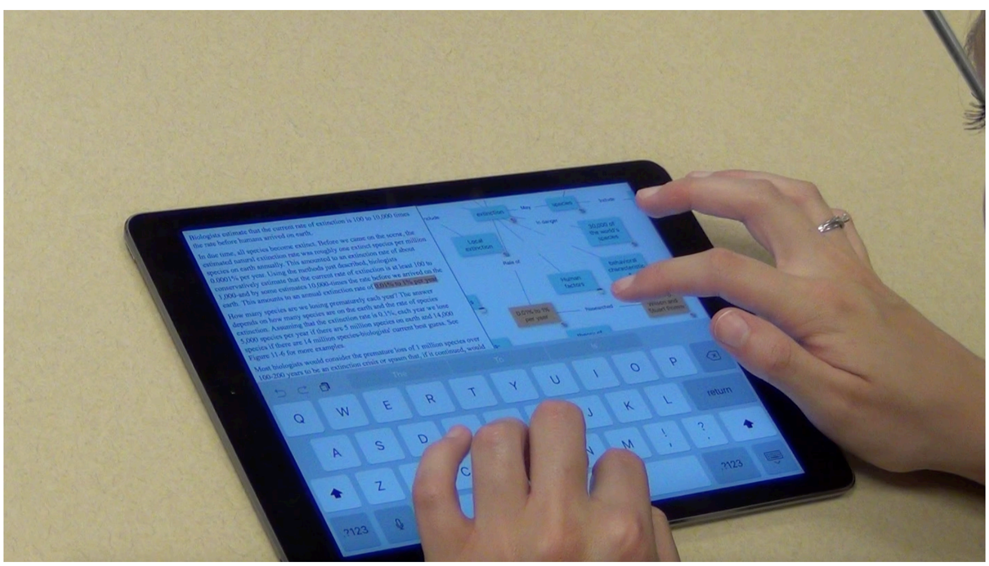


Figure 4. 2. A participant interacting with the system during the think-aloud study.

4.3.2 Results

The goal of the think-aloud study is to get a preliminary evaluation of the application and collect qualitative data to find out usability issues and make adjustments to the features in the application. Considering the small number of participants, it is not meaningful to conduct any statistical analysis or learning measurements on the data. Therefore, in this section, I will describe the general and qualitative findings of how students use the application for concept mapping and feedback for each feature.

General	**Click to Add**	**Navigation**
• "It would be nice to have arrows instead of just lines for the links" • "It would be nice if I can draw on the map with a stylus" • "I like how you can drag the nodes around" • "It would be nice to have a title section for the entire concept map"	• "I made my own node because it makes more sense than the text" • "The color coding makes a lot sense" • Some users had issue selecting the right words using one finger. • "Sometimes it's more accurate to just create your own node"	• Used more often when the map got larger. • "The navigation features helped me revisit the key concepts" • "To review the content, I'll follow the map structure and tap on the nodes to revisit each page"
Map of View	**Note Taking**	**Web view**
• Constantly dragging it to the side to avoid it from blocking content. • A lot of users chose to hide it. • "It is not super helpful as I don't know that the dots are." • "I don't see myself using it too much" • "It would be nice to have a zoom in and zoom out feature"	• Frequently used • "That seems important, let me add it as a note to my map" • "I want to add this concept but I'm not sure where to put it. I'll just add a note instead" • "It would be nice to have a copy and paste option when taking notes"	• Not frequently used • "It's nice that it automatically searches the concept for you" • Only one user added nodes from the webpage and linked them with their maps • "Do I have to code from the web page?" • "I like the web view a lot, although I didn't use it a lot."

Table 4. 1. Insights about the system in general and each specific feature.

Table 4.1 shows key insights including key points extracted from observation notes and dialogue transcriptions, that are classified into six categories. In the following paragraphs, I will discuss how each feature were used as well as feedbacks for each feature gathered from the study.

Dual Window

The dual-window design was well accepted by students, the display of both the reading material and the concept map view allowed students to compare and relate between the concept map and the content. Although students had the ability to vertically rotate the iPad to enable full-screen reading, all the participants used the dual-window view throughout the study.

Click to Add

The click-to-add feature was frequently used by the learner. Students commented that the click-to-add feature facilitated the concept map construction. Interestingly, students also used the "+" button to add nodes with their own words. The action of adding their own nodes could be a potential indication of learner generating their own understanding and knowledge beyond what's given in the reading material. One potential problem with the click-to-add feature was that some students selected an entire paragraph to add as a node, and the map view was not able to display all the text in the node. Hence, there should be a word limit of how many words learners can select for adding a concept map node.

Hyperlink Navigation

Another feature that demonstrated promising benefits was the hyperlink navigation feature. Learners used the hyperlink navigation feature to quickly read related content in the text. Behaviors such as tapping on two nodes back and forth or creating links after hyperlink navigation could be indications that learners are constantly comparing and relating concepts.

It is worth noticing that the use of hyperlink navigation largely depended on the number of nodes in the map. When students first started with the system, hyperlink navigation is hardly used as there were not enough nodes for navigation. As the map grew larger with a sufficient number of nodes in the map for navigation, students used the hyperlink navigation feature more frequently to compare between concepts related to the nodes. Therefore, some navigational guidance at the beginning of the concept mapping activity might be promising to promote the benefits of hyperlink navigation.

Map of View

During the study, certain features did not demonstrate learning benefits and needed improvements. The map of view feature was not well accepted by the testers. Participants suggested that the map of view was constantly blocking content in the concept map canvas and caused a lot of distractions. In addition, even when the map grew larger than the concept map window, it was still pretty easy to navigate the canvas by scrolling the view. Therefore, there needs to be an option to hide the map of view and display it when users request it.

Note Taking

The note-taking feature was frequently used by students. Students tend to add some additional information about the node once they added it to the map. Students added notes on almost a third of the concept nodes in the map. However, the content they input to the notes are mostly explanations directly copied or rephrased from the textbook content, which can be quickly referenced with the highlighting in the text. Few students wrote relationships with other concepts or self-generated knowledge into the notes. What's more, few of the notes were revisited once learners finished the input. Hence, the effect of the note taking feature might be limited.

WebView

In the think-aloud study, the web view was hardly used. Students mainly focused on the reading material and did not have time to search for additional resources. While some students did visit additional resources on Wikipedia and Google, the information was not direly related to the learning material and did not contribute to the concept maps. Table 4.2 summarizes the implications and plans for improvements, derived from students' interactions with the system and verbal feedback from the study.

Feature	Usage	Key Insights	Improvements
Click to Add	High	Saves time; yields more nodes being added	Adding a word limit to the selection
Navigation	High	Facilitated the access to related information and comparisons among concepts; low usage at the beginning	Provide some navigational guidance in the beginning of the activity
Map of View	Low	Not so helpful, constantly blocks concept map content	Add the ability to hide the map of view
Note Taking	High	Used a lot but few are revisited; Lot of copying and pasting from the content	Some scaffolding on what to add to the notes
Web View	Low	Hardly used; Hard to find relevant information	Integrate more content related resource as bookmarks

Table 4. 2. Summary of the think-aloud study finding and implications.

4.4 Discussions and Conclusions

The think-aloud study took a preliminary peek into how students use *MindDot* for concept mapping activities. While some features have promising potential to facilitate the process of identifying key concepts and establishing relationships among them, the study revealed some limitations of using the system. Therefore, to fully reveal the benefits of the innovations in *MindDot*, it is highly desirable to provide guidance on how to leverage all the features in the system to learn from concept mapping more effectively. In the following chapters, I will describe several empirical investigations and design iterations of the system. Based on empirical implications, each iteration is a step forward from the previous version by incorporating new features and designs to address discovered challenges. Chapter 5 describes an empirical investigation that examines the hyperlink navigation feature. It enhances the system by establishing a process-based learner model, which can be used to for diagnosis and assessment purposes. Chapter 6 furthers the system by integrating template-based support with concept map-based navigation. Later in Chapter 7, I present and evaluate an intelligent feedback system that supports effective learning behaviors. I then finalize this work by summarizing findings from all the design iterations and evaluations and conclude with implications for future designs for concept mapping-based support.

CHAPTER 5

UNDERSTANDING THE CONCEPT MAPPING PROCESS

In the chapters above, I have presented a preliminary exploration of template-based support. The work provides insights into how expert templates should be designed to support learning. To further develop advanced affordances to support concept mapping, Chapter 4 presented a concept mapping system *MindDot*, which serves as a fundamental platform that provides technological capabilities for future innovations. A major innovation of the system is integrating the learning content with the concept mapping tools through a dual window design. This connection between the two views allows learners to create concept maps directly from using touch gestures. Concept nodes created using this gesture are hyperlinked with the textbook content, which provides navigational capabilities using learner-generated maps. This chapter continues the research trajectory by exploring learner map-based navigational support to address research question Q_2.

Chapter 2 has described previous work that explored concept map-based navigation. Such navigational aid is usually based on an external map, created by the instructor, for navigational index. Limitations of this approach lie in the cognitive load caused by the external expert map. Learners who are unfamiliar with the index map are likely to experience disorientation and fail to benefit from the quick access to information. In my system, navigational aid is provided based on the map learners themselves create. Each navigational anchor is added after users read the content and created a node from it. In this way, learners are familiar with not only the concept map, but also all the related content that are hyperlinked with the map. Thus, the hyperlink navigation support in *MindDot* has great potential to promote learning results.

Apart from providing students with affordances such as template support and navigational aid, this work also aims to support concept mapping with effective instructions and feedback. Previous work has revealed that offering metacognitive feedback to support beneficial learning strategies in concept mapping has tremendous potential to promote learning results. However, a major constraint of these works is that the learning evaluation mainly focuses on the outcome, that is, the maps learners create (Wu *et al.*, 2012; Hirashima *et al.*, 2015). Few have qualitatively evaluated learning behaviors during the concept mapping process, which is highly representative of learning characters. Research work in the literature has evaluated learning strategies in reading comprehension and found that support the development of these strategies can be highly effective. However, the innovative affordances provided in *MindDot* introduced new ways of interacting with the concept map and learning content. Compared to traditional learning approaches such as reading comprehension, these novel interactions reveal aspects of the learning process that were previously hidden. Previous learning strategy models in reading comprehension contexts might not be capable of modeling all the interactions in *MindDot*. Therefore, there is a need to develop a learner model to evaluate the learning implications of different strategic use of the affordances as well as behavioral patterns in *MindDot*.

We have discussed in Chapter 1 that two fundamental behaviors in concept mapping are accessing key information and making comparisons. Hence, the learning model should accurately model how learners access key information in the content and how relations are compared and illustrated in the map. Prior research in reading comprehension has modeled these behaviors with different learning strategies (Bereiter and Bird, 1985; Salmeron, Canas and Kintsch, 2010; Ponce and Mayer, 2014b). A major focus of all these strategies is the comparison between different segments in the text. For example, the *backtracing* strategy permits comparison between what learners are currently reading and what they previously passed. Similarly, the *demanding relationships* strategy requires the learners to explicitly compare and establish relationships among concepts and generate knowledge beyond what's presented in the content. Similar evaluations have also been conducted in the concept mapping context. For example, in Ponce and Mayer's work (Ponce and Mayer, 2014b), they modeled the learning process through eye tracking devices. Results indicated that learners engaged in concept mapping activities generated more Integrative Saccades (up-down) and Constructive Saccades (left–right), and students who performed more of these saccades achieved higher learning outcomes. Granted that eye-tracking method in this work was able to capture the comparisons between concepts, it only traces learners' attention within the reading content, and was not capable of modeling how comparison and reasoning take place when learners are building and interacting with the concept map. Therefore, there is a need to develop a model that evaluates the complete process of how learners process the content, compare related concepts, and how these relationships are explicitly denoted in the map.

Based on the specific concept mapping scenario in this work, I propose a **comparative strategy**, that refers to the use of behaviors and activities that involve the creation of relationships and knowledge networks among different concepts. The comparative strategy model in this thesis work furthers prior work in modeling concept mapping process by incorporating map-oriented comparing behaviors such as generating links between related concepts and relating the map with the content. Similar to reading comprehension contexts, where teaching students to use effective strategies yields better learning, supporting the development of comparative strategies can be highly beneficial.

I hereby propose three hypotheses: H_1: The hyperlink feature improves learning. H_2: The hyperlink feature facilitates comparative strategies. H_3: The use of comparative strategies predicts learning outcomes. We investigate our hypotheses through a classroom study with 32 high school students. We discuss the implications of the study findings for developing a system that uses intelligent tutoring to promote comparative strategies during concept mapping.

5.1 Study Design

We conducted a study to test whether our digital textbook application improves learning (H_1), improves the use of comparative strategies (H_2), and whether the use of comparative strategies is related to learning (H_3). We worked with a high school teacher who typically uses concept mapping activities in her classes. In this study, our digital textbook application is used as a substitute for the paper-and-pencil based tools typically used for the concept mapping activity. During the study, students read a textbook chapter and, over the course of 5 classroom periods, constructed a concept map to represent the knowledge structure of the chapter. We investigated students' interactions with the system and their corresponding learning outcomes.

5.1.1 Method

We recruited 32 participants from a high school 12th grade earth sciences class. All participants had previous experience with concept maps. The application was installed on an iPad 2 Air, with a 9.7-inch display and a multi-touch interface. The learning material consisted of a chapter from the 15th edition of *Living in the Environment: Principles, Connections, and Solutions*, the textbook that was being used in the class. The textbook displayed in the application was manually edited by us to fit the screen of the iPad. The original chapter had 27 pages and the iPad version had 58 pages.

Students were assigned to two conditions (hyperlink and non-hyperlink) via a randomized block design to control for the pretest score. All students worked individually and kept his or her iPad for the duration of the study. Students in the hyperlink condition used the system described above. They were able to create concept maps from the book and tap on the nodes to navigate to the related pages, with relevant words in the textbook and concept map nodes highlighted. Students in the non-hyperlink condition used the same system, but with no hyperlink navigation or highlighting on words and concept map nodes.

Students began the study with a pretest, which was taken on a Thursday. The intervention, in which students used our application, began the following week on a Monday, and lasted 20 minutes per day for 5 consecutive days. On the first day, all of the participants were given a 10-minute in-app training session (tailored to condition) where they learned about how to use the application features through a step-based tutorial. Our intervention was integrated into normal classroom practice and was part of the broader unit on earth sciences taught by the teacher. Therefore, each day after using our system to create their concept maps, students received a related lesson from their teacher and continued to engage with related content on Monday and Tuesday the following week. Similarly, if students finished creating their concept map before the end of the fifth day, they worked on related content the teacher had prepared (e.g., an online reading task). The posttest was given on a Wednesday after the study was completed. During the study, all students' actions were logged, and the final concept maps were uploaded to a server for analysis.

5.2 Measures

Learning. The pretest consisted of 30 multiple choice questions covering the whole chapter and was designed by the high school teacher. The posttest consisted of the same questions as the pretest but in a different order. This was in accordance with the common practice of the classroom teacher, who constructed similar pre and posttests for every unit she taught. Learning results are measured by normalized gains (Jain, Nandakumar and Ross, 2005).

Comparative strategies. The use of comparative strategies refers to behaviors and activities that contribute to the comparison of different concepts and the construction of a coherent knowledge structure. We model comparative strategies within our particular learning environment using the following three variables.

1. *Back navigation.* An important characteristic of comparative strategies is the comparison among different concepts. In reading context, it is reflected as attention switches in different parts of the book. In our system, the .epub book was custom made to fit the iPad screen. The original chapter had 27 pages, and the iPad version had 58 pages. Therefore, key concepts in the material are scattered on different pages. To review relevant content and make connections among concepts, learners will need to go back and forth between pages. Thus, we consider back navigation as a proxy for comparative strategies. Back navigation is the count of times a student navigates back a previous page after reading forward in the text. Several "back" actions in a row are counted as a single back navigation, but once the learner moves forward again,

the next time they go back, a new back navigation will be counted. Hyperlink navigations where students move back in the text are also counted as back navigations.

2. *Cross-links.* Cross-links connect concept nodes from different pages of the content. These can be beneficial to student comprehension as they often represent creative leaps on different parts of the knowledge framework. They are critical elements in knowledge structures and are good indications of comparative strategies. Thus, for each student, we compute the number of cross-links as an indicator of the comparative model. For the students who received the template support, cross-links in the pre-made templates were not counted.

3. *Context switch.* In order to establish connections between concepts while constructing the concept maps, students will need to constantly refer to the learning content. Thus, how often students are referencing the learning material during concept mapping would be another indication of comparative strategies. Here, we compute context switches, that is the number of times students' attentions switch from the textbook view to the concept map view. Our log file records which view students are interacting with for each action and every time a student switches the interaction view from one view to another is counted as a context switch.

The variables above allow us to model generative learning from different perspectives. However, we still need an overall model that quantifies the generative strategy as a whole. To compute an overall model that considers each variable as an equally important factor, we first used the feature scaling method to rescale the three variables into [0, 1]. Then we averaged the three variables to get the generative strategy score.

Concept map properties. We also computed three basic properties of the students' concept maps themselves:

1. *Total node*. The total number of concept nodes in the concept map.
2. *Total link*. The total number of links in the concept map.
3. *Link/node ratio*. Link/node ratio is computed as the number of concept links over the number of concept nodes in a given map. The link/node ratio indicates the overall connectivity of a concept map. The higher the link/node ratio is, the more connected a concept map is.

Student activities. Finally, we computed three variables from the log data that reflected student activity within the application.

1. *Total actions*. Total action is the total number of actions for each student.
2. *Navigation actions*. Navigation actions include turning pages and using hyperlink for navigation.
3. *Hyperlink navigation actions*. A hyperlink action is when a student clicks on a hyperlinked concept map node for navigation.

5.3 Results

Overview of Student Activity. In this section, we first present an overview of how students used our system to create concept maps for learning. As discussed in the method, not all students engaged in concept mapping for all study days, either due to being absent or completing the activity early. The actual attendance days are not significantly different between conditions, $F(1, 28) = 1.579$, $p = 0.219$. 23 students attended for 5 days (11 in the hyperlink condition, 12 in the non-hyperlink condition) and 7 students attended for 4 days (4 in the hyperlink condition, 3 in the non-hyperlink condition). Students who attended 5 days performed marginally less total actions than those who attended 4 days (p = 0.063). Two students (one in each condition) who attended less than 3 days are excluded from the analysis.

Next, we looked at the basic properties of the concept maps that students produced (see Table 5.1). Overall, students created a mean of 40.90 nodes (*SD* = 19.75) and a mean of 37.80 links (*SD* = 19.14). We conducted a MANOVA with condition as the independent variable and number of concept nodes, number of concept links, and link/node as dependent variables. There was no significant difference between condition on the overall model ($F(3, 25) = 0.303$, $p = 0.823$, Wilks’ = 0.965, partial = 0.035), and no significant effects of condition on the individual dependent variables.

Condition	**#Concept Nodes**		**#Concept Links**		**#Link Over Node**	
	Mean	SD	Mean	SD	Mean	SD
Hyperlink	42.42	18.91	38.40	19.48	0.91	0.16
Non-Hyperlink	39.60	21.15	37.20	19.45	0.93	0.11

Table 5. 1. Variables for modeling concept map outcomes

As a proxy for student engagement, we examined whether student activity varied across conditions. We first examined whether the hyperlink feature influenced the total navigation and total actions. A one-way ANOVA revealed that there was no significant difference between condition on total actions performed ($F(1, 28) = 2.081$, $p = 0.160$), with the hyperlink condition having a mean of 371.80 actions (*SD* = 108.55) and the non-hyperlink condition having a mean of 452.93 actions (*SD* = 188.83). Similarly, there was no difference in number of navigation actions ($F(1, 28) = 2.705$, $p = 0.111$), with the hyperlink condition conducting on average 191.53 actions ($SD = 82.79$) and non-hyperlink conducting 276.33 actions ($SD = 181.74$). Students used the hyperlink navigation action a mean of 23.25 times, which is 12.14% of the total navigation actions taken.

H_1: The hyperlink feature improves learning.

Our hypothesis was that the use of the hyperlink feature facilitates students in making connections between concepts, and thus, improves learning. To evaluate this hypothesis, we conducted a two-way repeated-measures ANOVA with condition as a between-subject variable and test time as a within-subject variable. Results show that both conditions demonstrated significant learning results ($F(1, 28) = 50.244$, $p < 0.001$), but there was no significant difference between conditions ($F(1, 28) = 0.18$, $p = 0.68$). Pretest and posttest results are shown in Table 5.2.

Condition	**Pretest**		**Posttest**		**Normalized Gain**	
	Mean	SD	Mean	SD	Mean	SD
Hyperlink	13.71	3.79	18.93	4.08	0.34	0.16
Non-Hyperlink	13.40	4.12	19.47	3.77	0.33	0.21

Table 5. 2. Pre and posttest scores.

H_2: The hyperlink feature facilitates comparative strategies.

The primary prediction in our work is that the navigational support and highlighting of key information in both views provided by the hyperlink feature would yield more connections among different concepts as well as more references and comparison between the textbook and the concept maps. Table 5.3 shows three indicators of comparative strategies and the overall generative score.

We conducted a MANCOVA with the above features of comparative strategies as dependent variables, and condition as an independent variable. We used total actions as a covariate, as a proxy for how active students were when interacting with the application. The overall model was significant between conditions, $F(3, 25) = 13.74$, $p = 0.001$, Wilks' = 0.537, partial = 0.463. Looking at the individual variables, back navigation ($F(1, 27) = 10.993$, $p = 0.003$, partial = 0.289) and context-switch ($F(1, 27) = 15.785$, $p < 0.001$, partial = 0.369) were significantly higher in the hyperlink condition. However, number of cross-links was not significantly different between conditions ($F(1, 27) = 3.768$, $p = 0.063$, partial = 0.122). Overall, the hyperlink feature significantly increases the use of comparative strategies.

Condition	Back Navigation		Cross-links		Context Switch		Overall Generative Score	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Hyperlink	34.67	11.41	13.73	10.06	114.40	55.92	0.43	0.18
Non-Hyperlink	26.93	14.03	10.47	8.13	63.60	23.77	0.28	0.15

Table 5. 3. Variables for modeling comparative strategies.

H_3: The use of comparative strategies predicts learning outcomes.

Here, we examine whether the use of comparative strategies relates to learning outcomes. We represent the comparative strategies using the overall generative score metric, introduced in the measures section. We conducted a generalized linear mixed model with condition, overall generative score (centered by mean) and the interaction of condition and overall generative score as independent variables, and learning gain as a dependent variable. We found that the interaction between condition and overall generative score significantly affects learning gain ($F(1, 26) = 6.26$, $p = 0.019$). To explore this interaction, we performed a correlation between generative behavior and normalized gain for each condition. For the hyperlink condition, generative behaviors are positively correlated with learning ($r(13) = 0.623$, $p = 0.013$). For the non-hyperlink condition, generative behavior does not predict learning ($r(13) = -0.302$, $p = 0.274$). Thus, the more comparative strategies students use, the higher their learning gain, but only in the hyperlink condition.

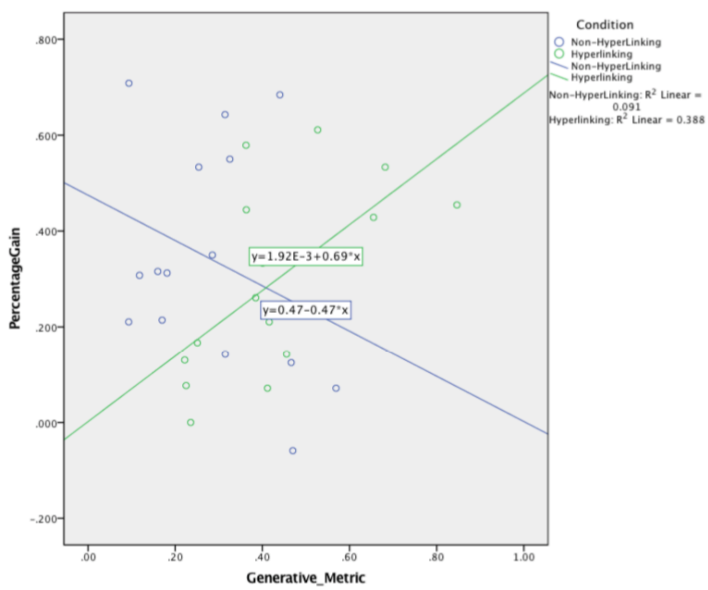


Figure 5. 1. Correlation between the comparative strategies and learning in each condition

5.4 Discussion

This study aims to evaluate how *MindDot* assists students in the development of the comparative strategies. In a study with 30 high school students, we found that the use of the hyperlink feature increases comparative behaviors. While these comparative behaviors were related to learning in the hyperlink condition, they were not in the non-hyperlink condition. Students in the hyperlink condition were more likely to exhibit comparative strategies within our system, comparing and connecting concepts in different segments in the book, as well as relating the concept map with the textbook. Students in the non-hyperlink condition were more likely to process the textbook material in a linear order. The fact that hyperlink students performed significantly more generative learning behaviors reinforces our hypothesis that the navigational support and visual comparison of key information facilitate students in comparing and establishing connections among concepts across pages.

Research has demonstrated that the use of the comparative strategies has the potential to improve learning (Ponce and Mayer, 2014b). This is indeed what we find within the hyperlink condition, as students who exhibit more comparative strategies score better on a multiple-choice test. However, this is not the case in the non-hyperlink condition. We argue that the benefits of comparative strategies come with drawbacks, as comparing and connecting concepts located on different pages requires extraneous effort, especially when students are not provided with proper visual aids and navigational support. Unlike previous research on learning strategies, where the content used was pretty simple, consisting of only a few pages (Doctorow, Wittrock and Marks, 1978), the reading material in our study consisted of 58 pages that students read over 5 days, requiring a much larger effort to process. While students in the hyperlink condition are able to use the concept map to view relevant resources, students in the non-hyperlink condition are challenged with additional effort when comparing different concepts. It is not only physically demanding, as they have to flip through several pages manually, but also cognitive challenging due to the complex content structure. The benefits of using comparative strategies are more likely to be hindered by the high cognitive load caused by inefficient navigation. Thus, to reveal the benefits of the comparative strategies, proper visual aids and navigational support need to be given to students.

5.5 Limitations

This study has some limitations. The total sample size of the study is 32, with 30 used for analysis. Despite the significant differences between conditions, the overall effect might be not representative of the population due to the insufficient sample size. In addition, following the teacher's regular practice, the pre and posttests consist of the same questions in different orders, and thus there may have been a testing effect. Further, to adapt the class schedule, our study lasted 20 minutes per day for 5 days, leaving the students another 20 minutes for other class activities like group projects, presentations, etc. These additional resources might have caused variance within the learning effects.

5.6 Conclusions

To summarize, this chapter presents an empirical evaluation of *MindDot*. Results indicated that the hyperlink navigation feature promoted the development of comparative strategies, and the use of comparative strategies enhanced learning with the help of hyperlink navigation. This investigation has several contributions. First, the study validated the hypothesis that comparison-based learning strategies are not only effective in reading comprehension, but also in concept mapping. Second, although the comparative strategies model presented in this work was a preliminary exploration of the cognitive learning process during concept mapping, it decomposes the use of comparative strategies into measurable components, such as the number of back navigation and the number of context switches. These measurable characteristics can be used for qualitative assessment and diagnosis purposes. What's more, instructions on supporting comparative strategies can be more effective when adapting to these learning characteristics. Third, the fact that learners in the non-hyperlink condition didn't benefit from using comparative strategies points out the need for effective support in using comparative strategies. Instructions on how to access related information and hints about relevant concepts are highly promising in revealing the effect of comparative strategies.

Although the hyperlink navigation feature demonstrated its impact on facilitating comparative strategies, it still has some limitations that need to be addressed. The challenge is that the hyperlink navigation is based on nodes learners create, when there's not enough nodes for navigation, the ability to quickly access related information is largely limited. Therefore, when learners just started concept mapping, or when learners are having issues finding key concepts to add to the map, the hyperlink navigation is less impactful. The next chapter continues the exploration of supporting comparative strategies in concept mapping. I will first present an integration of the hyperlink feature and template-based support, which enhances the navigational capability of the system as well as facilitating the process of the expert generated template. I then further the modeling of comparative by incorporating sequential behavioral patterns and finalize the chapter with implications for future support designs.

CHAPTER 6

SUPPORTING EFFECTIVE COGNITIVE BEHAVIORS IN CONCEPT MAPPING

In this chapter, I continue the exploration of modeling and supporting comparative strategies in concept mapping. Work in this chapter builds on major implications concluded from the last chapter, that is, the hyperlink feature enhanced the development of comparative strategies, and the use of comparative strategies in concept mapping is highly effective with navigational aid. Despite these promising results, there are still some challenges that remain to be addressed.

The first one is that the hyperlink feature promoted comparative strategies but did not yield learning improvements. This might have been caused due to several reasons. First is that in order to follow the instructor's classroom practice, additional teaching activities were introduced each day after the concept mapping session, causing external variance to the learning outcome. Another reason could be some limitations within the hyperlink navigation design. A major drawback of the hyperlink navigation design is the disorientation of the navigations. As Puntambekar pointed out (Puntambekar and Stylianou, 2005), map-based navigations might not always be effective. Learners involved in hypertext learning systems not only have to understand the content, but they also need to understand the structure of the system, knowing where a particular concept falls in the big picture and what other concepts it is related to. Consequently, the flexibility and nonlinearity in hypertext navigation might cause confusion and disorientation, and in turn, diminishing the benefit of quick access to information and the ability to develop learner-oriented navigation paths. Research in the literature has proposed several ways of facilitating learning with hypertext systems. For example, Shapiro (Shapiro, 2000) examined the effect of support hypertext-based learning with interactive overview maps. Empirical data showed that the influence of an overview guided the development of learners' internal knowledge structures. The effect is especially strong with low prior knowledge students. Similarly, Dee-lucas (Dee-lucas, 1996) tested the effect of hierarchical overviews in hypertext learning environments and found that hierarchical overviews can enhance learners' ability to locate and organize the required information in ways that are more appropriate to their learning goals. Other works furthered overview with support such as indices, search capabilities and hot text (words in the text that can be sleeted to view additional content). Research on these methods suggested that these facilities can aid learners in developing effective study strategies (Halasz & Conklin, 1989, Heller, 1990). Therefore, the hyperlink navigation needs to be enhanced by additional support that can serve as navigational guidance. Without such support, learners are likely to randomly tapping nodes in the map and navigate to different sections in the content without specific purposes. Another drawback of the current hyperlink navigation design is that the navigational capability requires a certain number of nodes and a well-organized structure in the map. As hyperlink navigation uses learner-generated nodes, the effect of the feature is pretty limited during the early stage of concept mapping. In addition, Kinchin has pointed out that low-learning students during concept mapping are more likely to create chain or spoke structures (Kinchin, 2001). These structures usually describe simple relations and contain little hierarchical information about the complete knowledge structure. Therefore, navigational paths developed from these map structures may not be beneficial.

Based on the discussion presented above, I hereby describe a method of enhancing the hyperlink navigation feature by integrating with expert templates. When learners start the concept mapping task, they will receive an incomplete template as a basic structure to expand. All the nodes in the template are created using the "click to add" gestures and are hyperlinked to the page where they are added from. Learners can tap on nodes in the template and review relevant content. Key concepts in the text, as well as the corresponding nodes in the map, are both highlighted for better comparison. The novelty of this work is the integration between the hyperlink and template support, which has the potential to reduce the limitations discussed above and also amplify the benefits of both approaches.

To begin with, the expert template can serve as a navigational guide for students in the early stage of concept mapping. Before learners add any nodes to the map, they can use the expert template to preview key concepts in the content. By doing this, learners are able to get a grasp of a high-level overview of the knowledge structures in the content and decide what pages to focus on, which can be highly beneficial to strategic planning, goal setting, and self-monitoring according to the self-regulated theory (Zimmerman, 1990; Pintrich, 1999). In addition, research has shown that template-based support has a prominent effect on improving the concept map qualities (Sugihara *et al.*, 2012). With the help of the expert template, learners are more likely to construct concept maps with higher complexity, more cross-section connections and better organized hierarchical structures. These high-quality maps have great potential to permit meaningful navigational paths.

On the other hand, the hyperlink navigational aid also enhances the template support. We have discussed in Chapter 2 that a major limitation with the template-based support is the workload caused by the unfamiliar structure, which is caused by the gap between the amount of knowledge required to understand the template and the amount of prior knowledge the learner has. This external structure is more likely to hinder learning when the learners struggle to find related resources or content to help understand the template. The hyperlink navigation feature eliminates the process of flicking through pages just to find the explanation of a concept. With the navigational aid, students using *MindDot* are able to tap on nodes in the template and directly navigate to related pages and review the content that explains concepts in each node.

Based on the discussion above, students with integrated support are more like to process the content while constantly navigating to different sections in the content to establish relationships among concepts. Therefore, we envision that the hyperlink and template support together would further facilitate the development of the comparative strategies. Therefore, we hereby propose three hypotheses.

H_1: Hyperlink and template support improves learning.

H_2: Hyperlink and template support facilitates the development of comparative strategies.

H_3: Comparative strategies predicts learning.

6.1 System Design

The concept map-based learning system *MindDot* presented in this chapter is a step forward from the initial version described in Chapter 4. It contains the same infrastructure, including features such as dual-window view, click to add nodes, hyperlink navigation. The innovation of this work is the integration of the hyperlink navigation and the template feature. When students first load the application, the system provides students with an incomplete expert template as a support for their concept mapping activity. The template presented in the study was created by me and consists of 8 key concept nodes and 7 links connecting them. The nodes are created from 6 different pages and 5 of the links are cross-links, each connects two concept nodes from different pages of the content. The nodes and links were selected to form a basic framework of the key concepts in the content and are easy to expand on. All the nodes in the template are hyperlinked to relevant pages. With the navigational support provided by the hyperlink feature, students can tap on the nodes in the template and read related content (aided through the keyword highlighting in the text). This feature has the potential to reduce the effect to process and understand the template structure. At the same time, the template serves as a navigational framework, guiding students to pay attention to where those key concepts are mentioned in the content.

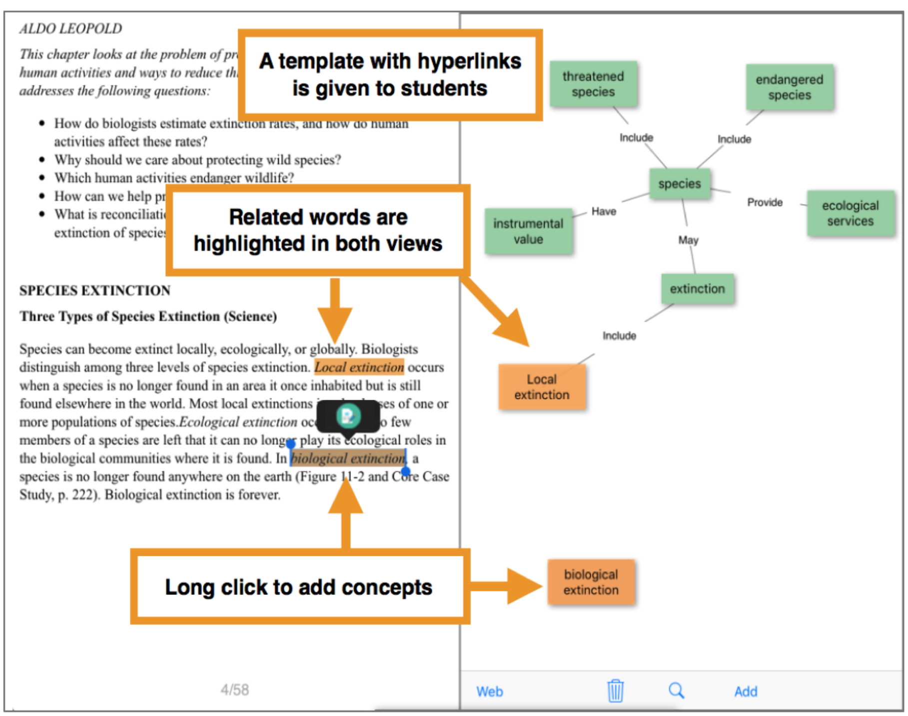


Figure 6. 1. Screen shot of the concept mapping system

6.2 Experimental Investigation

To comprehensively examine how hyperlink and template support facilitates the development of comparative strategies during concept mapping and how they affect learning, we conducted a controlled study, in which students read a section of a biology textbook chapter and constructed a concept map using our application. Pre and posttests were given to students and log data were collected to investigate students' interactions with the system and their corresponding learning outcomes.

We recruited 59 undergraduate students (19 male and 40 female). *MindDot* was installed on an iPad 2 Air with a 9.7-inch retina display and a multi-touch interface. The learning material consisted of the chapter *Sustaining Biodiversity: The Species Approach* from a science textbook authored by *Miller G* (2011). The textbook chapter displayed in the application was manually edited by us to fit the screen of the iPad. The entire chapter was 10 sections spanning 58 pages; in the study, however, due to the limited time, students were only required to read the first 20 pages of the given content (4 sections).

The goal of our study was to test the effect of the two major features: the hyperlink and the template. Thus, our study had four conditions:

1. **Hyperlink + template (H+T):** In this condition, students had the hyperlink and template features discussed above. Students with the template were asked to expand the template and build their concept maps based on it. However, students had the ability to make edits to the template to better fit their own understanding.

2. **Hyperlink alone (H):** In this condition, students still had the hyperlink feature for navigation and highlighting, but they constructed their concept maps from scratch.
3. **Template alone (T):** Student in this condition did not have the hyperlink feature for navigation, but they received an incomplete template to build on. The template in this condition had no hyperlinks, nor were the related keywords in the template and text highlighted during navigation.
4. **No hyperlink or template (N):** In this condition, students received minimum support as they had neither the hyperlink feature nor the incomplete template.

Students were randomly assigned to conditions, with 15 in condition H+T, 14 in condition H, 15 in condition T and 14 in condition N. Students began the study with a pretest, which consisted of 12 multiple choice questions. After the pretest, all participants were given a 5-minute in-app training session (tailored to condition) where they learned about how to use the application features through a step-based tutorial. Students were then asked to spend 30 minutes to read the content and leverage all the features mentioned in the training to create the best concept map they could. If students finished reading the content before 30 minutes, they were told to refine their maps. Similar to the two studies presented in the previous chapters, learning was measured via pre and post test scores and comprehensive strategy was measured using the same metric described in the first study.

6.2.1 Results and Discussion

H_1: The hyperlink and template support improve learning. A repeated-measures ANOVA on test scores with test time as the within-subjects' variable showed that students demonstrated significant learning between the pretest and posttest across all conditions ($F(1, 55) = 10.97$, $p =$

0.002). Results are presented in Table 6.1, including 2 control questions and 10 main assessment questions.

Condition	Pretest		Posttest	
	Control Questions	Main Questions	Control Questions	Main Questions
H+T	0.40 (0.63)	7.27 (1.62)	0.13 (0.35)	8.60 (1.05)
H	0.50 (0.65)	7.85 (1.70)	0.29 (0.47)	8.64 (1.78)
T	0.44 (0.51)	7.94 (1.84)	0.60 (0.51)	8.38 (1.40)
N	0.21 (0.45)	7.57 (1.22)	0.07 (0.27)	7.42 (1.15)

Table 6. 1. Mean pre and posttest scores. Standard deviations are in parentheses

We further conducted an ANCOVA test with the hyperlink and template feature as the independent variables, posttest as the dependent variable and pretest as the covariate. The hyperlink feature had a significant impact on learning ($F(1,55)=7.54$, $p=0.008$, $\eta_p^2=0.123$). A marginal effect was found on learning with the template support ($F(1,55)=2.93$, $p=0.093$, $\eta_p^2=0.052$), and no effect was found on the interaction between the hyperlink and template support ($F(2,54)=0.762$, $p=0.387$, $\eta_p^2=0.014$). In contrast, a similar repeated-measures ANOVA on the two control questions revealed that for the control questions, there was no significant learning between the pre and posttest ($F(1, 55) = 2.42$, $p = 0.125$). An ANCOVA test on the control questions revealed no significant effect on the hyperlink feature ($F(1,55)=1.466$, p=0.231, $\eta_p^2=0.03$) and the template feature ($F(1,55)=2.230$, $p=0.141$, $\eta_p^2=0.04$). There was an effect on the interaction between the hyperlink and template feature ($F(1,55)=7.50$, $p=0.008$, $\eta_p^2=0.12$). Nevertheless, it is unlikely that effects on the main assessments were due to students' ability to guess the correct answers to the questions or a testing effect. H_1 was partially supported, as the hyperlink feature significantly improved learning and template feature had marginal benefits.

H_2: The hyperlink and template support facilitate the development of comparative strategies. Table 6.2 shows the means and standard deviations for the three components of comparative strategies that we are tracking as well as the total number of actions.

Condition	# Back Navigation	# Cross-link	# Context Switch	#Action
H+T	20.13 (12.76)	13.60 (6.42)	82.27 (25.22)	357.2 (134.7)
H	32.42 (20.42)	7.86 (5.79)	105.7 (51.79)	449.1 (213.7)
T	12.86 (12.76)	13.38 (5.45)	51.38 (20.49)	367.3 (103.8)
N	15.07 (9.40)	7.57 (5.83)	42.71 (15.71)	350.1 (105.7)

Table 6. 2. Indicators of comparative strategies. Means are presented, with standard deviations in parentheses.

We conducted generalized linear models on each factor in the comparative strategy model with the two types of support (hyperlink and template) as independent factors and total number of actions as a predictor variable, a proxy for how active students were when interacting with the application. All two-way interactions were included in the model. Data used here represent absolute counts of the three factors. The template support had no effect on back navigation ($F(1, 58) = 0.04$, $p = 0.86$), context switch ($F(1, 58) = 2.10$, $p = 0.15$) and cross-link ($F(1, 58) = 2.34$, $p = 0.13$). The hyperlink support had no effect on back navigation ($F(1, 58) = 1.50$, $p = 0.23$), context switch ($F(1, 58) = 0.29$, $p = 0.60$) and cross-link ($F(1, 58) = 0.54$, $p = 0.47$). The interaction between the hyperlink feature and the template feature had no effect on back navigation ($F(1, 58) = 0.21$, $p = 0.65$), context switch ($F(1, 58) = 1.60$, $p = 0.21$) and cross-link ($F(1, 58) = 0.45$, $p = 0.51$). The interaction between the hyperlink feature and total actions had significant effect on back navigation ($F(1, 58) = 6.41$, $p = 0.014$) and context switch ($F(1, 58) = 5.05$, $p = 0.029$) and no effect on cross-link ($F(1, 58) = 0.53$, $p = 0.47$). The interaction between the template and total actions had no effect on back navigation ($F(1, 58) = 0.50$, $p = 0.48$), context switches ($F(1, 58) = 2.34$, $p = 0.13$) and cross-link ($F(1, 58) < 0.001$, $p = 0.99$).

Factor	Condition	Mean - SD	Mean	Mean + SD
#Back Navigation	H	13.10 (2.64)	24.42 (1.98)	36.43 (2.42)
	NH	11.32 (3.16)	13.92 (1.94)	16.69 (3.32)
#Context Switch	H	62.68 (4.74)	89.67 (3.56)	118.30 (4.35)
	NH	34.07 (5.67)	47.47 (3.48)	61.67 (5.96)

Table 6. 3. Marginal means of back navigation and context switch at M-SD, M, and M+SD total actions.

The marginal means for the hyperlink by total actions interaction are shown in table 3. We can see that as total actions increase, the difference between conditions becomes more prominent. H_2 was partially supported, as the interaction between the hyperlink feature and total actions affected back navigations and context switches.

H_3. Student use of comparative strategies is more predictive of learning outcomes than the quality of their concept maps. Here, we evaluated the effect of comparative strategies on learning. We conducted a partial correlation, where we control for pretest score on the 10 main assessment questions, and then examine the relationships between the main posttest score and the three measures of comparative strategies. Results indicated that all three variables in the comparative model were significantly correlated with learning: cross-links ($r(56)$=0.26, p=0.049), back navigations ($r(56)$=0.36, p=0.005) and context switches ($r(56)$=0.39, p=0.002).

Condition	# Nodes	# Links	Map Score
H+T	12.87 (7.51)	12.40 (8.86)	2.73 (2.15)
H	18.07 (10.92)	15.00 (10.29)	4.57 (1.02)
T	16.33 (8.70)	15.67 (9.80)	1.73 (1.03)
N	16.47 (7.30)	12.07 (8.80)	4.40 (1.55)

Table 6. 4. Concept map evaluation for each condition. Means and standard deviations are presented

We then explored the relationship between concept map nodes, links, scores and learning. Table 4 shows the number of nodes added, number of links added, and map scores across conditions. A one-way ANOVA test revealed no effect of condition on number of nodes ($F(1, 58) = 0.93$, $p = 0.43$) or number of links ($F(1, 58) = 0.55$, $p = 0.65$). Partial correlations (controlling for pretest) indicated that posttest was not correlated with number of nodes ($r(56)$=0.16, p=0.23), or number of links ($r(56)$=0.20, p=0.11). As we used different scoring methods for the template condition and non-template condition, the map score was different between conditions ($F(1, 58) = 27.13$, $p < 0.001$). Thus, we computed those correlations separately. For the template condition, the map score was marginally correlated with posttest score ($r(27) = 0.338$, $p = 0.07$). For the non-template conditions, the map score did not affect posttest score ($r(27) = 0.119$, $p = 0.545$), controlling for pretest.

To summarize, all three comparative strategy variables were correlated with learning, while the map score in the template conditions marginally predicted learning. None of the other concept mapping variables were significantly correlated with learning.

6.2.2 Visualizations of concept mapping progress

To take steps towards a more appropriate real-time model of comparative strategies that monitors student interactions during concept map construction, we created two types of visualizations of student behaviors during concept mapping: **Sequence diagrams** and **Navigation path diagrams**. Both visualizations provide different lenses on the use of comparative strategies. Through these visualizations, we can identify the patterns associated with high and low student learning, and lay the groundwork for designing a real-time algorithm for mapping student behaviors to those patterns.

Sequence Diagram

In designing the sequence diagram, we consider the whole concept mapping activity as several sequences of actions, where each sequence includes the behaviors that students perform when creating a concept node. Every time students finish creating a node, we start a new sequence and record all their actions until they create the next node. In our system, students perform many different actions (e.g. turning book pages, click to add node, hyperlink navigation). However, for the sequence diagram, we consider the overall concept mapping task as combinations of three high level actions: reading, linking nodes, and adding nodes. Adding nodes actions are used to delimitate the sequences, and each sequence describes the key cognitive behaviors students perform before adding the next node. This design helps us answer questions like "How much effort does a student spend in reading and comparing before creating a node?" Or "Are links created right after a node is created, or after the student consults the content?" These action by action analysis provide fine-grained insights about how our two forms of support affect students' reading and comparing behaviors. Thus, the sequence diagram aims to model the reading and linking behaviors between adding nodes actions. In order to understand whether students were performing comparative strategies in reading and linking behaviors, we further sub-coded them into the following four categories:

1. **Compare (P).** The compare action represents back navigation (hyperlink navigations where students move back in the text are also counted) which indicates that students are making comparison between concepts in the content.
2. **Read (R).** Read actions mean that students are processing the content by following the linear order presented in the material.
3. **Link (K).** A link action happens when a student connects two concept nodes that are created in the same page. Although a link indicates that students are establishing relationships among concepts, the two concepts being linked are close in the overall knowledge structure.
4. **Cross-link (C).** Cross-link actions are when students link two concepts from different pages. Creating cross-links can be beneficial as the student is connecting different segments in the content, which indicates that the student is summarizing and re-organizing the knowledge structures presented in the content.

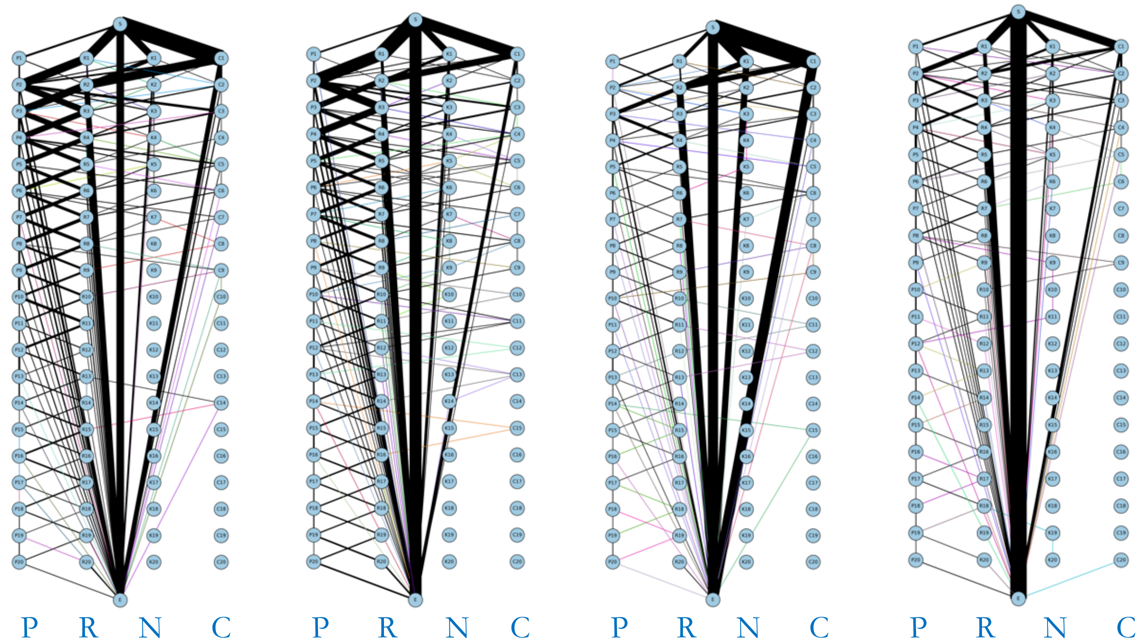


Figure 6. 2. sequence diagrams for each condition

Figure 6.2 shows sequence diagrams for each condition, aggregated across all participants in the condition. Each sequence diagram begins with a starting state “S” and ends with an ending state “E”. In between the starting state and ending state, there are 20 rows of states (20 is the maximum number of actions any student took to create a node). Each row has the four classified states (P, R, K, C) discussed above. When students start using the system or just finished creating a node, a new sequence is generated from the starting state “S”. For each following action students perform, we classify it into the 4 categories presented above and draw a line from the current state to the corresponding state in the next row. When students create a concept node after a series of actions, we end the sequence and draw a line to the ending state “E”. In our sequence diagram, each sequence is represented as path with a unique color. If paths have overlapping sections, we change the color of the overlapping part into black. The thickness of the lines is a visual indicator of the number of students taking that path.

The 4 aggregated diagrams in figure 3 capture all the sequences students performed in each condition. Visual observation in the four diagrams found clear differences between conditions. Overall, diagrams from the hyperlink plus template condition and hyperlink condition look very similar while the template condition and no support condition look much alike, suggesting that the hyperlink support had a stronger effect to the behavior patterns than the template support. In general, the average length of all the paths are much longer in the two hyperlink condition compared to the no hyperlink conditions, indicating that students with hyperlink support are performing more actions before adding nodes. What's more, diagrams from the two hyperlink conditions have more paths and transitions on the left side, suggesting that students with hyperlink support performed more reading and comparing actions within the content. In addition, students with hyperlink support had more transitions between reading states and linking states, and were more likely to add additional links at deeper level states. This means that students with hyperlink support spent more effort reading and comparing relevant concepts in the learning content before establishing their relationships in the concept map.

Nevertheless, there're still some differences between template conditions and no template conditions. First, the line between S and C_1 in the template condition is much thicker compared to the no template condition, validating the statistical result that the template support yielded more cross-inks. Another difference is that the line that directly connects S and E in the template conditions are thinner than the two other condition without template.

This means that students without the template support had more cases where they consecutively added nodes from the content without any reading or linking action in between. On the other hand, students with the template support spent more effort on reading and lining before creating the next concept node.

To further reveal how different behavior patterns relate to learning, we present two typical diagrams from a high learning student in the hyperlink condition (full score in posttest) and a low learning student in the template condition (negative learning gain). The two presented diagrams are two typical examples from the high learning group and low learning group and are representative of each group in general.

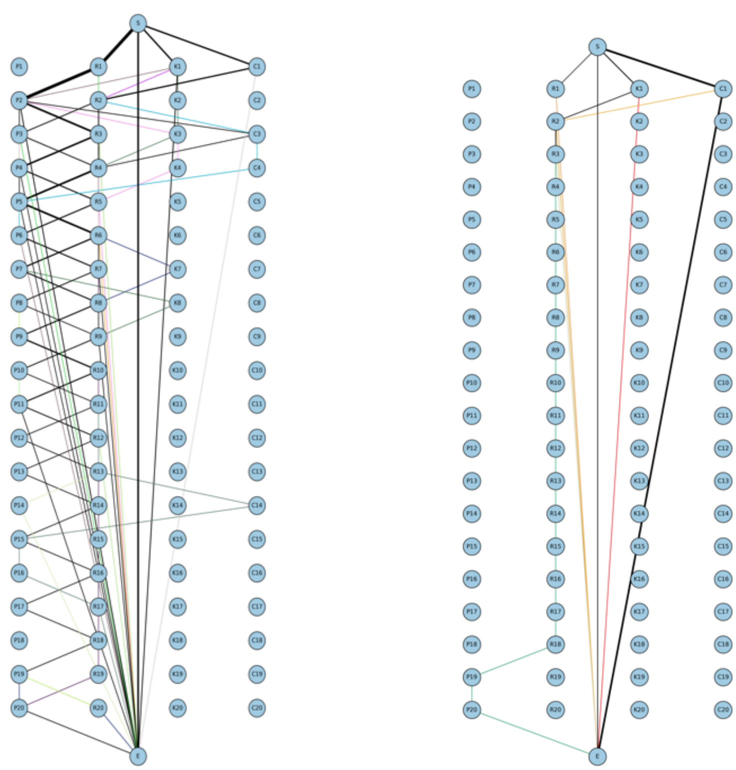


Figure 6. 3. (a) Concept mapping sequence from a high learning student. (b) Concept mapping sequence from a low learning student.

Figure 6.3 shows a clear difference in behavioral patterns between the high learning student and the low learning student. In the high learning diagrams, the vertical length of the overall interaction path is much longer than the low learning ones, suggesting that student with high learning gains are performing more meaningful behaviors before creating nodes. Additionally, in the high learning diagrams, there are more horizontal switches (e.g., P to K, P to C, R to K). In the measure section, we have discussed that cross-links help students visualize how a concept in one domain is related to a concept in another domain, showing that the learner has established an inter-connected knowledge structure. These horizontal switches in the high learning diagram indicate that students benefit more from cross-links if they carefully read and compare those related concepts in the content before creating those links. In contrast, in the low learning diagram, there are few meaningful behaviors made when creating nodes. Most of the sequences end within 3 levels. Although students in the low learning diagram also created cross-links, they created cross-links immediately after they added a node, without any reading and comparing behavior in the content. Thus, cross-links are more beneficial if they are created after careful reading and comparison in the content. Thus, we identify a set of 3 prominent patterns in student' learning behaviors. These patterns do not encompass all solving behavior in *MindDot*, but instead capture key instances of strategic behavior in concept mapping.

Read and Compare (RPRP). A critical element of comparative strategies is the comparison among different concepts, occurring when students review relevant content in different parts of the book. In our high-level comparative model, the back navigation measured how much students are making comparisons in general. The sequence diagram further revealed that the high learning students had way more interactions and switches between reading and comparing actions (Figure 6.3 (a)). This pattern indicates that it is not those individual back navigations that enhanced learning. In fact, it's the constant reading and comparing action pairs that yield positive impact on learning. Therefore, we consider the Read and Compare pattern to be a positive pattern that indicates that the student is making beneficial cognitive comparison within the reading content.

Read and Link (RC, RK, PC, PK). The sequence diagram demonstrated clear difference in terms of how concept links are added during learning. In the low learning diagrams, there are black lines that connect "S" state and "K_1", "C_1" and lines that connect "K_1" and "C_1" to "E". This means that for the low learning students, all the links are added immediately after a node is created, without any reading or comparing activity in between. However, for the high learning students, most of the links are added after a few pairs of reading and comparing activities. We noticed that for the low learning student, there were a few cross-links created. However, without reading and comparing relevant content in the material, it might be that these cross-links tend to be less effective. Therefore, reading and comparing before creating links among concepts could potentially yield better learning results. By inspecting the visualization, we identify Read and Link as a good learning pattern.

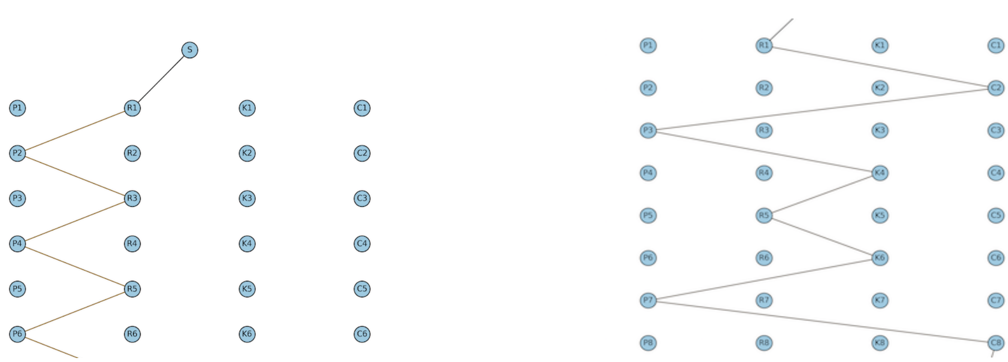


Figure 6. 4. (a) Read and compare (b) Read and link

Read Read Read (RRR). The Read Read Read pattern is in contrast with the Read and Compare pattern. Low learning students often have sequences where they read several pages in a row, without making comparisons or creating links to other concepts. The high learning students, on the other hand, had fewer consecutive reading behaviors. Hence, we consider Read Read Read as an ineffective behavior pattern.

Start and End (SE). Although in figure 6.3, the low learning student had fewer direct paths between S and E, in general, low learning students had higher direct paths than high learning students. This tells us that the identification of key concepts through the addition of concept nodes would be more beneficial alongside other cognitively beneficial behaviors (e.g. reading, comparing, and linking concepts). The start and end pattern is likely a negative pattern.

Figure 6. 5. (a) Read read read (b) Start and end

The four presented behavioral patterns provided insights about how students pursue the comparative in a more action-based level. The two positive patterns suggested that reading and comparing in the learning content are critical components of comparative strategies. The Read and Compare pattern showed that the constant interactions and switches between reading and comparing had positive impact on learning. What's more, while cross-links are helpful towards learning, they would be more beneficial if students are actively reading and comparing relevant concepts in the content before establishing the links.

Navigation Path Diagram

The sequence diagrams presented above show behavior patterns students perform when creating the concept map. However, they do not contain any timing or paging information. Thus, questions such as "When are all the nodes added during the learning process?" and "Do the concept maps students create cover the whole content?" remain unresolved. These questions help us understand when and on what pages are students performing comparative strategies. Therefore, to model how much content students cover with their maps and when are the nodes added, we present a second visualization: a navigation path diagram that better illustrates the order in which students read pages and add nodes over time.

Figure 6.6 shows two navigation path graphs from the same students in the sequence diagram. The vertical axis denotes the page number, and the horizontal axis illustrates the time stamps. The blue line in the graph illustrates the page order read by the student throughout the study. The creating node action is denoted as red dot in the diagram. The x-axis represents when the nodes are being added and the y-axis represents the page number students are reading when creating the node. The two graphs presented in figure 6.6 visualizes the learning process of a prototypical high learning and a low learning student, both representative of high learning and low learning students in general.

One big difference between the two types of students lies in the page reading path. In the high learning student's diagram, the page number gradually increases over time, but there are lots of zigzags in the reading path, meaning that the student is frequently referring to previously read content to make connections. Another difference between the high learning students and low learning students is how nodes are created during reading. In the high learning graph, the blue dots are more spread out both horizontally and vertically, indicating that the high learning student is not only creating nodes from a wider range of pages, he's also creating nodes constantly and continuously in the learning sessions. In the low learning graph however, the blue dots are more clustered towards the bottom-left corner, which means that the low learning student only created nodes in the first few pages and in the beginning of the learning stage.

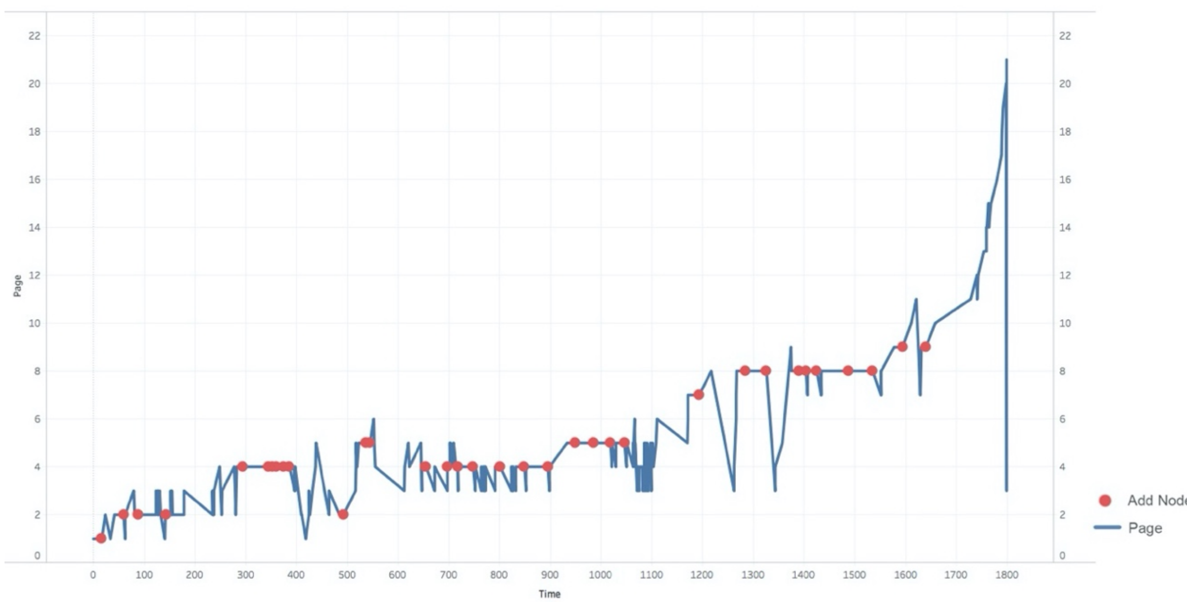
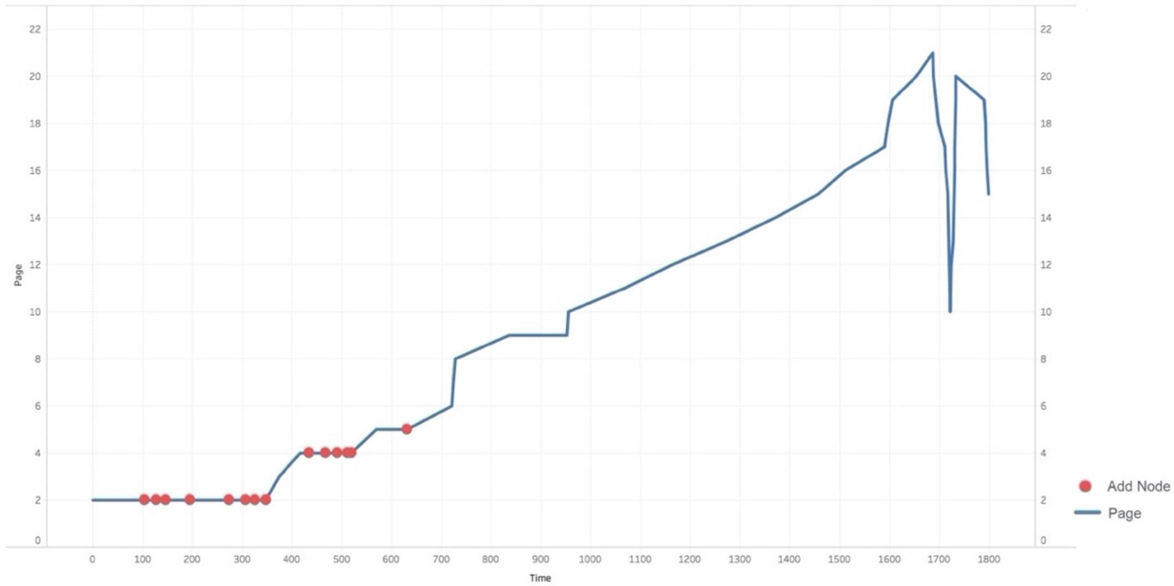


Figure 6. 6 (a) Navigation path graph from a high learning student



(b) Navigation path graph from a low learning student

This creates three additional key dimensions of student learning strategies: **vertical coverage**, **horizontal coverage**, and **zigzags**. The vertical coverage of the nodes captures how many pages of content are used by students to create their concept nodes. An indication of a high vertical coverage would be that the red dots representing adding node actions are more spread-out vertically, covering more than half of the page numbers. The horizontal coverage of the nodes denotes how often students are selecting key concepts to add to the map during the learning phase. Similarly, an indication of high horizontal coverage is that the red dots are more spread-out horizontally, covering a more than half of timestamps. The path trajectory provides additional insights about how students are comparing concepts. The high learning student had more zigzagged navigation path, suggesting that the student was constantly reviewing previously read content, while the low learning students' navigation path is smooth and more linear, indicating that the learner was passively processing the content in a linear order.

To demonstrate how students performed these visual patterns in the high learning and low learning groups, we graded each student's map by evaluating whether the map had a zigzagged path, high horizontal and vertical coverage through visual observations. We gave one point to each dimension if the map meets the definition of each dimension discussed above. Similar to the sequential pattern, we only present descriptive results, shown in Table 6.5. Results suggest that all three patterns are higher in the high learning groups, meaning that high learning students are more likely to cover more text pages, refer back to previous pages, and add concepts throughout the learning session.

Groups	Zigzag	Horizontal Coverage	Vertical Coverage
High Learning	8	9	7
Low Learning	2	5	5

Table 6. 5. Counts of students that demonstrated each visual pattern in the high and low learning subgroups.

6.3 Discussion and limitations

The work in this chapter aims to understand how to provide support in concept mapping to facilitate the development of comparative strategies and improve content learning. I presented a new design iteration of *MindDot*, which supports comparative strategies through the integration of two learning features: A hyperlink feature and a template feature. A study with 59 students revealed that while both hyperlink support and template support improved comparative strategies (H_2), only the hyperlink support influenced learning (H_1). All three factors in the comparative strategy model were highly correlated with learning outcomes, while other outcome-based metrics were not (H_3). We then investigated how students employ comparative strategies in concept mapping with the help of two types of visualizations. In this section, I discuss the insights from my study and data visualizations.

6.3.1 Effects of Hyperlink and Template Support

In this study, I found that the hyperlink support improved both comparative strategies and learning. This is a demonstration of the power of computer-based hyperlink support for concept mapping, and suggests that this support is effective when students construct their own maps. It may indeed be that Zeiliger (Zeiliger, Reggers and Peeters, 1995) and Puntambekar (Puntambekar and Stylianou, 2005) did not find positive effects of hyperlinked concept maps because students were using fully complete maps that they did not construct on their own. This result is also in contrast with the work presented in Chapter 5, that took a similar approach but only found effects on comparative strategies. The study in Chapter 5 took place in the classroom, and had related limitations: students engaged in learning activities other than concept mapping, and students had different levels of exposure to the concept mapping activity, due to absences. In contrast, this study was a lab study, and thus there was more control over the learning activities and time on task.

The study's higher internal validity may have increased the ability to detect effects, although the lower external validity means that a classroom study should be conducted in the future to see if the result will generalize. In addition, I found that the expert template support did not seem to be as effective at improving learning, echoing the results described in Manlover's work (Manlove, Lazonder and De Jong, 2007). The template in this work is integrated with hyperlinks to content, aiming to reduce the effort of processing and understanding the given structure, which is a major concern with traditional pre-made templates (Davies, 2010).

Results from the data analysis suggested that hyperlink and template support had differential effects on comparative strategies. The hyperlink support improved back navigations and context switches together with total actions. Students who were more active in the study benefited more from the hyperlink. The template support had the most effect on cross-links, although not significant. However, when examining the correlations between comparative strategies and learning, I found that back navigations and context switches were more highly correlated with learning than cross-links. Thus, the template feature may be less effective because even though it improves the number of cross-links students create, there is less of a relationship between cross-links and learning. My sequential patterns indicated differences in outcomes between a student creating a cross- link after careful reading and a student creating a cross-link after little reading. It is possible that the template entices students to create cross-links between their own node and a template node without fully understanding the relationship between the two nodes, and thus those particular cross- links do not improve their understanding of key concepts. Chang's work (Chang, Sung and Chen, 2001) provided hints to students based on the comparisons between student maps and expert template found significant learning improvements. Thus, it is desirable to offer support to students when integrating their maps to the template.

Different concept map grading methods were applied between students in the template condition and without. Thus, it is not statistically meaningful to compare the between condition effect. Nonetheless, the map scores in the template condition had a marginal effect on learning outcomes, suggesting that with the template support, the correctness and completeness of the concept maps reflect learning outcomes. Therefore, correctly adding nodes to the expert template might have stronger learning benefits than adding to learners' own structures. Overall, characteristics of the concept maps are less predictive to learning than characteristics in the learning process

6.3.2 Assessing Comparative Strategies Building

Building on the comparative strategy model devised in the previous chapter, the two visualizations provide additional insights into learning strategies during concept mapping, allowing me to identify specific behavioral patterns that reflect how students are making comparisons between concepts. From the sequence diagram, I extracted three behavioral patterns, with the two positive patterns showing the importance of comparisons both within the text and between the text and the concept map. This suggests that reading and comparing behaviors in the learning content are critical components in concept map-based learning environments. The path navigation diagram evaluates comparative strategies from a different perspective, suggesting that students who read more pages, add nodes over time, and move back and forth within the text over time will benefit more. Taken together, these visualizations refined the comparative strategy metric with behavioral patterns that demote cognitive characteristics that are hard to capture by just action counts.

6.3.3 Insights for Future Concept Mapping Tools

Based on the findings presented above, I propose 3 design recommendations for future concept map-based learning environments.

Integrate tools with learning content. Current concept mapping tools (Cañas and Novak, 2008) tend to serve as external software that allow students to construct concept maps in different learning scenarios. The advantage of this approach is its compatibility with different learning contexts. However, this separation means that it is hard to provide effective scaffolding to support students' interactions between the learning content and the concept map, which is a critical component of concept mapping. The foundation of *MindDot* is the coherent integration between the learning content and the concept maps. This integration enables students to construct concept maps directly using the text in the content and in the same time, creates hyperlinks that connect nodes in the concept map with locations of key concepts in the content for navigation. This integration might also apply to the use of concept mapping with multimedia content. For instance, in online learning environments (Tsai, Lin and Yuan, 2001), one could design a concept mapping tool that allows students to use words or paragraphs from web pages to construct concept maps, and later, to use the nodes to navigate back to related content. In video-based learning environments, we could develop tools that not only connect specific nodes in the map with timestamps, as in (Lim, Lee and Grabowski, 2009), but also key objects in specific frames or additional resources related to the concepts mentioned in the video.

Provide support that doubles as an assessment. One advantage of our system is that the support we provided (e.g., the hyperlink support) allowed us to collect meaningful data about students' learning strategies. By examining how students used the hyperlinks, we were also able to make inferences about the ways in which they compared concepts. For these types of systems, it is useful to consider ways to make students' thinking visible, as first suggested by Anderson (Anderson *et al.*, 2009) in his discussion of principles for cognitive tutoring systems. By collecting sequential information on how students create concept maps, we have a real-time window into their cognitive and metacognitive processes as they attempt to make sense of the text.

Adaptively support comparative strategies. By tracking student behaviors within our system, it becomes possible to assess student comparative strategies and provide them with feedback in real time. Concept mapping activities have the potential to serve as the foundation for behavior-based intelligent tutoring systems (Vanlehn, 2006) that monitor student interactions with the system and provide feedback that facilitates comparative strategies. For example, if a student has been focusing on the concept mapping view and spends less time reading (high occurrence of SE and low occurrence of RP pattern), we could provide a feedback message such as "You are doing great at building your concept map, would you like to take a break from the map and read more about the concepts in the textbook?" Much of the work in the literature has focused on providing feedback based on the quality of students' concept maps. We believe that feedback in concept mapping could be more effective if students' behaviors during the learning process are taken into consideration.

6.4 Limitations

This presented work is limited in several areas that should be investigated in future studies. First, 59 students were used for analysis. Each of the four conditions had at most 15 participants. In addition, the empirical investigation in this work was a 90-minute study conducted in a research lab instead of a classroom. Thus, a future classroom study with a larger sample size would produce results that are more representative of the population. Lastly, in the study, students were given 5 minutes to review their maps after construction, with the goal of amplifying learning benefits of concept mapping. Although actions in the review stage are excluded from the comparative strategy model, the review session might have influenced the learning effects. This study design also makes our results difficult to compare with prior studies in the field.

6.5 Conclusions

In this chapter, I presented a new design iteration of *MindDot*, which is a step forward from the previous system by innovative integration of two types of support, hyperlink navigation, and expert template. The strength and novelty of our system lie in its ability to assist students in developing comparative strategies. An empirical study showed that students with hyperlink support outperformed the ones without hyperlink support. The system also demonstrated a promising impact on supporting comparative strategies. I then presented a fine-grained understanding of how students employ comparative strategies, finding that there were indeed certain sequences of behaviors in the text (e.g., reading before adding a link) that suggested that students are making comparisons. Finally, I derive three major design recommendations for future concept mapping systems to foster the development of comparative strategies and enhancing learning outcomes: integrate tools with learning content, provide support that doubles as assessment, and adaptively support comparative strategies.

I have discussed in the introduction chapter that this thesis work aims to address three major challenges, that is **developing efficient concept mapping tools**; **modeling student behavioral patterns**, and **providing adaptive diagnostic feedback**. So far, I have tackled two of these challenges. I developed a concept mapping system *MindDot*, that supports concept mapping with innovative features such as dual-window display, click-to-add gestures, and a coherent integration between hyperlink navigation and template feature. I have also developed a comparative strategy metric that decomposes the comparative learning strategy into measurable components. This model can then be used to qualitatively evaluate the strategic moves learners apply during concept mapping and provide diagnostic feedback to foster the development of comparative strategies. With these concluded findings, the next chapter will start to explore the unsolved challenge, that is, how to provide accurate and effective feedback in concept mapping? In the next chapter, I will present an intelligent feedback system that integrates traditional out-based assessment with process-based evaluation. An empirical examination will be described to test the effect of the feedback system. I then finalize the chapter with data analysis results and implications for future feedback system designs.

CHAPTER 7

SUPPORTING COMPARATIVE STRATEGIES WITH ADAPTIVE FEEDBACK

So far, I have presented the design and iteration process of *MindDot*, which supports concept mapping through the integration of two affordances, template support, and navigational aid. Statistical evaluations have shown these affordances facilitated comparative strategies and enhanced learning. Despite these benefits, the system did not offer any active instructions or feedback to guide students in developing comparative strategies. Without proper instructions that explain and fosters comparative strategies, learners are more likely to use these features instinctively, without having a specific goal to actively developing comparative strategies. Thus, providing these features might not be adequate to support comparative strategies. Learners who demonstrated high usage of comparative strategies might be able to compare and relate even without these affordances. Similarly, students who lack the awareness of comparative strategies are likely to neglect the assistance of these features and fail to benefit from them. I have described that one of the three major challenges in concept mapping is the lack of effective instructions to support learning. Hence, this chapter continues the research agenda by exploring the effect of adaptive feedback in concept mapping.

Previous work in the literature has explored providing feedback to support concept mapping and achieved promising effects in learning. Traditional methods directly support the learning outcome. For example, correcting a misconception in the map, pointing out missing concepts and links. However, these approaches are constrained when it comes to supporting comparative strategies, as they mainly assess the maps students create and do not evaluate the learning process. This limitation constrains traditional feedback mechanisms from determining whether students encounter difficulties developing comparative strategies and what instructions should be provided. The previous two chapters in this work have demonstrated the benefits of developing comparative strategies in concept mapping. Therefore, it is equally important to evaluate the learning process and provide instructions to support better learning strategies.

Research in the literature has also explored providing process-based metacognitive feedback to support learning strategies in concept mapping. Leelawong and colleagues compared the effect of content-based corrective feedback with process-based metacognitive feedback in a concept map-based learning system. Empirical evaluations suggested that while the metacognitive feedback fostered beneficial learning strategies such as information seeking, self-assessment, and monitoring, it was not as effective as the content-based corrective feedback in promoting learning results (Leelawong and Biswas, 2008). A significant limitation with metacognitive feedback is usually abstract and general, which contains little information about the learning context. The lack of content-related information limits metacognitive feedback from guiding learners performing expected behaviors. For example, when a user adds several concept nodes consecutively without comparing and creating links, a metacognitive feedback message such as "You've been adding several concept nodes, it might be a good time to compare and create some connections." might not be sufficient to foster the compare and relate behaviors. It is likely that the learner established the metacognition of developing compare and contrast behaviors from the feedback, but he still encounters difficulties spotting related concepts, or creating high-quality cross-links due to misconceptions, confusion, and lack of understanding in the content. Without essential knowledge to establish relations among concepts, even if the learner performed comparative behaviors such as back navigations, cross-link after receiving the feedback, these behaviors might not have the same benefits to facilitate deep learning compared to the ones where the actively research for related concepts and make connections. Therefore, instead of providing feedback prompts described above, a message such as "You've added some great nodes to your map. Can you show me how would you relate the concept "seed" with "sunlight"?" might be more effective as it gives hints about two potentially related concepts and encourages the learner to compare and connect them. Based on the discussion above, the development of comparative strategies requires not only the metacognition of beneficial behaviors and strategic moves but also a certain level of understanding of the content. Consequently, to support comparative strategies, there is a need to provide metacognitive instructions as well as content-related instructions.

To address this gap in research, I hereby propose the design of a feedback tutor that combines traditional outcome-based feedback methods with process-based evaluation and personalization. I have discussed that the advantage of process-based feedback is the accurate modeling of learning strategies and learning achievements, and the benefit of outcome-based feedback is the fine-grained content-related support. The feedback tutor in this work integrations the two forms of affordances. Feedback is triggered based on the learning process evaluation, and the message is tailored by evaluating learners' concept maps. This integration reduces the limitations of traditional feedback approaches in several ways. First, this combined-feedback approach augments outcome-based feedback by evaluating the learning process. Previous chapters have shown that behavioral patterns in the learning process can be highly representative of learning characteristics such as motivation and metacognition and are more predictable to learning than outcome-based metrics. The process-based evaluation can provide additional diagnostics of student learning, and in turn, enhance the accuracy of the feedback. Second, the combined feedback enhances traditional metacognitive feedback with specific instructions directly related to the domain content. I have discussed in the related work section that a potential drawback of metacognitive feedback is the abstraction of the feedback and the lack of specific instructions about the next steps. These content-related instructions in this proposed approach close the gap between the abstract and high-level strategic moves and specific actions students apply to their learning. In the next section, I will present the design of the feedback tutor and describe the integration of the outcome-based instructions and process-based feedback.

7.1 Implementing the feedback system

This section describes the design of the feedback tutor in *MindDot*. The interface of the system is demonstrated in Figure 7.1. The tutor, shown as an abstract light bulb on the bottom right corner, is designed to facilitate the use of the expert template and hyperlink navigation to foster the development of comparative strategies. Feedback from the tutor is presented as pop-up messages. The feedback system is driven by diagnostics of the learning process as well as concept map qualities such as correctness and completeness.

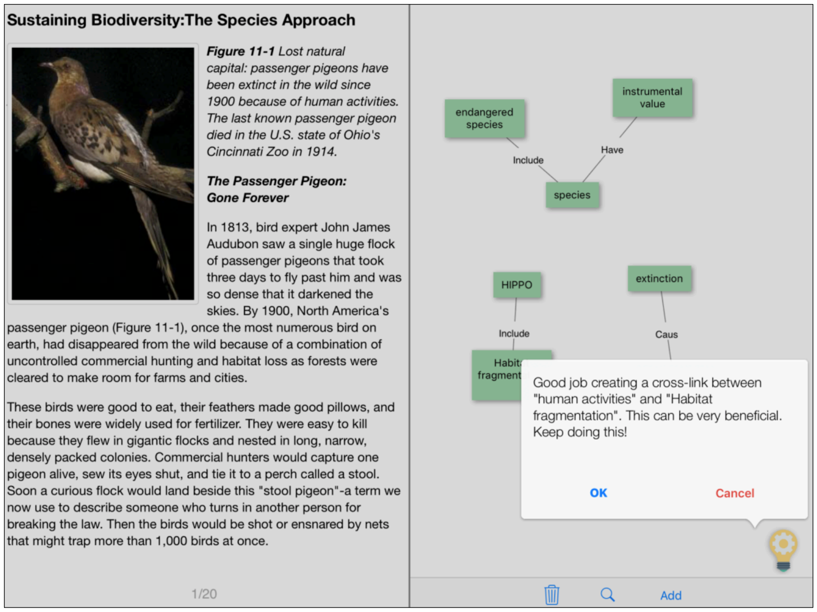


Figure 7. 1. Screenshot of the feedback tutor.

When students use the system, the feedback tutor tracks student activities and constantly extracts behavioral patterns from the action sequences. The system then classifies these behavioral patterns into different categories and determine what feedback to provide and when to provide them. Work presented in Chapter 6 has decomposed the development of comparative strategies into 3 overall factors (back navigation, context switch, cross-link) and 3 behavioral patterns (RRR, RL, SE). These factors and patterns were shown to be highly representative of the cognitive learning process. Therefore, they were used as guidelines for the feedback tutor. In addition, this work further presents 4 additional patterns that capture learning dynamics that were not modeled in the previous work, such as lack of engagement, low interactions with the template.

Table 7.1 shows a summarized table of the 10 behavioral patterns and the corresponding feedback messages. Each type of feedback is designed to support a specific behavior pattern.

Student Behavior	Pattern	P/N	Process-based Message	Content-based Instruction
Learners consecutively read more than 3 pages	Read read read	N	Remind students to add concepts while reading the textbook	Search for missing concepts and display them for students to choose
Learners add 3 nodes without linking them	Start and end	N	Remind the learners to link nodes to the existing concept map	Provides a hyperlink that navigates to concepts that are related to what they added
Learners cross-link two concepts without reading them carefully.	Low quality cross-link	N	Remind the learners to read and compare before linking	Displays a compare view that directly shows pages of the two related nodes in the same time
Students construct concept maps without interacting with the template	No Template	N	Remind students to tap on nodes in the template to review and connect the template structure	Highlights template nodes that are related with the current map or ones that need to be expanded
Students do not add or link nodes for more than 2 minutes	No Action	N	Remind students to add nodes or links instead of passively reading	Provides hints for missing nodes or missing links
Students do not perform any back navigation for 140 seconds	No Back Navigation	N	Remind learners to constantly go back and compare related concepts	Displays hyperlinks that navigate to pages that are related to what the learner is currently reading
Students do not create any cross-links for 3 minutes	No Cross-Link	N	Remind learners to create more cross-links instead of regular links	Highlight nodes that are cross-related but are not linked in the map
Students performed a back navigation for the first time	First back navigation	P	Praise the learner and encourage them to perform more back navigations	Display information about related concepts in the current page and the previous page.
Students created a cross-link for the first time	First cross-link	P	Praise the learner for creating cross-links and encourage them to create more cross-links	Show information about the two concepts that are cross-linked
Students compared and linked related concepts	Compare and link	P	Acknowledge the positive pattern and encourage learners to perform more.	Show information about the two concepts that are being compared and linked

Table 7. 1. Summary of behavioral patterns and corresponding feedback

A specific feedback prompt is triggered when a key behavior pattern is detected. When a negative behavioral pattern is detected, the feedback message points out the ineffective behaviors that the learner is currently performing and provides instructions on what behaviors learners need to perform to develop beneficial learning strategies. When a positive behavioral pattern is detected, the tutor acknowledges the beneficial behaviors and encourages the learner to perform more of these behaviors. Feedback from the tutor contains two parts, the process-based feedback and the content-related instructions. The process-based feedback is the diagnoses learner's current learning strategies, and the content-related instructions advises what actions the learner should perform instead. I have discussed above that providing high-level metacognitive feedback might cause confusion to the learner. Thus, to provide more accurate instructions, the messages presented to the learner are tailored based on the evaluation of the learner's map and the learning content. In the following paragraphs, I will describe the design of each type of feedback.

7.2 Knowledge Model

The content related instructions are generated based on an expert knowledge model we constructed. The expert knowledge base consists of 25 pairs of key concepts. These concepts are selected based on knowledge examined by the test questions. Each concept in the knowledge base includes several synonyms, making the model more robust to different variations of expression and articulation. All the concepts in the model are linked with pages where they are mentioned. Thus, we are able to track missing concepts during map construction by comparing the concepts students include in their map and concepts exist in the expert model that are within a certain rage of pages (used in RRR feedback). We are also able to identify missing relationships by comparing links in the student map and links in the knowledge model (used in SE feedback).

7.3 Feedback Designs

Read read read (RRR) pattern:

The RRR pattern triggers when a student consecutively reads for more than 3 pages. It indicates that the student is reading the textbook in a linear order, without actively reviewing other relevant content or establishing relationships with other concepts. Thus, when an RRR pattern is found, the tutor will remind the student to add concept nodes or create links with other nodes. The navigational diagram shows that high learning students tend to have higher vertical coverage on the map. Which means that their maps cover more pages in the content. Thus, facilitating students to construct maps that cover concepts in more pages could be highly beneficial. Therefore, in addition to the feedback message, the tutor provides an additional content-related instruction, that is a “select to add” window, which displays key concepts the learner missed in previous pages. The “select to add” windows displays a maximum of four concepts and students are asked to select one from the four presented concepts. If a learner only missed one key concept, it will only display the concept that the learner missed. The “select to add” window is triggered when the learner clicks on the “show me some” button in the feedback view. Students can select the nodes provided by the agent and click on “add this concept” to add them to the map. Nodes created in this way are also hyperlinked with the content, allowing students to tap on them and review related text.

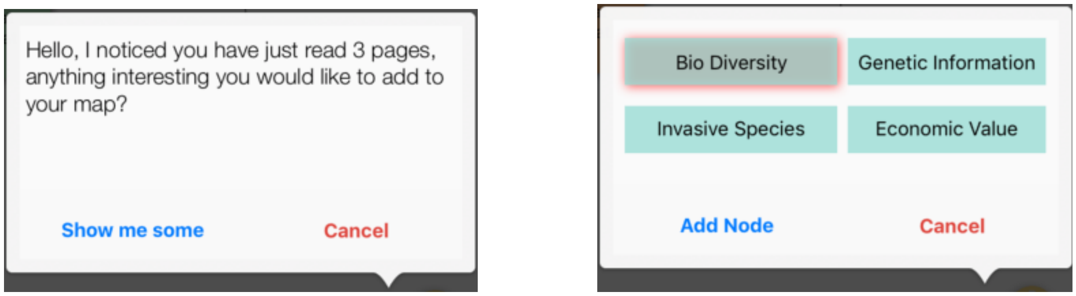


Figure 7. 2. RRR feedback

Start and end (SE)

The SE pattern suggests that the student is consecutively adding several nodes in the same page, without reading relevant content or linking with other concepts. When the SE pattern is identified, the system will prompt a feedback message to remind the learners to link the added nodes to the existing concept map. The SE pattern suggests that the student is consecutively adding several nodes in the same page, without reading relevant content or linking with other concepts. In this case, the system first searches for relevant concepts in other pages. If there are relevant nodes found, the system provides a feedback indicating the student that there are relevant content in other pages shown in Figure 7.3 (a). To further support the comparison of related concepts, a hyperlink to related concepts is presented with the feedback. When the learner clicks on "See related concepts", the tutor directly navigates to the page that contains the related concepts. Relevant text and nodes in the map are both highlighted for better comparison, shown in Figure 7.3 (b).

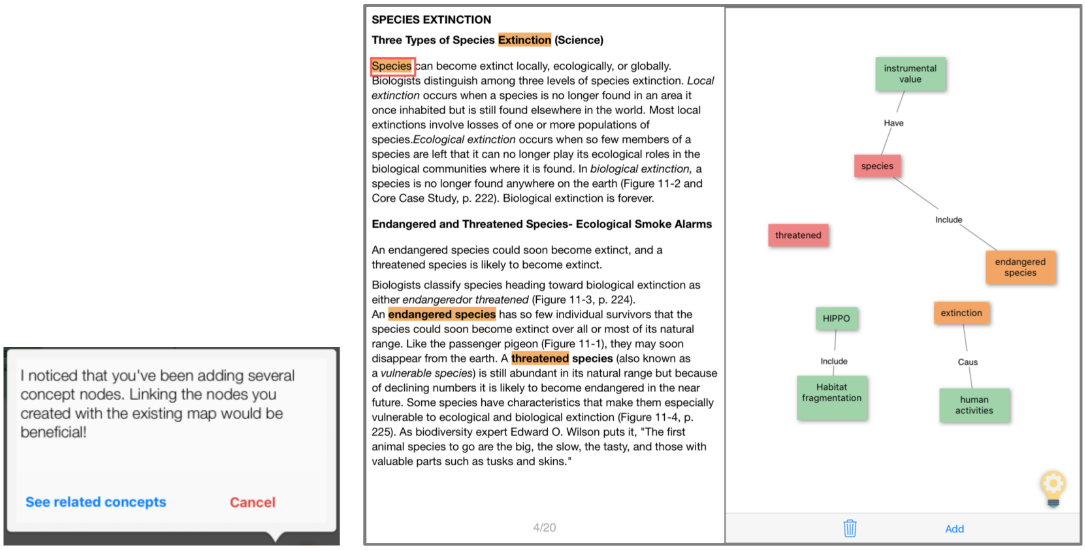


Figure 7. 3. (a) SE feedback message. (b): System navigates to related pages and highlights relevant content (red box) in the text as well as related nodes in the map (highlighted in red)

Low quality cross-links

Our sequential patterns indicated differences in outcomes between a student creating a cross-link after careful reading and a student creating a cross-link after little reading. It is possible that the template entices students to create cross-links between their own node and a template node without fully understanding the relationship between the two nodes, and thus those particular cross-links do not improve their understanding of key concepts. Chang's work (Chang 2010) provided hints to students based on the comparisons between student maps and expert template found significant learning improvements. Thus, it is desirable to offer support to students when integrating their maps to the template. This type of feedback aims to foster cross-relationship comparison when creating concept links. When a student creates a cross-link between two concept nodes, the system checks the reading behaviors the student performed before creating the link. The system first computes the time the leaner spent on the two pages that contain the linked nodes. When the student hasn't spent enough time (10 seconds) reading these two pages, and there is no comparative reading activity (e.g. back navigation, context switch) performed on these pages. The system provides a feedback suggesting the student to spend more time on reading the two concepts. To provide convenience in comparing the two related concepts, when learners click on the button “compare them”, the system shows a compare view that splits the window into two views, each displays the page that contains one of the two concepts to be compared.

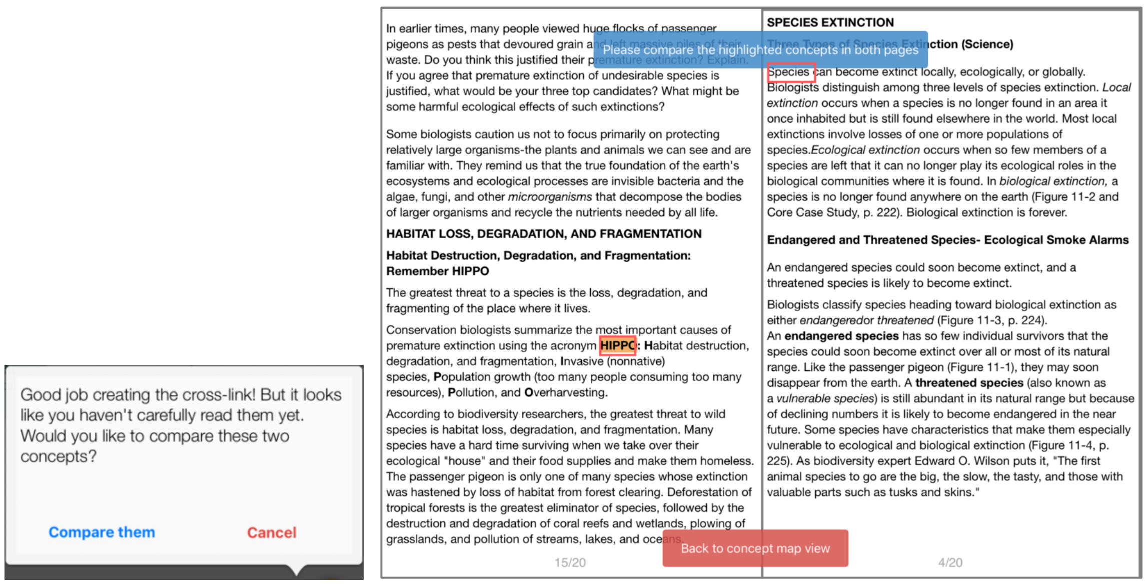


Figure 7. 4. (a): Low quality cross-link feedback message. (b): compare view that highlights related concepts

No Action Feedback

Our navigational path diagrams revealed that high learning students tend to have higher horizontal coverage. In these diagrams, red dots are more spread-out horizontally, covering a more than half of timestamps, indicating that the learner is constantly adding new nodes and links to refine the concept map throughout the learning period. On the other hand, low learning students tend to add nodes and links at the beginning of the learning period, and gradually stop expanding the map. Thus, the no action feedback is triggered when a user does not add any new nodes or links to the map within 2 minutes. Figure 7.5 (a) displays an example of the no action feedback message. To encourage the creation of concept nodes, the no actions feedback is also integrated with the "select to add" window. When the learner clicks on the "show me some" button, the "select to add" window is displayed with key concepts that the learner has missed. The learner can select one of the displayed nodes and add it to the map.

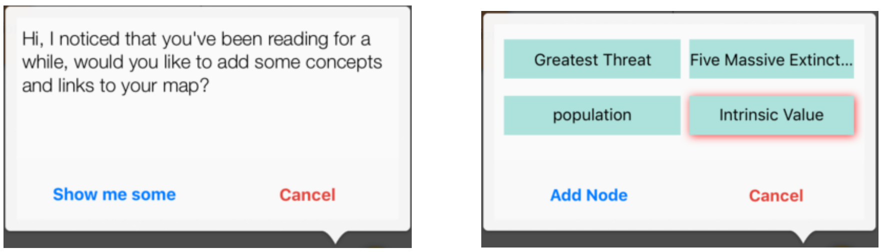


Figure 7. 5. (a) No action feedback in content condition. (b) Feedback displays missing nodes

No Back-Navigation Feedback

Back navigation is an important characteristic of comparative strategies. It captures the active comparison among concepts in different sections in the content. The use of back navigation can be highly beneficial towards learning gains. Thus, when the user does not perform any back navigation within 140 seconds, the system provides a feedback that reminds the student to review and compare concepts that has been read before.

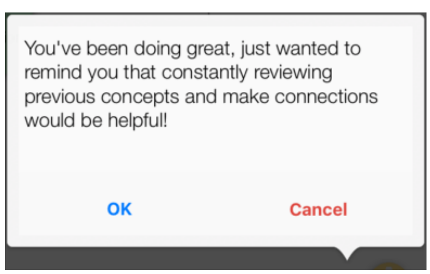


Figure 7. 6. An example of the no back navigation feedback

No Template Feedback

The expert template is designed to serve as a foundation for the concept mapping activity. Students are expected to tap on the nodes in the template to preview what they are about to learn. Previous studies on the template revealed that it expanding the template structure faciliated comparative strategies. Thus, after learners have spent 10 minutes in the activity, the tutor evaluates the interactions with the template. If there are nodes in the template that have not been expanded, the no feedback will be triggered. Figure 7.7 shows an exmple of the no template feedback. When learners click on the "Tell me more" button, the tutor hilights the nodes in the template that needs to be expanded.

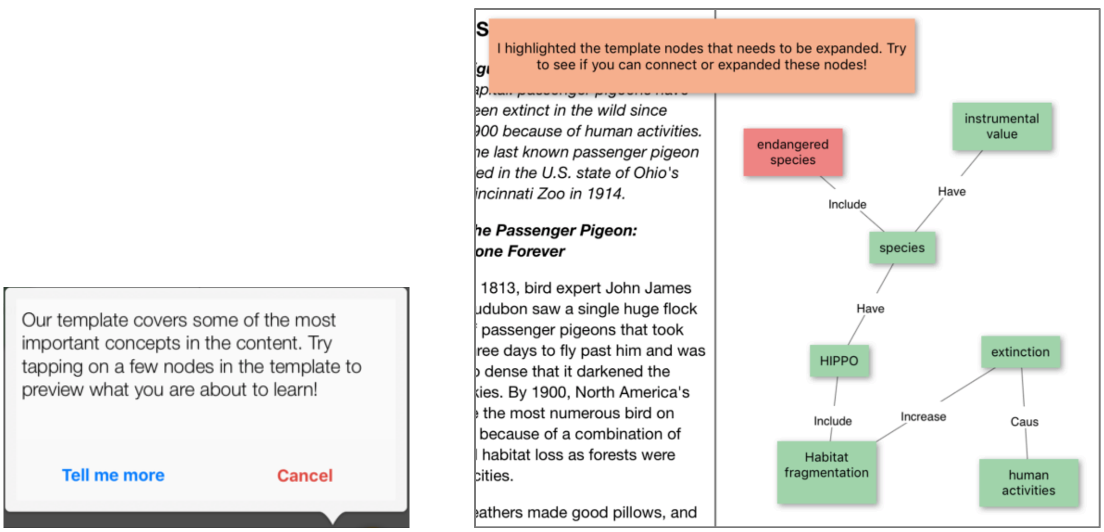


Figure 7. 7. (a) No template feedback in content condition. (b) System highlights a node in the template that is related to what the user is reading.

Positive Feedbacks

When positive patterns are detected, the system gives the student a praise about the actions. The goal of providing these positive feedbacks is to remind the students that these are beneficial behaviors and they should keep performing these actions. However, frequent reminder of these actions is likely to cause distractions to the students. Thus, when the first time a student performs a positive behavior pattern, the system shows a pop-up feedback with a detailed message explaining the good learning behavior that the student performed.

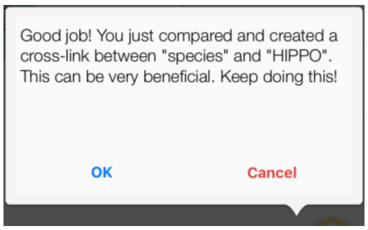
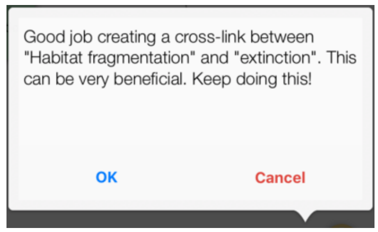
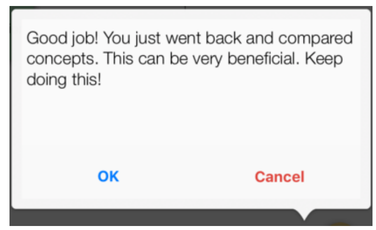
Compare and Link	First cross-link	First back navigation
		

Table 7. 2. Examples of 3 types positive feedback

7.4 User Study

I conducted an in-lab controlled study to examine how the proposed feedback method influences the use of comparative strategies and its learning impact. The study had two sessions, the main session, designed to evaluate the direct effects of the feedback tutor, and a transfer session, designed to measure the behavioral changes and the effects of the tutor when all instructions are faded. During each session of the study, students used *MindDot* to read a few pages from a textbook chapter and constructed concept maps with the support of the feedback tutor. Pre and posttests were given to students, and log data was collected to investigate students' interactions with the system and their corresponding learning outcomes.

The primary goal of this experimental study was to demonstrate that providing feedback based on both the learning process and quality of the map facilitates the development of better learning strategies and enhances learning outcomes. Thus, the combined feedback tutor in *MindDot* described in the previous section was compared against two other versions of the system. One was the control condition, where the students used the system to create concept maps without any instructions. In the second condition, the tutor only provides metacognitive feedback without any content-related information. To facilitate the development of comparative strategies, students in all three conditions received the template support and the hyperlink navigation support. I describe the three conditions in more detail below:

No feedback (NF): The system in the no-feedback group represented the control condition to help establish the differences between learning without feedback and learning with different types of instructions. Students in this condition receive the technological affordances presented in previous chapters, including expert template, hyperlink navigation, click to add nodes, and dual-window design. However, there were no instructions or hints provided while learners use the system.

Process Feedback (PF): Students in this condition have all the affordances in the no-feedback condition. Besides, learners received metacognitive feedback to facilitate the use of comparative strategies. The tutor contains all 10 types of feedback described above and provides feedback when specific behavioral patterns are detected. The feedback messages contain diagnostic information on the learners' current learning strategies and suggestions about future behaviors. For example, when a student reads 3 pages without adding nodes (RRR pattern), the tutor will prompt a message saying, "Hello, I noticed you have just read 3 pages, anything interesting you would like to add to your map?". A major difference between process feedback and the feedback method described above is that process feedback does not contain any content-related instructions, such as hints about missing concepts or hints about related concepts.

Combined Feedback (CF): The combined feedback group represents the experimental condition. Students in this condition received the full feedback described in the previous section.

The primary goals for the study were to study the (i) differences in learning between students who received combined feedback, process feedback and no feedback, (ii) differences in use of comparative strategies between conditions, (iii) effectiveness of combined feedback in preparing students for future learning, when feedback is removed and (iv) differences in feedback responses. Based on the discussions presented earlier, I hereby propose the following hypotheses:

1. Combined feedback enhances learning results.
2. Combined feedback facilitates the development of comparative strategies.
3. Combined feedback promotes comparative strategies and learning in the transfer session.
4. Combined feedback is more effective in correcting learning behaviors.

7.4.1 Experimental Procedure

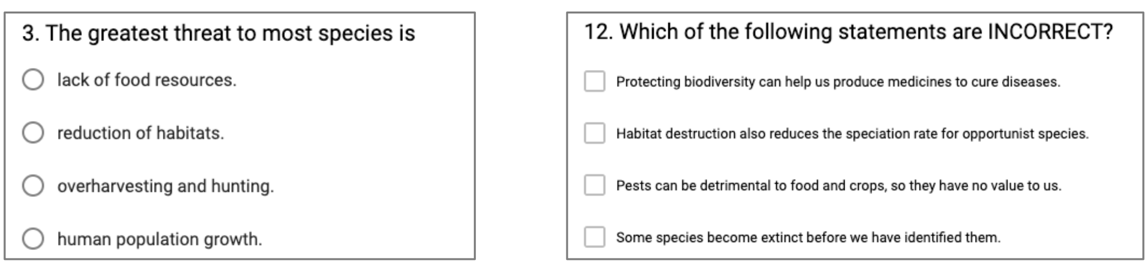
We recruited 50 students from Arizona State University for the study and excluded 4 graduates from the data analysis. *MindDot* was installed on an iPad 2 Air with a 9.7-inch retina display and a multi-touch interface. Two chapters of the learning material were included in the application. The learning material for the main session consisted of a section from the 15th edition of *Living in the Environment: Principles, Connections, and Solutions*. The textbook section displayed in the application was manually edited into a 20-page book to fit the screen of the iPad. The content for the transfer session consisted of a science article *Water on the Earth* from ReadWorks.org. The article was edited into a 5-page book in the application. Students were randomly assigned to conditions, with 13 in the no-feedback condition, 16 in process feedback condition, and 15 in combined feedback condition.

Students began the study with a pretest. In order to save time for the study, the pretest contains questions for the main session and the transfer session. After the pretest, all participants were given a 10-minute in-app training session (tailored to condition) where they learned about how to use the application features. After the training, students began the main study session, in which they were asked to take 30 minutes to read the content and leverage all the features mentioned in training to create the best concept map they could. If students finished reading the content before 30 minutes, they were told to refine their maps. A counter-balanced posttest for the main study was given afterward.

Students then continued with the transfer learning session. Students were given 10 minutes to read to learning content and construct a concept map about the content. Students in all three conditions used the same version of the app, which had the expert template and navigational support, but no feedback was provided. After the reading section, a posttest for the transfer learning session was given to the students to assess learning outcomes.

7.4.2 Measures

Learning. The pretest and posttest questions for the main study were originally designed by a high school teacher that we worked with in a previous study and were modified to tailor college students. The main session pretest consisted of two parts. The factual questions consisted of 8 multiple choice questions that required fact-based answers. Students were asked to choose one correct answer from the 4 given options. The interpretive questions consisted of 4 check all that apply questions that require deeper understandings from the learning content. Students were asked to choose all correct answers from the 4 given options. The posttest consisted of the same questions but counter-balanced as well as two additional free input questions. The pretest and posttest for the transfer study session were modified from the assessment questions designed by the author from ReadWorks.org. The pretest consisted of 3 check all apply questions, and the posttest contained the same questions in a different order as well as 2 additional free input questions.


3. The greatest threat to most species is

- lack of food resources.
- reduction of habitats.
- overharvesting and hunting.
- human population growth.

12. Which of the following statements are INCORRECT?

- Protecting biodiversity can help us produce medicines to cure diseases.
- Habitat destruction also reduces the speciation rate for opportunist species.
- Pests can be detrimental to food and crops, so they have no value to us.
- Some species become extinct before we have identified them.

Figure 7. 8 (a) Example of a factual question. (b). Example of an interpretive question.

Concept map evaluation. Similar to the work presented in Chapter 5, I computed three basic properties of the students' concept maps, which are the total number of concept nodes, total number of concept links, and link/node ratio. This metric models student engagement with the concept mapping tool. To measure the correctness and completeness of the maps, I mapped the 12 assessment questions for the main study session into 13 key concepts. 8 concepts that were presented in the template were excluded from the 13 key concepts. When a student correctly adds a concept as a node to the map, we give the student 1 point for that particular concept. Nodes created need to be linked to related nodes with valid relationships in order to be considered as correct. Nodes students add that are not part of the 13 key nodes were not scored. The final concept map score is computed as the sum of all the points for added concepts.

Comparative Strategies. This work models comparative strategies with the same metric proposed in my previous work. The metric models comparative strategies via three variables, that are back navigation, number cross-link, and context switch. Similar to the work in Chapter 4, I compute an overall model that quantifies the generative strategy as a whole. The overall model was computed by first rescaling the three variables into [0, 1] using feature scaling and then compute the average from the three scaled variables.

Feedback Response. This section proposes an evaluation of the learning behaviors after learners receive a feedback message. I present feedback response metric to assess how students corrected their learning behaviors from negative feedback. When a student received a feedback message, I extract the next 5 actions performed by the student. If the learner performed the expected behavior according to the feedback instruction, it is considered as a correct response to the feedback. For example, the expected behavior for the RRR pattern is adding a concept node. When a learner gets the RRR feedback message, if the learner adds a concept node within the next 5 actions, it is considered as a correct response to the feedback. Similarly, when a learner gets a no cross-link feedback message, the correct response would be creating a cross-link within the next 5 actions. Behaviors after the next 5 actions are not counted as learners are likely to have moved forward in the content. Table 7.3 presents a summary of the expected behaviors for each type of negative feedback.

Pattern	RRR	SE	Low Quality Cross-Link	No Template	No Action	No Cross-link
Expected Behavior	Add a node	Add a link	Compare the two related concepts	Expand a template node	Add a node or a link	Create a cross-link

Table 7. 3. Expected behaviors for each type of negative feedback

7.5 Results

Overview of the concept mapping activity. In this section, I first present an overview of how students used *MindDot* to create concept maps for learning. Table 7.4 presents the means and standard deviations of the four variables of concept map properties. In addition, I present the total number of navigations, that is the number of time learners navigate to another page in the textbook content. Overall, students created a mean of 20.52 nodes (SD = 8.61) and a mean of 18.65 links (SD=9.11). The average link/node ratio was 0.91 (SD = 0.22). Learners had a mean of 37.61 (SD=18.16) for the total navigation, that is the number of times they navigate to another page. I then conducted a MANCOVA test with the three variables of the concept map property, map score, and the total navigation as dependent variables, and condition as the independent variable. There was no significant difference between condition on total number of nodes ($F(1, 43) = 1.97$, $p = 0.15$) and concept map score ($F(1, 43) = 1.72$, $p = 0.19$) and total navigation ($F(1, 43) = 1.37$, $p = 0.87$). There were marginal effects between conditions on the number of links ($F(1, 43) = 3.05$, $p = 0.058$) and the link over node ($F(1, 43) = 2.57$, $p = 0.088$).

Condition	Total Node	Total Link	Link/Node	Map Score	Total Navigation
NF	19.50 (5.46)	15.65 (7.14)	0.80 (0.29)	3.86 (2.45)	39.00 (18.77)
PF	18.13 (8.63)	17.00 (8.07)	0.95 (0.18)	4.88 (1.96)	35.69 (18.09)
CF	23.81 (10.17)	22.94 (10.43)	0.96 (0.16)	5.38 (2.39)	38.31 (18.71)

Table 7. 4. Means and standard deviations of concept map preparties and total navigation.

H_1. Combined feedback enhances learning results. I conducted a repeated-measures ANOVA on pre and posttest scores, with test time as the within-subjects' variable. Free input questions are excluded for this analysis as repeated-measures ANOVA requires the variances of scores among the test variables to be equal. Results showed that students demonstrated significant learning between the pretest and posttest across all conditions ($F(1, 43) = 16.91$, $p < 0.001$). Means and standard deviations are presented in Table 7.5. The free input questions were graded independently by two researchers. The scores of the two graders were highly reliable (interval of 0.964 to 0.989 with 95% confidence).

Condition	Factual			Interpretive			Free Input
	Pre	Post	Normalized Gain	Pre	Post	Normalized Gain	
NF	4.7 (1.5)	4.9 (1.6)	0.07 (0.36)	11.6 (1.7)	11.9 (1.3)	0.11 (0.27)	4.79 (3.27)
PF	3.8 (1.5)	4.6 (1.5)	0.16 (0.22)	10.9 (1.4)	11.5 (2.0)	0.16 (0.30)	5.44 (2.83)
CF	4.5 (1.6)	5.3 (1.2)	0.21 (0.34)	12.1 (1.3)	13.5 (1.9)	0.37 (0.35)	7.25 (2.72)

Table 7. 5. Pre and posttest scores for the main learning session.

I further investigate the impact of different types of feedback on learning. For the factual questions, an ANCOVA test with posttest as the dependent variable, condition as the independent variable and pretest as a covariate revealed no significant effect among conditions. In contrast, an ANCOVA test on the interpretive questions indicated found significant learning differences between conditions ($F(1, 42) = 3.78$, $p = 0.031$). Post hoc tests using the Bonferroni method revealed that the combined feedback marginally elicited increments in the interpretive questions compared to students in the no feedback condition ($p=0.09$) and ones in the process feedback ($p=0.05$).

An ANCOVA test with the free input question scores as the dependent variable, condition as the independent variable, and total pretest score (including both factual and interpretive questions) as the covariate for prior knowledge, revealed significant differences between conditions ($F(1, 42) = 3.89$, $p = 0.028$). Post hoc tests using the Bonferroni method revealed that the combined feedback significantly improved performance in the interpretive questions compared to students in the NF condition ($p=0.028$). There were no learning differences between the CF condition and the PF condition ($p=0.20$). There were also no differences between the PF condition and the NF condition. Therefore, H_1 is mostly supported. Students who received combined feedback had higher learning results students who didn't receive feedback.

H_2. Combined feedback facilitates the development of comparative strategies.

Table 7.6 shows the means and standard deviations for the comparative strategy model. It is worth pointing out that the factors in the comparative strategies are absolute counts of certain actions. Therefore, the overall engagement in the system should be considered as a covariate.

I computed the total number of page navigation as a proxy for overall engagement. ANCOVA tests with condition as the independent variable, the three indicators of comparative strategies and the overall model score as the dependent variables and total number of navigation as the covariate showed no significant differences on the number of back navigations ($F(1, 42) = 1.40$, $p=0.26$). However, the analyses revealed that different types of feedback had significant effects on cross-links ($F(1, 42) = 3.45$, $p=0.041$). Post hoc tests using the Bonferroni correction showed that the combined feedback increased the number of cross-links over the no feedback condition ($p=0.047$). Number of context switches was significantly different between conditions ($F(1, 42) = 3.89$, $p=0.028$). Post hoc tests showed that number of context switch in the CF condition was marginally higher than the PF condition ($p=0.058$) and marginally higher than the NF condition (0.068). The overall comparative strategy model was significantly different between conditions ($F(1, 42) = 3.73$, $p=0.032$). Post hoc pairwise comparison showed suggested that students in the CF condition demonstrated higher use of comparative strategies over the students in the PF condition ($p=0.045$). Therefore, H_2 was supported. Students who received combined feedback had a higher user of comparative strategies than students who received process feedback and no feedback.

I evaluated the effect of comparative strategies on learning. I conducted a partial correlation, controlling for pretest (factual + interpretive), and examined the relationships between the posttest score (factual + interpretive + free input), and the three factors of comparative strategies. Results indicated that while cross-link was significantly correlated with learning ($r(43) = 0.41$, $p = 0.006$), the back navigation ($r(43) = -0.244$, $p = 0.106$) and context switch is not ($r(43) = 0.15$, $p = 0.307$).

Condition	# Back Navigation	# Cross-link	# Context Switch	Overall Model
NF	8.64 (4.59)	9.00 (5.21)	55.36 (17.00)	0.39 (0.21)
PF	6.00 (4.53)	10.50 (5.09)	55.19 (18.92)	0.35 (0.20)
CF	6.81 (4.10)	13.50 (4.61)	72.06 (21.13)	0.53 (0.18)

Table 7. 6. Indicators of comparative strategies.

H_3: Combined feedback had long term impacts on facilitating comparative strategies and learning.

Here, we evaluate the differences in learning and the use of comparative strategies in the transfer learning session, where all feedback is removed. Table 7.7 shows the means and standard deviations of the test scores. The free input questions were graded by two researchers and average of the scores of the two graders were statistically reliable (interval of 0.934 to 0.980 with 95% confidence). A repeated-measures ANOVA on pre and posttest scores (excluding free input questions), with test time as the within-subjects' variable, showed significant learning between pre and posttest for all conditions ($F(1, 43) = 20.37$, $p<0.001$). However, there is no significant differences found on learning between conditions ($F(1, 43) = 0.065$, $p=0.94$). An ANCOVA with the free input score as the dependent variable, condition as the independent variable, and pretest as the covariate revealed no significant differences between conditions ($F(1, 43) = 2.084$, $p=0.138$). I then conducted an ANCOVA test with all posttest questions (free input included) as the dependent variable, condition as the independent variable, and pretest as the covariate. Results showed that there was no effect found on learning between conditions ($F(1, 42) = 1.51$, $p=0.23$). Therefore, different types of feedback did not yield significant impacts on the transfer session when feedback was removed.

Condition	Pretest	Posttest	Normalized Gain	Free Input
NF	8.57 (2.34)	10.00 (1.30)	0.20 (0.21)	6.23 (2.61)
PF	8.94 (2.02)	10.38 (1.63)	0.20 (0.27)	7.27 (2.43)
CF	8.81 (1.90)	10.50 (1.46)	0.20 (0.23)	8.13 (2.12)

Table 7. 7. Pre and posttest scores for the transfer learning session.

Here, I further investigate the use of comparative strategies between conditions. Table 7.8 shows the means and standard deviations of the three factors for the comparative strategy metric and the overall model score, as well as the total number of navigations. A one-way ANOVA with total navigation as the dependent variable and condition as the independent variable showed that there was no effect found on total navigation ($F(1, 43) = 1.68$, $p = 0.20$). Therefore, students were equally engaged in the transfer learning session.

ANCOVA tests with the condition as the independent variable, three indicators of comparative strategies and the overall model score as the dependent variables, and the total navigation as the covariate were conducted. Number of back navigation was significantly difference between conditions ($F(1, 42) = 3.39$, $p = 0.043$). Post hoc tests showed that students who received combined feedback in the main session had significantly more back navigations in the transfer session than the ones who didn't receive feedback. There was no significant effect found between conditions on cross-links ($F(1, 42) = 2.20$, $p = 0.123$). The number of context switch was significantly different between conditions ($F(1, 42) = 4.02$, $p = 0.025$). Post hoc tests pointed out that students in the combined feedback had more context switches than the ones in the process condition. The overall comparative strategy model was significantly different between conditions (F(1, 42) = 4.57, p = 0.016). Post hoc tests showed that students in the combined feedback condition had a significantly higher usage comparative strategies than ones who received process feedback, and a marginal higher usage of comparative strategies than the students who didn't receive feedback. Therefore, H_3 was partially supported, while there was no learning difference in the transfer session, students who received combined feedback in the main study session had higher use of comparative strategies in the transfer session, where all instructions are removed.

Condition	# Back Navigation	# Cross-link	# Context Switch	Overall Model	Total Navigation
NF	2.29 (2.30)	9.00 (5.21)	76.43 (28.86)	0.42 (1.60)	10.79 (6.87)
PF	1.69 (1.58)	10.50 (5.09)	74.63 (23.84)	0.39 (0.15)	7.56 (3.44)
CF	3.18 (2.79)	13.50 (4.61)	94.38 (25.59)	0.51 (0.13)	10.25 (5.11)

Table 7. 8. Indicators of comparative strategies in the transfer learning session.

I evaluated the effect of comparative strategies on learning in the transfer session. I conducted a partial correlation, controlling for pretest scores, and examined the relationships between the posttest scores (free input included), and the three factors of comparative strategies. Results indicated that none of the measures for comparative strategies were correlated with learning: back navigation (r(43) = -0.002, p = 0.99), cross link (r(43) = 0.12, p = 0.45), and context switch is not (r(43) = -0.12, p = 0.45).

H_4: Combined feedback is more effective in correcting learning behaviors. Here, I examine how students reacted to the feedback message in the CF condition and the NF condition. Table 7.9 presents the means and standard deviations of some of the key factors for the feedback interaction, including the number of positive feedbacks, the number of negative feedback, the number of feedback response and the response rate. I conducted a one-way ANOVA test with the factors mentioned above as the dependent variables and condition as the independent variable. Results showed no difference between conditions on the number of positive feedback ($F(1, 30) = 1.11$, $p = 0.30$) and number of negative feedback ($F(1, 30) = 0.23$, $p = 0.63$). There was significant difference between conditions on the number of feedback response ($F(1, 30) = 8.45$, $p = 0.007$) and response rate ($F(1, 30) = 16.48$, $p < 0.001$). Thus, hypothesis H_4 was supported. Students who received combined feedback were more likely to respond to the feedback correctly.

Condition	**Positive Feedback**	**Negative Feedback**	**Feedback Response**	**Response Rate**
PF	1.81 (1.11)	6.13 (2.13)	2.83 (5.09)	0.46 (0.21)
CF	2.43 (2.10)	6.50 (2.28)	4.69 (1.89)	0.74 (0.17)

Table 7. 9. Indicators of feedback responses in the two feedback conditions.

7.6 Visualizations of the learning process

The data analyses presented above have demonstrated significant differences between the combined feedback condition and the process feedback condition in terms of learning achievements, use of comparative strategies, and feedback responses. However, metrics in the results section aggregated student behaviors from the whole session and provided little insights about specific sequential behaviors after learners received feedback. To develop an action-by-action understanding of how different types of feedback affect learning behaviors, I evaluate students' learning processes through the navigation path diagram.

The navigation path diagram follows the design presented in Chapter 6, in which the vertical axis denotes the page number and the horizontal axis illustrates the timestamps, measured in seconds. The black line in the graph illustrates the page order read by the student throughout the study. The blue circles on the lines indicate the action of adding nodes. The x coordinate of the circle represents the time of the action and the y coordinate records the page number that the learner is currently reading. To further illustrate the learning behaviors after learners receive a feedback message, I plot the receive feedback actions as red crosses "", and the cross-link actions as green stars "*". Figure 7.9 shows two prototypical diagrams. 7.9 (a) represents a high learning student from the combined feedback condition (0.67 on normalized gain for interpretive questions), and 7.9 (b) represents a low learning student from the process feedback condition (0 on normalized gain for interpretive questions).

Some of the differences discussed in Chapter 6 were revealed again in this comparison. The first difference between the two types of students is the page reading path. In the high learning students' diagrams, the page numbers gradually increase over time, and there are lots of zigzags in the reading paths, meaning that students were frequently referring to previously read content to make connections between different segments in the content. In the low learning students' graphs, the page numbers grow more smoothly. Although the students did go back to previous pages at certain points, they still passively followed the linear order presented by the content. Another difference lies in the vertical coverage. Students with high learning gains read more pages and created nodes from a wider range of pages whereas low learning students were more likely to read and create nodes from the first few pages of the content.

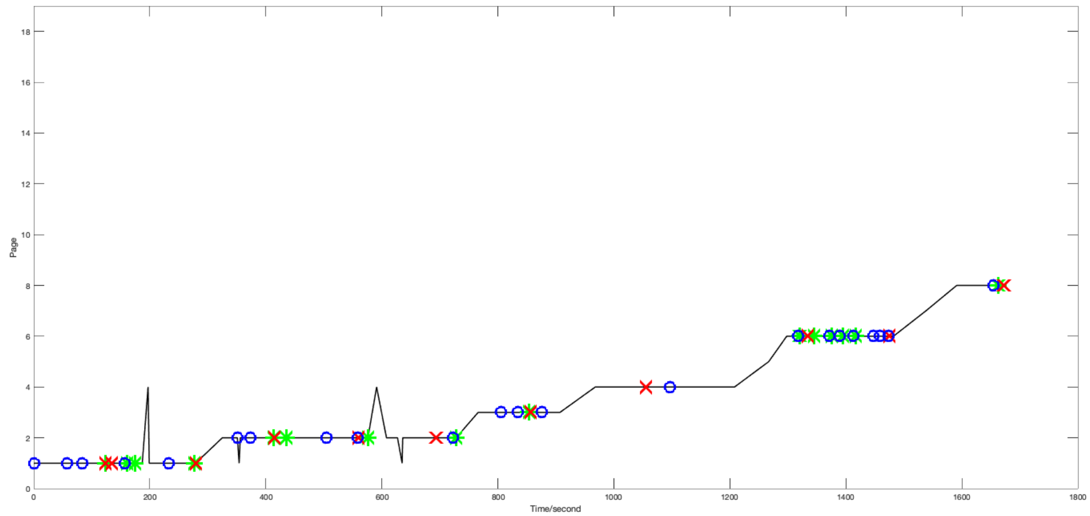
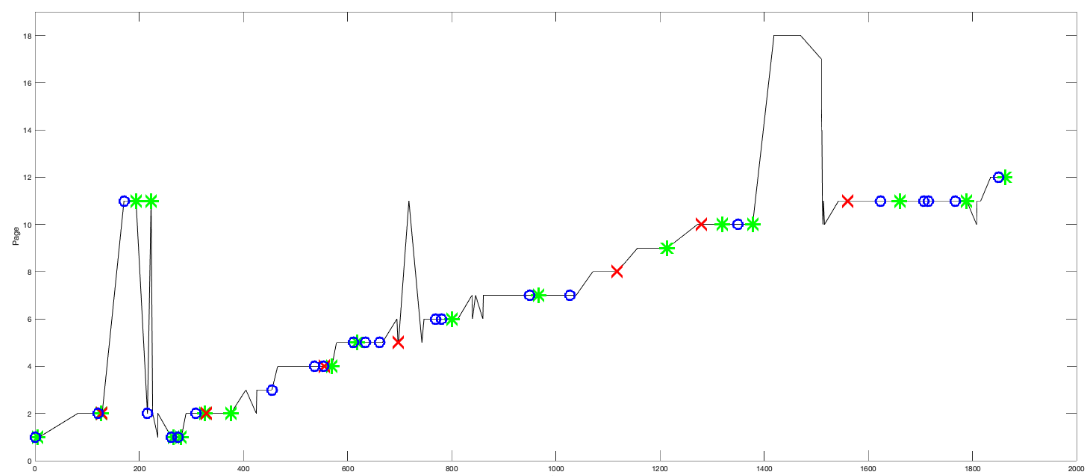


Figure 7. 9. (a) Navigation diagram from a low learning student in the PF condition



(b) Navigation diagram from a high learning student in the CF condition

There were also clear differences in behavioral patterns after feedback was received. Students in the combined feedback condition were more likely to perform comparing behaviors, which is demonstrated in figure 7.9 (b). A lot of the feedback actions (red “”) in the diagram are followed by small zigzags between adjacent pages or even vast leaps between different segments in the text. And these comparisons usually resulted in new concept nodes and cross-links being created. In figure 7.9 (b), we can see that adding nodes actions (blue circle) and cross-link actions (green "*") are spread around those zigzags in the navigation path, indicating that nodes and cross-links were created after comparisons. In contrast, figure 7.8 (a) shows that feedback actions from the low learning students were likely to be followed by a straight line through a certain time frame. Adding nodes actions and cross-link actions are spread out on the straight line instead of the zigzags. Also, even when students performed comparing actions, they were less likely to create new nodes or cross-links as a result.

We have presented three visual measurements (zigzag, vertical coverage, and horizontal coverage) of learning strategy from the navigation diagram in chapter 6. Visualizations in work furthered the previous model with two additional sequential patterns of student learning strategies**: Feedback & Compare** and **Compare & Add**. The feedback & compare pattern captures learners' immediate response to the feedback. In a feedback & compare context, learners followed the instruction from the feedback and performed comparing activities. A high occurrence of the feedback & compare pattern could be an indication that the learner is constantly applying the strategic instructions into practice. The compare & add pattern distinguishes meaningful comparisons with random reading behaviors. In a compare & add context, learners carefully read the related content and identify new key concepts and cross-section connections as a result for comparison, whereas student in a randomly reading scenario, learners passively follows the strategical instruction by navigating to different pages but didn't generate meaningful knowledge from these behaviors. Thus, a high occurrence of the compare & add pattern indicates that the compare and contrast behaviors learners perform are more effective.

To demonstrate how these visual patterns influence learning, I present an evaluation of the occurrences of these patterns from high learning and low learning students. I put the 10 students who had the highest learning gains (over 0.5 on normalized gain) into a high-learning group and put the 10 students who had the lowest learning gains (negative or 0 learning gain) into a low-learning group. I then visually inspected the diagrams for the high and low learning groups and graded each student's map by evaluating whether the diagram has a high occurrence of each pattern. Table 7.10 presents the count of students who had a high occurrence of each pattern. As I only used 10 students for each group, it is not a sufficient number to conduct a statistical analysis. Nevertheless, the absolute count of the students does suggest that high learning students were more likely to:

1. Refer back to previous pages.
2. Cover more content with the map.
3. Add concepts throughout the learning session.
4. Follow the feedback instructions.
5. Generate meaning learning through comparison.

Group	**Zigzag**	**Vertical Cover**	**Horizontal Cover**	**Feedback & Compare**	**Compare & Add**
Low Learning	4	4	5	2	1
High Learning	8	7	7	4	5

Table 7. 10. Counts of students that demonstrated each visual pattern in the low and high learning subgroups.

7.7 Discussion

This work continues the research agenda to explore how to provide adaptive feedback in concept mapping to facilitate the development of comparative strategies and improve learning achievement. I developed a feedback tutor in *MindDot* that evaluates student learning behaviors and concept map qualities to provide diagnostic feedback. The effect of the combined feedback was compared against a process-based feedback method and a control condition without feedback through a lab study with 46 undergraduate students. Data analyses revealed that combined feedback significant promoted learning results (H_1) and facilitated the development of comparative strategies (H_2). While there were no learning differences in the transfer session, where feedback support is removed, students in the combined feedback condition had higher use of comparative strategies when learning on their own (H_3). Lastly, students who received combined feedback were more likely to apply the instructions into practice (H_4).

7.7.1 Differences between feedback and no feedback

As expected, students in the CF condition showed promising learning improvements and better use of comparative strategies compared to the ones in the NF condition. This validated the hypothesis that diagnostic information in the combined feedback corrected misbehaviors and fostered beneficial learning strategies. What's more, the behavioral benefits carried over to the transfer learning session, where all the feedback was removed. This suggests that metacognitive instructions on comparative strategies were well received by the learner, and these benefits have long term impacts. While students in the CF condition had higher use of comparative strategies in both sessions, there were no learning differences found in the transfer session, where instructions and hints were removed. This indicates that the learning benefits from the main session were likely to be driven by the content-related instructions. Further comparisons between the PF condition and the NF condition showed that there were no significant differences in learning and the use of comparative strategies. Therefore, the process feedback alone had little impact on supporting comparative strategies and learning results. To effectively support concept mapping, content related instructions need to be provided.

7.7.2 Differences between combined feedback and process feedback

There were two major differences between the combined feedback and the process feedback. The first one was the content-related information in the feedback message, and the other is the content-related affordances integrated with the feedback prompt. For example, the "select to add" window that enables learners to directly ad missing concept nodes from the feedback, and the compare view that displays two the text page of the two related concepts at the same time. The data analysis showed that students were more likely to respond to combined feedback with expected behaviors. The navigation path diagram further decomposes the process of responding to feedback into two behavioral stages, feedback & compare and compare & add. The feedback & compare pattern denotes the process of actively searching for related information after receiving hints from the feedback. The compare & add pattern distinguishes meaningful comparing behaviors with random reading behaviors. Therefore, the content-related instructions and affordances supported comparative strategies by encouraging the search for related information in the text and enhancing the quality of the comparison. Without the content-related information, students who lack essential knowledge about the content might encounter difficulty applying the high-level strategic instructions into practice. In addition, even if learners performed the desired behaviors, without the content-related hints, learners might not end up identifying the relationship and as a result, fail to generate meaningful learning outcomes.

7.7.3 Comparative strategies and learning

The work presented in Chapter 5 and 6 both showed that the use of comparative strategies is highly correlated with learning. However, there was no significant correlation found between the two. This might be caused by the limited time students had with the concept maps. The study in Chapter 5 was conducted in a high school class and lasted 20 minutes per day for 5 days, which was a total of 100 minutes. Although the content used was twice the length of the content in this study, students still had plenty of time working on their maps. In the study presented in Chapter 6, while students used the same content and were given the same amount of time for concept mapping, they were given an additional 5 minutes to use the created map to review the chapter. Observations from the review session suggested that students frequently used the hyperlink navigation to review the content and identify new relationship by adding new nodes and links. However, in this study, in order to leave time for the transfer learning session, students were only given 30 minutes for the main learning session and 10 minutes for the transfer learning session. The work in chapter 5 has demonstrated a major constraint of comparative strategies is that the development of comparative strategies is mentally challenging and time-demanding. Students without proper support may not benefit from using comparative strategies. Therefore, it is possible that students in this study were mainly trying to finish reading the content in time and didn't have time to reflect on previously read content and develop comparative strategies. It is also possible that students who constantly used comparative strategies didn't finish the whole content due to limited time. Thus, to fully reveal the benefits of comparative strategies, it is critical to provide adequate time for the activity.

7.7.4 Limitation

This presented work is limited in several areas that should be investigated in future studies. First, the empirical investigation in this work was a 120-minute study conducted in a research lab instead of a classroom. The use of comparative strategies can be potentially influenced by different factors such as type of support, the learning content, and time. Thus, a future study with settings closer to classroom settings would produce results that are more representative of the population. Second, the combined feedback was compared to process feedback and no feedback. However, there was no content feedback condition for further comparison. Thus, it is hard to distinguish if the benefits of the combined feedback were only driven by the content-based information or the combination of content and the process instructions. Last, this study had a total of 46 students. The small sample size may have been partly responsible for the lack of statistical significance in some of the marginal effects found in the study.

7.8 Conclusions and Future Work

This work continues the research plan and approaches the research question Q_4 with the design of an adaptive feedback tutor in *MindDot*, that provides diagnostic instructions based on the evaluation of students' learning behaviors and concept map qualities. The strength and novelty of this work is that it furthers traditional content-based feedback methods in concept mapping with process-based diagnostics. The empirical evaluation showed that the combined feedback method facilitated the development of comparative strategies and promoted learning results. The combined feedback demonstrated promising effects in correcting misbehaviors in concept mapping, and these benefits persist in the preparation for future learning tasks when feedback is removed. I provided a fine-grained understanding of how learners react to feedback via a navigational path diagram. The data visualization extracted two additional behavioral sequences: feedback & compare and compare & add, which models the process of employing strategical instructions into practice.

This work highlighted an important factor of using comparative strategies, that is the demand of time. The use of comparative strategies might not be as effective when learners are under time pressure. Thus, a future direction for this work would be designing affordances that support the learners to make better use of their time. For example, monitoring the time learners spend within the system and provide necessary feedback or setting up learning goals and agendas based on learners' prior knowledge. It is also worth pointing out that the design of the feedback tutor proposed in this work largely relies on the technological affordances provided in the system, such as the ability to track both reading and concept mapping activities, the integrated hyperlink navigation and template support, and the scaffoldings integrated with the feedback message. Therefore, another future direction for this work could be designing a more generalized feedback model and expanding the scope of the combined feedback mechanism into different learning contexts and platforms.

CHAPTER 8

FINAL DISCUSSIONS AND CONCLUSIONS

In this thesis work, I explored the broad theme of supporting learning with concept maps. The fundamental research question for this work was **"How do we leverage computer technologies to intelligently support concept mapping in ways that promote learning?"** This question was approached by examining and addressing three major challenges. That are:

1. Computer systems need to provide effective cognitive support to concept mapping.
2. There is a need to understand how learners create concept maps.
3. Student need effective instructions in concept mapping

In the following paragraphs, I briefly review the work in each chapter and present a discussion that describes how each challenge was addressed. I then summarize the contributions of this thesis work and discuss their implications. I end with a discussion of the limitations and future directions of this work.

The first topic that I approached was designing effective cognitive support to facilitate learning with concept maps. The work in Chapter 3 took a preliminary step in tacking research question Q_1 by experimenting with different designs of the expert template. Although the personalized expert template design in this work did not yield significant learning impact. It did reveal learning differences in different types of nodes in the template. These differences pointed out some directions for future scaffolding designs, such as assisting the interaction between the expert template and learners' maps, supporting the search and access to key information, facilitating the reference between the content and the concept map.

Based on the design implication found in Chapter 3, Chapter 4 continues the research agenda by developing *MindDot*, a concept map-based learning environment that supports concept map construction through innovative features such as dual-window display, click to add, hyperlink navigation, web view and note-taking. One of the core features in *MindDot* is the hyperlink navigation, which directly facilitates the two fundamental behaviors in concept mapping, that are **accessing key information** and **comparing related concepts**. The effect of the hyperlink navigation was examined in Chapter 5 via a controlled study. In addition, Chapter 5 began the investigation into the second proposed challenge, that is understanding how learners create concept maps. The work proposed a comparative strategy metric that models the process of comparing related concepts and creating relationships and knowledge networks among them. Results in Chapter 5 showed that the hyperlink navigation feature promoted the development of comparative strategies, and the use of comparative strategies enhanced learning with the help of hyperlink navigation. The key contribution of this work was the development of the comparative strategy model, which was a preliminary exploration of the cognitive learning process during concept mapping. This model decomposes the use of comparative strategies in the concept mapping contexts into measurable components, such as the number of back navigation and the number of context switches. These measurable characteristics can be used for qualitative assessment and diagnosis purposes. What's more, instructions on supporting comparative strategies can be more effective when adapting to these learning characteristics.

Chapter 6 continues the exploration of modeling and supporting comparative strategies in concept mapping. Based on the finding from Chapter 5, Chapter 6 presents a new iterated design of *MindDot*, which supported concept mapping with an integration of the hyperlink navigation and the expert template. An empirical study was conducted to evaluate the effects of these affordances. Study results suggested that the hyperlink support had a positive impact on the development of comparative strategies and enhanced learning, while the template support had marginal effects on learning. The work in Chapter 6 further provided a fine-grained understanding of how students employ comparative strategies through two types of visualizations of the learning process. The process visualizations revealed how learners process the content and construct the concept maps in an action-by-action manner. These visualizations demonstrated several behavioral patterns that are highly reprehensive of the cognitive learning process and can be used for diagnostic purposes.

Finally, in Chapter 7, I consolidated all the research findings described in the previous chapters and approached the last proposed challenge, that is providing diagnostic feedback to support concept mapping. Based on the previous investigations on comparative strategies and the behavioral patterns presented in Chapter 6, I develop an adaptive feedback tutor in *MindDot*, that provides diagnostic instructions based on the evaluation of students' learning behaviors and concept map qualities. Empirical evaluations on the feedback tutor showed that the combined feedback method facilitated the development of comparative strategies and promoted learning results. The combined feedback demonstrated promising effects in correcting misbehaviors in concept mapping, and these benefits persist in the preparation for future learning tasks when feedback is removed. I then provided a fine-grained analysis of how learners react to feedback via a navigational path diagram. The data visualization extracted two additional behavioral sequences: feedback & compare and compare & add. These patterns were highly representative of the cognitive process of employing strategical instructions into practice and can be used for further diagnostic purposes. Table 8.1 shows a summary of all the studies presented in this thesis work.

	Features being tested	**Number of Participants**	**Learning Differences**	**Comparative Strategies**
Study 1 (Chapter 3)	Personalized template design	38	Not Significant	N/A
Study 2 (Chapter 5)	Hyperlink navigation	32	Not Significant	Hyperlink > No hyperlink **
Study 3 (Chapter 6)	Hyperlink navigation + expert template	59	Hyperlink > No hyperlink **	Hyperlink > No hyperlink *
Study 4 (Chapter 7)	Feedback tutor	46	CF > PF > NF *	CF>PF *

Table 8. 1. Summary Results from the Four Studies. (* $p < 0.05$, ** $p < 0.01$)

8.1 Discussion

In the paragraphs above, I have reviewed the studies presented in previous chapters. In this section, I will describe how each of the 3 major challenges for this thesis work was addressed.

8.1.1 Challenge 1

The first challenge to be explored was designing computer systems to provide effective cognitive support in concept mapping. Chapter 2 has described some of the commonly used concept mapping software such as the CmapTools, and Mind Vector. Although these tools provide features like fast input, easy modification, and map sharing, they only support concept mapping in the editing level and lack cognitive support. In recent years, research in the literature has furthered the design of computer-based concept mapping systems by providing cognitive support. Template support and navigational aid are two commonly used methods of supporting concept mapping. However, there are still some unsolved limitations within each method. Three research questions were proposed to tackle these challenges. Here, I discuss how each research question was answered.

Q_1: Do different template designs affect learning in concept mapping?

Providing learners with templates is a commonly used way of supporting concept mapping (Chang, Sung and Chen, 2001; Schau *et al.*, 2001; Novak and Cañas, 2008). This approach usually involves an incomplete map structure created by the instructor. A major limitation with this approach is the high mental effort to process the external map structure, especially when learners are not familiar with the domain content (Kinchin, 2001). Therefore, a possible way of improving the template-based design would be designing templates that fit each students' individual needs. Chapter 3 presented a study that explored the effect of different template designs. Exploratory results suggest that students learned more from concepts that are added to the map compared to ones that were not added. In addition, for the provided concepts in the template, students may benefit more from ones that are close to the interacted region. Therefore, Q_1 was partially answered. Although the personalized design had limited impact, the learning differences in different regions in the template indicate that the design of the template can affect learning results.

This result has several pedagogical implications for future studies. First, the fact that students learned more from the nodes that are close to the interacted region suggested that meaningful learning was likely to happen during the integration between students' maps and the template structure. This validated previous work in the literature which pointed out that it is learners' active attempt to incorporate new concepts into their current knowledge structures fosters meaningful learning, rather than simply memorizing concept definitions or relationships (Novak and Cañas, 2006b). Thus, there could be potential instructions that assist learners in integrating their maps with the template. For example, walking students through the template or providing hints on potentially concept links between the template and student map. In addition, the results reinforced the importance of two fundamental behaviors in concept mapping, that are the **access to key information** and the **comparison of related concepts** (Nesbit and Adesope, 2006). The results suggested that students benefited less from the nodes they didn't directly interact within the template. The "close" and "far" nodes in the template can be distinguished by the amount of fundamental behaviors learners perform with them. Filling in the incomplete template required learners to review concepts in the template and then search for related missing concepts in the content. Therefore, when integrating their maps with the template, learners were constantly comparing and relating the template with the learning material. The comparison between the map and the material were more likely to generate meaningful learning, echoing Paivio's dual coding theory (Clark and Paivio, 1991), which suggested that the relation between verbal and visual codes provide additional retrieval paths for both types of information and in turn, stimulus learning. Consequently, with little interactions with the "far" nodes in the template, learners were less likely to access and read the related information in the content. Therefore, when learning with concept maps, proper support in accessing key information and comparing related concepts would be highly beneficial.

The study in Chapter 3 pointed out another limitation with current concept mapping tools, that is the lack of support in the two fundamental learning behaviors. A lot of the current concept mapping tools discussed in Chapter 2 are independent of the learning content, and there is no navigational support between the concept map and the learning content. This might be another reason that the personalized template approach didn't reveal learning improvements. Without proper navigational aid, the comparison between the template and the content could be cumbersome as learners might struggle to pinpoint all the concepts nodes in the template to the learning content. Therefore, I foresee design opportunities to integrate the learning content with the concept mapping and provide affordances that connect related parts in between the two segments.

Q_2: Is map-based navigation more effective with learner generated maps?

Work in Chapter 3 highlighted the importance of supporting two fundamental behaviors in concept mapping, that are accessing key information and comparing related concepts. To further develop advanced affordances to support these behaviors, Chapter 4 presented a concept mapping system *MindDot*, which serves as a fundamental platform that provides technological capabilities for future innovations. A major innovation of the system is integrating the learning content with the concept mapping tools through a dual window design, which allows learners to create concept maps directly from touch gestures. Concept nodes created using these gestures are hyperlinked with the textbook content, which provides navigational capabilities using learner-generated maps. The navigational aid in this thesis work differs from previous research in what map is used for navigation. I have discussed earlier that prior work using expert-generated maps were constrained by the high cognitive loads required to process the template (Kinchin, 2001; Schau *et al.*, 2001). In *MindDot*, navigational aid is provided based on the map learners themselves create. Each navigational anchor is added after users read the content and created a node from it. In this way, learners are familiar with not only the concept map but also all the related content that are hyperlinked with the map. Therefore, the cognitive load to use the concept map for navigation is largely reduced.

Chapter 5 and 6 presented two studies that evaluated the navigational feature. The study in Chapter 5 showed that the navigational aid had promising impacts in facilitating the comparison between concepts but didn't improve learning results. However, this work was limited in several ways. For instance, to adapt the class schedule, our study lasted 20 minutes per day for 5 days, leaving the students another 20 minutes for other class activities like group projects, presentations, etc. These additional resources might have caused unpredictable variance within the learning effects. What's more, the original 10-page content was edited into a 50-pages textbook in order to fit the relatively small iPad screen. The increase of the pages might have caused challenges in navigation and comparing related concepts. Nonetheless, findings in Chapter 5 did point out valuable pedagogical implications. Results in the hyperlink condition validated prior research in the literature which demonstrated that the use of the comparative strategies improves learning (Ponce and Mayer, 2014b). However, this is not the case in the non-hyperlink condition. This suggested that the benefits of comparative strategies come with drawbacks, as comparing and connecting concepts located on different pages requires extraneous effort. When learning from the 50-page content in the study, students who were not provided with visual aids and navigational support might encounter difficulty accessing related resource. Thus, in the non-hyperlink condition, the benefits of using comparative strategies were more likely to be hindered by the high cognitive load caused by inefficient navigation. To reveal the benefits of the comparative strategies, proper visual aids and navigational support need to be given to students.

Based on these findings, the study in Chapter 6 addressed these limitations by controlling the learning activities in the study and editing the content into 20 pages. Results suggested that hyperlink navigation significantly increased learning results. Therefore, Q_2 was answered. Navigational aid based on learner-generated maps can be highly effective in facilitating the access to key information and comparison between key concepts, and in turn, promote learning. However, the results in Chapter 5 suggested that the benefits of the navigation aid can be affected by various factors such as the learning materials, learning activities, environments, etc. To fully reveal the benefits of hyperlink navigation, these factors need to be taken into consideration.

Q_3: What are the effects of an integrated template and navigational support?

Prior work in exploring template-based support and navigational aid has shown several limitations with these approaches. The limitation with the template support lies in the demand of mental effort to process the external structure (Kinchin, 2001). The constraint with the hyperlink navigation is the disorientation caused by the flexibility in the navigation (Puntambekar and Stylianou, 2005). In addition, the hyperlink navigation requires a certain number of nodes and a well-constructed structure to get started. Therefore, the effect of the hyperlink navigation feature might be limited in the early stages of the task. To solve these challenges, Chapter 6 presented an integration of the template feature and the navigational aid. This integration benefits both features in several ways. First, the expert template can serve as a navigational guide for students in the early stage of concept mapping. Before learners add any nodes to the map, they can use the expert template to preview key concepts in the content. By doing this, learners are able to get a grasp of a high-level overview of the knowledge structures in the content and decide what pages to focus on. On the other hand, the hyperlink navigational aid also facilitates the understanding of the template by connecting the nodes with relevant information in the content, which eliminates the process of flicking through pages just to find the explanation of a concept.

This integration was evaluated by an empirical study in Chapter 6. Results indicated that the students received the integrated support outperformed the ones with the hyperlink only and template only support, as well as ones with no support. Further analysis showed that the hyperlink support improved both comparisons between concepts and learning results. This demonstrated the benefits of providing navigational aid based on learner-generated maps. It may indeed be that Zeiliger (Zeiliger, Reggers and Peeters, 1995) and Puntambekar (Puntambekar and Stylianou, 2005) did not find positive effects of hyperlinked concept maps because students were using fully complete maps that they did not construct on their own.

The template support, on the other hand, had positive influences in comparisons between concepts but did not seem to be as effective at improving learning, echoing the results described in Manlover's work (Manlove, Lazonder and De Jong, 2007). The template in this work was integrated with hyperlinks to the content, with the goal of facilitating the processing and understanding of the template structure. However, the results indicated that while the integration facilitated the access to key information and the comparison among concepts, it did not fully ameliorate the limitation of the template-based support. Therefore, Q_3 was answered. The integration between the template and navigational support facilitated the comparisons between concepts and promoted learning gains. However, to fully reveal the benefits of the template-based support, further affordances or instructions are needed.

8.1.2 Challenge 2

The second challenge proposed in this thesis work was understanding how learners create concept maps. We have discussed that a major limitation with current methods in evaluating learning with concept maps is the neglect of the learning process (Rice, Ryan and Samson, 1998; McClure, Sonak and Suen, 1999). Current map-based assessments only evaluate *what* is in the map, without considering *how* it's created. Evaluating the cognitive process of concept constructions can be highly important as learning behaviors, and strategic moves in the learning process are representative of learner characteristics such as objectives, motivation, and misconceptions. Thus, the research question I propose for this challenge is **Q4: "Is a process-based learning model more predictive of learning than an outcome-based model?".** This thesis work tackles this research question by evaluating the concept mapping process with a comparative strategy model. This model decomposes the process of comparing and relating concepts into three measurable components: back navigation, cross-link, and context switch. The comparative strategy model was evaluated by several empirical studies in this thesis work. The study in chapter 5 compared the use of comparative strategies and its learning impacts between the hyperlink condition and the non-hyperlink condition. Results showed that the hyperlink feature facilitated the use of comparative strategies and the use of comparative strategies promoted learning in the hyperlink condition.

The results with the hyperlink condition validated prior work that showed the benefits of comparative strategies (Ponce and Mayer, 2014b). As students exhibit more comparative strategies, they score better on a multiple-choice test. However, this is not the case in the non-hyperlink condition. This indicates that the benefits of comparative strategies come with drawbacks, as comparing and connecting concepts located on different pages require extraneous effort, especially when students are not provided with proper visual aids and navigational support. While students in the hyperlink condition are able to use the concept map to view relevant resources, students in the non-hyperlink condition are challenged with additional effort when comparing different concepts. It is not only physically demanding, as they have to flip through several pages manually, but also cognitive challenging due to the complex content structure. Thus, to reveal the benefits of the comparative strategies, proper visual aids and navigational support need to be given to students.

Chapter 6 presented another study that evaluated the effect of comparative strategies among four conditions, that are hyperlink + template, hyperlink, template, and no scaffolding. Data analyses revealed that both hyperlink and template feature had positive impacts on fostering comparative strategies. For the students who received scaffoldings in concept mapping (H+T, H, and T), the use of comparative strategy was highly correlated with learning. Students who didn’t receive support did not benefit from comparative strategies. This result again validated the findings from the study in Chapter 5 that with proper support.

Apart from the quantitative model, I further measured the use of comparative strategy through two types of data visualizations, the sequential diagram, and the navigational diagram. These visualizations provided fine-grained understandings of how students employ comparative strategies, finding that there were indeed certain sequences of behaviors in the text (e.g., reading before adding a link) that suggested that students are making comparisons. Therefore, Q_4 is answered. The comparative strategy model and two visualizations modeled the process of comparing and relating concepts, and the use of comparative strategies can be highly beneficial to learning. In addition, developing comparative strategies can be mentally challenging. To fully reveal the benefits, proper support such as navigational aid should be provided. The contribution of this finding is that it not only validated prior work in the literature that certain reading behaviors and eye movement patterns can be highly beneficial to learning (Bereiter and Bird, 1985; Ponce and Mayer, 2014b) , but furthered current understanding of comparative strategies to tailor different technological affordances the concept mapping environments.

8.1.3 Challenge 3

The third challenge I explored in this work was providing effective feedback in concept mapping. A major limitation with current feedback methods in concept mapping is that learning diagnostics only evaluates the outcome map students create and neglects the cognitive process of the map construction (Hwang, Wu and Ke, 2011b; Sugihara *et al.*, 2012; Hirashima *et al.*, 2015). This thesis work furthered prior research by presenting a feedback mechanism that incorporated both content-based model and process-based evaluation to offer instructions to corrects errors in the map and foster beneficial learning strategies. The research question **Q_5: "Does outcome and process combined feedback improve the benefits of concept mapping"** was investigated by an experimental evaluation presented in Chapter 7, which compared combined feedback with process-based feedback and no feedback. The study showed the combined feedback demonstrated significant advantages in fostering comparative strategies and promoting learning compared to the process feedback and no feedback. The combined feedback was also shown to be more effective in correcting misbehaviors and ineffective learning strategies, and these benefits persist in the preparation for future learning tasks when feedback is removed. The navigational path diagram further revealed that students who received the combined feedback were more likely to compare and contrast concepts after receiving feedback, and these comparisons were more likely to generate new knowledge or relationships.

Further analysis revealed additional implications. While students in the combined feedback condition showed higher usage of comparative strategies in both main learning and transfer sessions, learning differences were only found in the main session where feedback was provided. This indicated that the learning benefits were mostly driven by content-related instructions. Similar results have also been found in the literature. Leelawong and Biswas' work that compared direct feedback with metacognitive feedback revealed that direct content-related feedback can be more effective in helping students make initial progress on a new learning task (Leelawong and Biswas, 2008). Results in Chapter 7 provided additional evidence that content-based instructions can be critical in supporting students the early learning stages.

On the other hand, students who received process feedback showed no advantage in comparative strategies and learning results over the ones with no feedback. This result suggested that students in the process feedback condition didn't correctly react to the metacognitive instructions and perform the expected behaviors. Research in the literature (Lippmann Kung and Linder, 2007) have shown that the effect of metacognition is differentiated by how learners respond to it. Lippmann Kung and Linders' work showed that the transitioning metacognition, where learners perform the expected behaviors after developing it, seemed to be more effective than non-transitioning metacognition, where learners do not correctly react to it. Therefore, it is likely that the process feedback did increase students' metacognition about comparative strategies. However, without essential knowledge about the content, students might encounter challenges to employ the developed metacognition into practice. The occurrence of the Feedback & Compare and Compare & Add patterns again, validated that students received combined feedback were more likely to develop comparative strategies and generate new knowledge over the ones with process feedback. Hence, process feedback alone is inadequate to foster comparative strategies and promote learning. To facilitate the transition from metacognition to practice, content-based instructions need to be provided.

8.2 Contributions

By addressing the three challenges and answering the proposed research questions described above, this work makes these following contributions.

1. **Developing an intelligent concept mapping system that provides cognitive support.** This thesis presented an intelligent concept map-based learning system *MindDot* that supports concept mapping activities through the integrated navigational and template aid

as well as an adaptive feedback tutor. Empirical evaluations have provided evidence that *MindDot* has positive impacts on fostering the development of comparative strategies and promoting learning results.

2. **Establishing a learner model that evaluates learning strategies in concept mapping and predicts learning results.** In this work, I presented a comparative strategy metric that evaluates different learning strategies in concept mapping. This proposed model decomposes the process of comparing and relating concepts into measurable components, which can later be used qualitative assessments and diagnostic purposes. The visualizations of the concept mapping process further provided action-by-action understandings of how learners employ comparative strategies into practice. Sequential patterns extracted from the data visualizations provided additional insights of learning characteristics such as motivation, engagement, misunderstanding. Study results showed that the comparative strategy model and these behavioral patterns were highly predictive of learning results. The comparative strategy model furthers previous research on assessing concept mapping activities by incorporating the evaluation of different types of learning behaviors.

3. **Designing a feedback tutor that fosters beneficial learning strategies in concept mapping and enhances learning.** I developed an adaptive feedback tutor in *MindDot*, that delivered diagnostic instructions by evaluating students' learning behaviors and concept map qualities. Empirical evaluations on the feedback tutor showed that the combined feedback method facilitated the development of comparative strategies and promoted learning results. The combined feedback demonstrated promising effects in correcting misbehaviors in concept mapping and these benefits persist in the preparation for future learning tasks when feedback is removed.

8.3 Limitations and Future Work

This presented work is limited in several areas that should be further investigated. First, while this thesis presented four empirical studies, three of these studies were conducted in a research lab with college students. There were two pieces of content used for these four studies, and both were edited from high school textbooks. The gap between the target audience and the study participants might have caused variance in the learning results. In addition, the studies presented in this work had small sample sizes, which might have been partly responsible for some of the marginal results. Thus, future classroom studies with a larger sample size would produce results that are more representative of the population.

The concept mapping system *MindDot* demonstrated compelling effects on supporting comparative strategies and enhancing learning. However, there are still some unanswered questions regarding how learners use the affordances. For example, the template support was shown to be not as effective as the navigational aid. This could be potentially caused by the cognitive load to process the template. It is also possible that the nodes in the template reduced the amount of effort learners would spend on the corresponding concepts, and in turn, hinders learning. However, there is a lack of understanding in the mental process learners go through when interacting with the template. Therefore, one future direction of this work would be conducting an in-depth exploration of students' use of the expert template. The comparative strategy model in this work was shown to be highly predictive of learning and supporting the use of comparative strategy seemed to be effective in promoting learning. However, one limitation with the comparative strategy model is that there is a lack of understanding of the objectives behind these measured learning behaviors. The same behavior can be conducted with different objectives and can indicate different implications. For example, one student might navigate to previous pages as he notices that he forgets to add one node from previous pages. Another student navigates to previous pages as he is specifically searching for related concepts to what he's currently reading. It is also possible that a student turns to previous pages simply because he receives no back-navigation feedback. Thus, measuring the objectives of these behaviors could potentially enhance the accuracy of the comparative strategy model.

The combined feedback method showed its benefits in facilitating comparative strategies and promoting learning. However, it was only compared to a process feedback condition and a no feedback condition. It was unclear what benefits were driven by the content-related instructions and what was caused by the process-based instructions. Thus, future studies need to be conducted to further evaluate the effects of the combined feedback.

8.4 Future Work

In the section above, I have outlined the limitations of this thesis work. Apart from incremental research that could further validate the results from this work and strengthen some of the weak statistical findings, several directions for future work emerged from the discussion. In the following paragraphs, I will describe three research trajectory I believe to be among the most valuable.

Designing affordances to facilitate the template-based support

Template-based support can be highly influential to concept mapping as it directly affects the maps learners create. A major constraint with template-based support is the demand for cognitive effort to process the external template. This work explored two types of template-based scaffolding that are personalized templates and the integration of hyperlink and template support. However, the effect of these affordances was limited. The personalized template showed no advantage over fixed scaffolding, and while the hyperlinked template promoted comparative strategies, it didn't reveal learning impacts. The challenge of facilitating the understanding of the template and scaffolding the completion of the template remains to be solved. Therefore, one future direction would be enhancing the template-based support. While the proposed methods in this work had limited impacts, they revealed several pedagogical implications for future designs. One potential scaffolding could be designing an intelligent tutor that walks students through the template, explaining what key concepts will be learned and how the template structure is constructed. The walkthrough can also leverage the hyperlink navigation feature to give students a preview of the content. Another way of enhancing the template support could be providing additional connections to resources. For example, when students tap on the template node, in addition to showing relevant page, it displays extra instructional materials related to the concepts such as flashcards, images, and notes. These additional resources could potentially facilitate the understanding of the template.

Evaluating objectives behind the use of comparative strategies

This thesis work models the process of concept map construction with a comparative strategy metric and different types of visualizations. These evaluation methods help establish an overall measurement of the use of comparative strategies as well as step-by-step assessments. However, as I have just discussed above, a potential limitation with the comparative strategy model is that the objectives behind the measured behaviors remain unknown. Thus, one promising direction for furthering the comparative strategy would be assessing the objective behind key behaviors. There could be several ways to do it. For instance, there could be pop-up windows with self-report questions that ask the learners why they are performing these behaviors. One example of a self-report question could be, “Hi, can you tell me why do you go back to this page? A: misclick. B: I miss a node on this page. C: I’m looking for related concepts. D: I received feedback”. Another way of measuring objective could be using automated analysis. When a learner performs a key action, we can measure the current learning context and track the behaviors that learners perform next. For example, when a learner performs a back navigation, if he just received the no back navigation feedback, this behavior is more likely to be directly from the feedback. If the learner reads the page for a while and adds a node, he is more likely to be searching for missing nodes. Similarly, if the student reads two pages back and forth, he is more likely to be comparing related nodes. Thus, I foresee research work that measures objectives to further enhance the accuracy and robustness of the comparative strategy model.

Understand the effect of content-based instructions

The combined feedback in this work has shown to be highly beneficial in fostering comparative strategies and promote learning. However, it was only compared against a process feedback condition and a no feedback condition. There was no content instruction only condition as an additional control. Therefore, it is hard to distinguish what benefits were caused by the content instruction and what impacts were driven by the process feedback or the interaction of the two. It is likely that providing just the content instruction can achieve the same results with the combined feedback, indicating that all the benefits were caused by content instructions. It is also possible that the content instruction alone has limited impact.

This would suggest that the impacts were driven by the interaction of the process feedback and content-related instructions as learners need the process feedback to develop metacognition and the content instruction to transit metacognition into practice. Therefore, future work to compare the effect of the content only feedback and combined feedback could bring promising insights to the feedback mechanisms in this work.

8.5 Conclusion

In this dissertation work, I explored research questions regarding learning with concept mapping, including designing computer-based concept mapping systems, modeling the concept mapping process, and providing effective feedback to support learning. I presented *MindDot*, a concept map-based learning system that supports learning with the integration of hyperlink navigation and incomplete templates, as well as personalized feedback. Combined results from empirical evaluations on *MindDot* revealed that *MindDot* had a promising impact on fostering effective learning strategies and promoting learning outcomes. This theses work contributes to the growing literature in supporting concept mapping with innovative technological affordances and improved feedback mechanisms. It also pointed out directions for future research work to address challenges that remain unsolved.

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