Thinking Skills and Creativity 23 (2017) 175–187

Contents lists available at ScienceDirect

Thinking Skills and Creativity

journal homepage: http://www.elsevier.com/locate/tsc

Systems thinking in chemistry classroom: The influence of systemic synthesis questions on its development and assessment

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ARTICLE INFO

Article history:
Received 20 March 2016
Received in revised form
14 November 2016
Accepted 3 January 2017
Available online 6 January 2017

Keywords:
Higher-order thinking
Systems thinking
Systemic synthesis questions [SSynQs]
Chemistry instruction
Chemistry assessment

ABSTRACT

The present study deals with the two main concerns presented in the systems thinking literature: its development and assessment. The study sample included 119 high school students who studied organic chemistry during the 2012/2013 school year. In order to achieve the study's objective, the following steps were undertaken. Firstly, the students were divided into the two groups, one experimental (E) and one control (C). The formed groups were subjected to different learning environments, which provide us the possibility to examine the efficiency of the new instructional tool (systemic synthesis questions, [SSynQs][1]), comparing it with the traditional one. In addition, the research included [SSynQs] and conventional questions as the assessment tools which we used in order to collect data related to students' systems thinking. In order to evaluate students' responses on [SSynQs], the scoring rubric was developed and resulted in four levels of systems thinking. The findings indicated that differences between the E and C groups' abilities to think systemically grow linearly with the complexity of defined levels. Namely, unlike their peers forming the C group, the students exposed to the [SSynQs] made meaningful progress, reaching the highest levels of systems thinking. Nevertheless, the interesting finding appeared in observing the gender as independent variable: The female students in the E group outperformed males from the same group, showing better ability of dynamic and cyclic systems thinking. The reason for that could be found in learning style differences, however, this issue will be discussed in more detail in our future research.

1. Introduction

A desired and generally recognized outcome of science education in many countries around the world is scientific literacy of the students (Avargil, Herscovitz, & Dori, 2013; Dori, Tal, & Tsaushu, 2003; Fensham & Bellocchi, 2013; Sadler & Zeidler, 2009; Vachliotis, Salta, & Tzougraki, 2014). Several different definitions have been used for scientific literacy, considering the following aspects: intellectual, attitudinal, societal, and interdisciplinary (Holbrook & Rannikmae, 2009). Holbrook and Rannikmae (2009) have indicated that many authors see scientific literacy on the intellectual bases, defining it as "what

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[1] [SSynQs] – Systemic synthesis questions.

http://dx.doi.org/10.1016/j.tsc.2017.01.003

we expect students to know and be able to do as a result of their science learning experiences" (Sadler & Zeidler, 2009; p. 910). This definition is in alignment with Abd-El-Khalick, Bell, and Lederman (1998), who considered scientific literacy as deep understanding of the scientific concepts, principles, theories, and processes, as well as the awareness of the complex relations between them. Acknowledging this definition on the one hand, and Holbrook and Rannikmae's (2009) observations on the other hand, intellectual capabilities of scientific literate students could be considered as their higher-order thinking skills.

Higher-order thinking skills have been widely discussed by many authors (see Avargil et al., 2013; Barak, Ben-Chaim, & Zoller, 2007; Fensham & Bellocchi, 2013; Zohar & Dori, 2003), in order to make clear distinction between higher and lower-order thinking. According to Newmann (1990), higher-order thinking occurs when students must analyze, interpret, and manipulate concepts in the presented problem which cannot be solved by applying routine procedures. In chemistry, such routine procedures (lower-order thinking) include listing concepts (e.g. members of a homologous series of alkanes), inserting numbers into formulae (e.g. in chemical calculations), or applying memorized rules (e.g. mechanism of the substitution reaction). On the other hand, higher-order thinking skills characterize non-algorithmic, complex and multiple nature (Resnick, 1987), and include skills like posing questions, formulating arguments, critical thinking and *systems thinking* (Dori et al., 2003; Zohar & Dori, 2003).

The focal point in the systems thinking is the term *system,* which generally represents complex and unified whole of parts or components (Vachliotis et al., 2014), which are interrelated and interdependent (Anderson & Johnson, 1997). According to this, properties attributed to the system are not those of individual components, as in the system, status of one component affects the status of the other components (Ben-Zvi Assaraf & Orion, 2005). It should be mentioned that many phenomena around us are examples of such complex systems – "ecosystems" (ecology), "hydro-cycle" (earth science), "solar system" (astronomy), "immune system" (medicine), "cell" (biology). Studies about complex systems are well established in biology. It is well known that biological systems are usually complex as they are in open-ended interaction with neighbouring systems, and as such can display properties as non-linearity, emergence, interdependence, multiple causes and consequences. However, closed, or even isolated systems could also be complex. For example, chemistry contains a rich diversity of such systems, as it deals with the smallest particles which join together to form others. In organic chemistry there are more than 60 million organic compounds as a result of carbon's atom ability to form the different chains: open (straight and branched) and closed ones. Each compound should be observed as a concept with specific properties (molecular formula, structural formula, functional group, name, physical properties, reactivity), which distinguish this concept from the others, and/or link selected concepts with the appropriate ones through the set of relations. Such complex networks of concepts can constitute sub-systems, which further form complex systems. The description of complex systems in organic chemistry is highly dependent on the organization and dynamic of several sub-systems (e.g. chemical equilibrium in organic reactions: treating an aldehyde with an amine to generate imine, as well as the molecule of water which should be further removed from the sub-system). However, this important and difficult topic has not been investigated much in chemistry, and according to Ludlow and Otto (2008) it is time for chemists to more deeply investigate systems chemistry, notifying the examples of mixtures and oscillatory reactions.

Most approaches that are based on complex systems consider a specific way of thinking – a systems thinking described in the "Literature framework".

2. Literature framework

2.1. The construct of systems thinking

After accepting the idea of the significance of the complex systems in science education (Ben-Zvi Assaraf & Orion, 2005, 2010), the systems thinking was introduced as the ability to deeper understand and interpret system's characteristics and behavior (Batzri, Ben-Zvi Assaraf, Cohen, & Orion, 2015; Evagorou, Korfiatis, Nicolaou, & Constantinou, 2009). In addition, Salisbury (1996) considered systems thinking as the ability to effectively structure the relations that exist in the system between components. Hence, students as systems thinkers should not only identify systems' components, but also recognize inter-relations and multiple relations between them; explore and understand emergent properties; and analyze phenomena in a wider context (Ben-Zvi Assaraf & Orion, 2005; Evagorou et al., 2009).

Accordingly, the difficulty of the students to deal with the complex systems was not surprising for the researchers, who used several different tools in order to measure students' systems thinking. For example, properly designed conventional (objective) questions (open-ended, multiple-choice, etc.) could be used as valid and reliable tools for assessing systems thinking (see Brandstädter, Harms, & Großschedl, 2012; Riess & Mischo, 2010; Sommer & Lücken, 2010), usually in combination with another, more complex tools, such as drawing arrow diagrams (Riess & Mischo, 2010), and/or concept maps (Brandstädter et al., 2012; Sommer & Lücken, 2010). Furthermore, along with video analysis, the questionnaires and interviews have been the most frequently used (Brandstädter et al., 2012). However, the inadequacy of existing instructional methods in helping students to understand complex system has been recognized (Arndt, 2006; Ben-Zvi Assaraf & Orion, 2010; Salisbury, 1996). In traditional education, teachers hand facts to their students that are usually fragmented or chunked, instead to be linked to others (Arndt, 2006; Salisbury, 1996). Such a learning approach reduces complexity of thinking (Salisbury, 1996), and could hardly result in its development. Nevertheless, science education literature offers several studies which present instructional methods capable of encouraging students' systems thinking. While Evagorou et al. (2009) and