Ogata, H. et al. (Eds.) (2015). Proceedings of the 23rd International Conference on Computers in Education. China: Asia-Pacific Society for Computers in Education

Investigating a Scientist's Use of a Visualization Tool to Visualize the Concepts of Carbon Cycling

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Abstract: Teaching students learn to think like scientists is one of the purposes of science education and the premise of this study is to understand the processes of scientists' visualization. In order to understand the involved aspects while scientists visualizing the complex concepts, this study interviewed one scientist and explored his thinking processes while he constructed visualizations of the concept of carbon cycling in the ecosystem. The interview consisted of visualization tasks with think-aloud and the follow-up retrospective. By the analysis of the information of interview of a scientist, this study found that cognitive skills, metacognitive skills, visualization skills, conceptual knowledge, metacognitive knowledge, and meta-level visualization knowledge were interactively used by a scientist. We identified six strategies demonstrated by the scientist constructing visualizations. Moreover, two critical points influenced the visualization task were identified. By the cross-case comparison and revealing the gap between scientists and novices in the future, this study spurs discussion to propose concrete scaffolding in instruction and curriculum design for students.

Keywords: Visualization, thinking process, strategy, critical point

1. Introduction

The processes of visualization are important core activities in the development of science and science education. Visualization, in its broad sense, means the making of meaning for internal and external representations which are mentally available to oneself and physically available to others (Gilbert, 2008). In respect of the development of science, scientists try to provide explanations of natural phenomena, form visualizations of what is happening at the macro level from exemplar phenomena, and build models of this complex world (Gilbert, 2005; National Research Council [NRC], 2012). In respect of the development of science education, students should have competence in developing and using visualizations, which involves being able to construct drawings or diagrams as representations of events or systems, represent and explain phenomena with multiple types of models, and discuss the limitations and precision of a model (NRC, 2012). Teaching students to learn to think like scientists and develop models for the complex phenomena is one of the purposes of science education. As diSessa (2004) mentioned that technology is changing the representational basis of science, using visualization tools as a scientific modeling vehicle can bring innovation in science, technology, engineering and mathematics (STEM) education. The latest science education framework integrated both science inquiry and engineering design and emphasized on the practices of science which is based on the understanding of how scientists and engineers work (NRC, 2012). Equally important and worth exploring about the scientists' work is how scientists use visualization tools, or specifically, what strategies scientists employ, to create their visualization of complex phenomena such as the concept of carbon cycling which involves multiple scales (Mohan, Chen, & Anderson, 2009). This study focuses on one scientist. By understanding the scientist's strategies and the critical points in thinking processes of visualization, it can be used as a reference when designing meaningful learning activities which integrated visualization tools. Strategies mean a planned series of actions for achieving some goals; critical points mean a key point of time, a crisis or a turning point important to the success of an operation in this study. This study analyzed one biological scientist's thinking process while he used a visualization tool to visualize the concepts of carbon cycling. The research questions addressed in this study are:

1. What strategies did a scientist use to facilitate his constructing visualization process of the concept of carbon cycling?
2. What were the critical points while the scientist successfully constructing visualization of the concept of carbon cycling?

2. Theoretical Background

2.1 Studies of Scientists' Modeling or Visualization Processes and Their Implications for STEM education

Scientists form visualization and build model to develop illustrations, explanations, and predictions about natural phenomena (Gilbert & Buckley, 2000; NRC, 2012). Some studies have already examined the differences between chemists and novices in terms of their representational skills and their use of representations. For example, Kozma and Russell (1997) found that chemists represent their understanding of the chemical phenomena, not merely using surface elements, but making connections between diverse representations to underlying chemical concepts and principles. In another study, Kozma (2003) found that chemists are skillfully making transitions between different levels of representation or to transform a given representation into another form of representation. He also found that different representations can be used flexibly by chemists for different purposes such as supporting one's own thinking, social interactions and discourse. Some studies focused on the metacognitive and cognitive aspects of visualization and modeling. DiSessa (2004) and Gilbert (2005) point out that the fluent use of visualization or representation entails metacognition. Chiu and Linn (2012) pointed out that both cognitive skills to interpret the scientific information and metacognitive skills to monitor their progress were needed while engaging in complex tasks such as inquiry with technology tools. Schwarz and White (2005) stressed the importance of knowledge about the nature and purpose of science model while modeling. Justi and Gilbert (2002) concerned about the knowledge and skills that necessary in the successful modeling process and emphasize on the intermediate mechanism of mental model. From the above can be seen that it attaches great importance to successful modeling or visualization in STEM education. Relative studies have been explored such as comparison of differences between experts and novices' modeling and skills or knowledge involved in modeling and visualization. A further question, for example, how a scientist use these skills and knowledge to successfully visualize, would be more constructive and instructive for STEM education. In order to teach students to think like a scientist, one premise is identifying how scientists think. Therefore, this study tried to analyze a scientist's thinking process while visualizing.

2.2 Visualization Tools and Related Studies

Computer technologies provide opportunities for creating flexible and diverse learning environments (Donovan, Bransford, & Pellegrino, 2000). In addition to the typical media such as video, animations, and simulations, several interactive environments of multiple-representations have been developed. For example, Ainsworth (2008) introduced a number of integrated multiple-representations environments such as SMV-Chem, Connect Chemistry, and DEMIST which contained the real experiment videos, molecular models, chemical equations, simulations, or dynamic graphs of chemistry and population dynamics. Ainsworth also introduced that SimQuest and PAKMA are interactive simulations which employed dynamic visualizations. Additionally, encouraging learners to construct their own representation start a number of learning such as knowing how to select appropriate representations and lead better understanding than interpreting a given representation (Ainsworth, 2008). MultiMedia and Mental Models (4M:CHEM) (Kozma & Russell, 1997) and ChemSense (Schank & Kozma, 2002) help students developing and constructing an integrated understanding of chemical concepts. Considering the flexibility of instructional space, the program on handheld devices was developed such as Chemation (Holt et al., 2005). Plenty visualization tools have been developed to connect molecular representations and phenomena representations. Equally important but still need to develop is the visualization tools of complex phenomenon across multiple scales such as the concept of carbon cycling in ecosystems. The concept of carbon cycling, an important topic of life science and earth science, encompasses biological, physical, human social and economic systems, and interactions across these systems; it also involves multiple scales included atomic-molecular, cellular, organismal, and ecological process (Mohan, Chen, & Anderson, 2009). It is difficult for students to learn because of the properties of both macroscopic and microscopic scales and also both concrete and abstract of carbon cycling (Lazarowitz & Penso, 1992). Moreover, the lack of existing proper visualization tools makes the construction of complex phenomenon across multiple scales more difficult. DrawScience (Chang et al., 2014) was developed for the above purpose and used by the case in this study, which the visualization tasks were designed regarding the topic of carbon cycling in ecosystems, to construct the complex concept involved symbolic, systematic and macroscopic level.

3. Methods

3.1 Participant

The case is a scientist who has developed expertise and is able to think and solve problems effectively specializing in the field of biological science. He was a postdoctoral researcher and has been studied on flora and fauna for more than 10 years. This study adopted purposeful sampling to select the information-rich case to illuminate the questions under study. The first author served in the role of researcher-interviewer.

3.2 Procedures and Interview Questions

The whole interview process consisted of two parts, think-aloud tasks and follow-up retrospective tasks. The interview draft questions were developed based on the literature review, and underwent several rounds of revisions by a science educator and a science teacher to reach agreement on the interview questions. At the beginning of the interview, the interviewee performed one practice task to practice thinking aloud. Then the interviewee was asked to perform a series of visualization tasks about carbon cycling and to think aloud as the interviewee did them. For the main task, the topic of the visualization tasks was carbon cycling and consisted of two subtopics including the processes of carbon cycling among the hydrosphere, biosphere, geosphere and atmosphere and the growth of a tree. There were 3 questions for the think-aloud tasks of construction of visualization such as "Please draw a picture to present the transformation processes and the formation of the carbon element among the hydrosphere, biosphere, geosphere and atmosphere."

The interviewee was asked to use a mobile application named DrawScience to construct his visualization (Chang et al., 2014). DrawScience allows users to visualize their ideas at the particulate, symbolic, systematic, and macroscopic levels on Android tablets. DrawScience was used as a formative assessment tool to obtain the case's ideas while visualizing. After the think-aloud task, this scientist was interviewed according to the follow-up retrospective to probe and confirm his thinking. There are 9 retrospective questions about the reflection of resources, understanding of purposes and limitations, and reflection of visualization criteria. The interview of the main task and the follow-up retrospective took about 60 minutes and was videotaped to facilitate the subsequent transcripts and analysis.

3.3 Data Analysis

The interview was transcribed with annotation to include the case's nonverbal gestures. The software package, NVivo, was used to aid the coding and analysis procedure. The interview transcripts were coded based on the coding scheme that we proposed in a previous study which included several categories of skills and knowledge (Hung, Chang & Hung, 2014). The scientist's performance was analyzed in the chronological order. From the comparison and integration of the scientist's thinking aloud and follow-up retrospective, strategies that the scientist used while constructing visualization were proposed in this study.

4. Findings

4.1 Strategies a Scientist Used to Facilitate Constructing Visualization Processes of Carbon Cycling

Based on the performance of think-aloud tasks of construction of visualization, the thinking process of a scientist while constructing visualization was listed in the chronological order and shown in Figure 1.

Through the inductive analysis of the case's data, it is found in this study that the scientist used at least three kinds of skills and three kinds of knowledge to perform the construction of visualization tasks: cognitive skills, metacognitive skills, visualization skills, conceptual knowledge, metacognitive knowledge, and meta-level visualization knowledge. From the perspective of the chronological order point of view, the following discussed strategies the scientist used to successfully complete the visualization task.

Strategy 1: Using cognitive skills to comprehend the task at the beginning of the visualization task.

At the beginning of the visualization task, the scientist reads the question to understand the information about the task. As the first block in Figure 1, he knew the topic of the visualization task is carbon cycling, which involved hydrosphere, biosphere, geosphere and atmosphere.

Strategy 2: Using metacognitive skills to plan the drawing framework.

After understanding the task, the scientist used the metacognitive skill to plan the drawing framework. In this study, the scientist decided to start drawing from the part he was familiar with, the biosphere, as the second block in Figure 1.

Strategy 3: Dividing the complex concept into several sub-concepts, then constructing visualization in accordance with the relevance between sub-concepts one by one.

The topic of constructing visualization task in this study is carbon cycling in ecosystems. Carbon cycling is a complex conception which involved several different forms of compounds of carbon and several physical and chemical reactions within and among the hydrosphere, biosphere, geosphere and atmosphere. The scientist divided concepts of carbon cycling into at least 7 sub-concepts, such as photosynthesis and its reactant and product, food chains and webs, respiration and its reactant and product, the dissolution of carbon dioxide, the formation of calcium carbonate, and sediment formation and the release of carbon dioxide (See the block no.3-1 to 20. Blocks with the same area of gray background belong one sub-concept). Based on the relationships of those sub-concepts, the scientists sequentially draw each sub-concepts.

Strategy 4: Retrieving relevant conceptual knowledge to explain the sub-concept, then using visualization skills and meta-level visualization knowledge to represent the details of the sub-concept.

Before actual drawing, the scientist used cognitive skills to apply own conceptual resources which were related to the task. Then he considered the purpose, functions and conventions of visualization and the advantage and limitation of software, and he used visualization skills, such as using different colors for different marking or symbolic representation for interpretation, to convey the meaning and thinking of images. For example, see the block no. 11 to 12-2, the scientist explained that carbohydrates are transferred into CO_2 by respiration, then he used an arrow to represent the process of respiration and used texts to indicate respiration.

Strategy 5: Monitoring the drawing progress with metacognitive skills after constructing one or several sub-concepts.

After the primary drawing, the scientist used metacognitive skills again to monitor and check whether the drawing task was complete or not (See the gray block no. 10, 13, and 14). If incomplete, he returned back to use cognitive and visualization skills to add to the lack or revise his drawing. This process was repeated several rounds until passed the monitoring and checking. At last, the scientist compeleted the constructing visualization task.

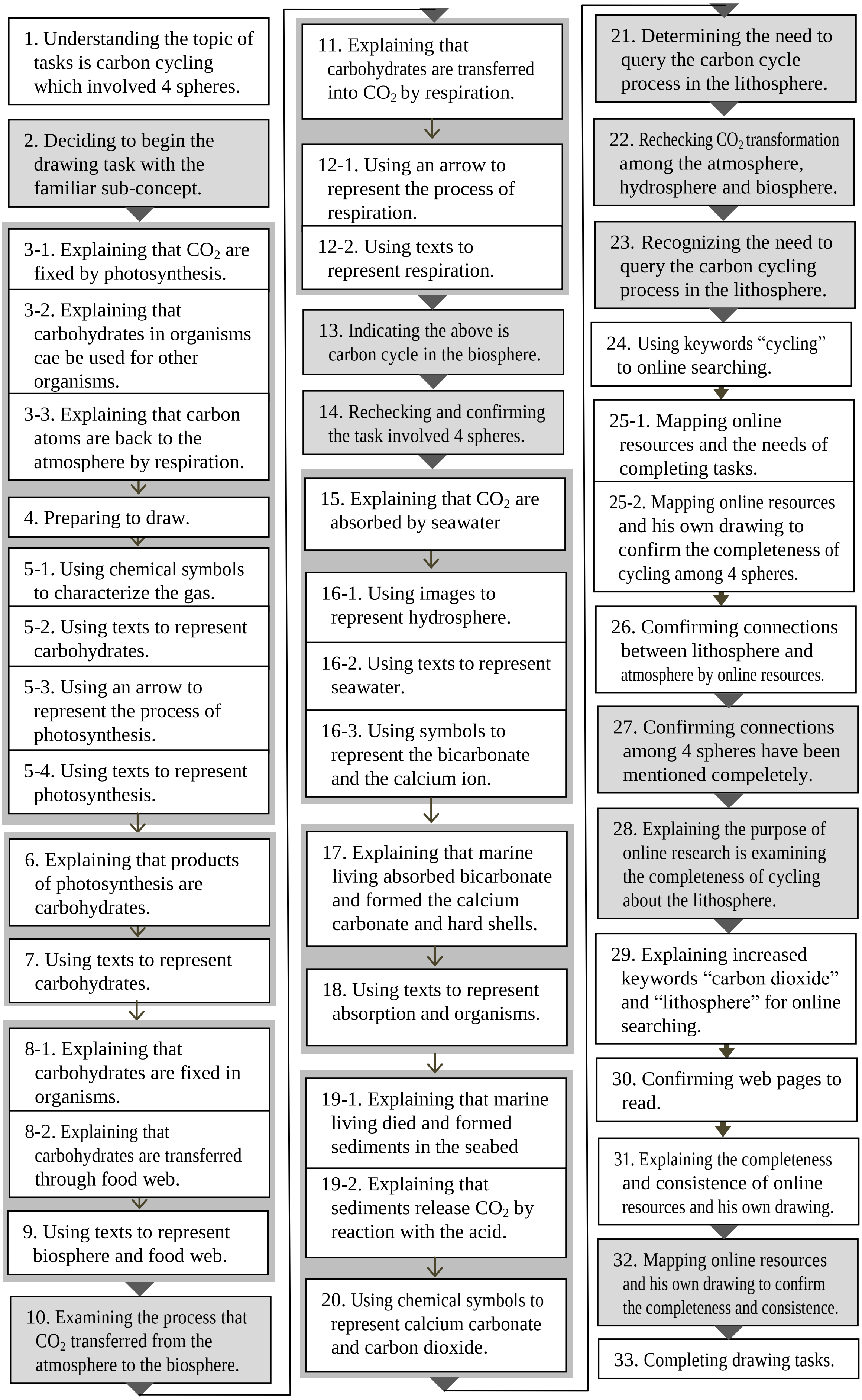

Figure 1. The Thinking Process of a Scientist while Constructing Visualization.

Strategy 6: Switching on the action of searching resources while identifying the knowledge about completing visualization tasks is insufficient.

Continuation of the previous monitoring strategy, if the scientist perceived and confirmed that relevant knowledge is not enough, he switched on the action to search for other resources. The scientist was limited to use Internet queries in this study and he selected some keywords to online researching. With several rounds of mapping online resources, the needs of completing tasks, and his own drawing (See the block no. 21 to 31), and with confirming the completeness and consistence between new resources and his own drawing, the scientist would determine the task was completed.

4.2 Critical Points While a Scientist Successfully Constructing Visualization of the Concept of Carbon Cycling

The analysis of strategies appeared that the scientist interactively used cognitive skills, metacognitive skills, visualization skills, conceptual knowledge, metacognitive knowledge, and meta-level visualization knowledge to complete the visualization task. In the thinking process of a scientist while constructing visualization (See Figure 1), there were two critical points while the scientist successfully constructing visualization of the concept of carbon cycling. The critical point 1 is in the occasion of the conversion of cognitive skills and visualization skills. For example, when the scientist explained that CO_2 are absorbed by seawater (See the block no.15), he needed to simultaneously use his meta-level visualization knowledge and visualization skills to choose the suitable representation and prepared to make the idea visible; then he used images to represent hydrosphere, texts to represent seawater, and symbols to represent the bicarbonate and the calcium ion (See the block no.16-1 to 16-3). If this conversion is not smooth, the sub-concept cannot be constructed.

The critical point 2 is the monitoring of metacognitive skills, such as the block no. 2, 10, 13, 14, 21 to 23, 27 to 28, and 32. In these monitoring stages, the scientist planned the drawing framework, recognized conceptual limitations, determined the need to search for the more resources. In addition, he mapped the new resources, original conceptions, and own drawing, reflected the purpose of the drawing task, evaluated and confirmed the completeness of the visualization progress. For the delicately converting, the scientist constructed visualization smoothly. Although whether there is still another critical point existed in visualization processes may need the more investigate, it is certain that the sufficient conceptual resources are needed in doing visualization task.

5. Concluding Remarks

By the analysis of the information of interview of a scientist, this study used a scientist's thinking process to illustrate the process that skills and knowledge used in constructing visualization. This study found that cognitive skills, metacognitive skills, visualization skills, conceptual knowledge, metacognitive knowledge, and meta-level visualization knowledge were used by a scientist while constructing visualization. Moreover, this research found at least six strategies that the scientist used to facilitate the visualization task and the two critical points influenced on the visualization task. Based on these strategies and critical points to interactively use of skills and knowledge, concrete scaffolding in instruction and curriculum design for students can be proposed, such as integrated some steps or functions in visualization instruction or designing visualization tools to prompt the use of conceptual resources, the transformation of cognitive skills to visualization skills, and the planning and monitoring of metacognitive skills.

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