Scientific reasoning skills: A theoretical background on science education

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Abstract
To enhance scientific content and investigative skills that help students to acquire problem solving and lifelong learning skills, the assessment of scientific reasoning in science education has gained momentum of late. The purpose of this paper was to review and synthesize empirical studies on scientific reasoning skills and science education with the view to help improve science education in Namibia. Different methods were used to select and identify studies for this review. First, the multi-dimensional reviews of studies were based on publications between the late 90s to March 2016. Second, the publications were searched from different academic databases, such as but not limited to, EBSCO, Science Direct, Web of Science, ERIC, and the search engine Google Scholar. Third, a wide range of search terms were employed in searching for diversified studies. Amongst others, the findings from the literature reveal that, science education is vital as it; i) promotes a culture of scientific thinking and inspires citizens to use evidence-based reasoning for decision making, ii) ensures that citizens have the confidence, knowledge and skills to participate actively in an increasingly complex scientific and technological world. The literature also reveal that inquiry based lessons promote scientific reasoning skills in students and that scientific reasoning skills have a long term impact on students' achievement. Furthermore, it was found that in the K-12 education in the United States of America (USA), China and in most Organization for Economic Cooperation Development (OECD) countries, the development of scientific reasoning skills has been shown to have a long-term impact on students' academic achievement.

Keywords: *scientific reasoning, science education, students' assessment, and science inquiry*

Introduction

Science education is the field concerned with sharing science contents and processes with individuals, and the world community at large (Adey & Csapo, 2012). The field of science education includes work in scientific contents, the scientific methods and reasoning skills, scientific literacy and teaching pedagogies (Bao et al., 2009; Osborne, 2013; Adey & Csapo, 2012). Engaging and maintaining children's interest in science is of national and international concern. As in many other countries, the need for reform has been recognized in Namibia (National Institute for Educational Development, NIED, 2010). International educational standards claim the importance of mastery of the scientific reasoning skills, scientific methods and understanding of the nature of science from the beginning in elementary (primary) up to secondary school (Mayer, Sodian, Koerber, & Schwipert, 2014). This then begs the question: What is scientific reasoning? International studies on scientific reasoning have defined scientific reasoning as a 'formal reasoning' (Piaget, 1965) or 'critical thinking', represents the ability to systematically explore a problem, formulate and test hypotheses, control and manipulate variables, and evaluate experimental outcomes (Zimmerman, 2007; Bao, Cai, Koening, & Fang, 2009; Kuhn, 2011). Basically, it represents a set of domain general skills involved in inquiry science supporting the experimentation, evidence evaluation, inference and argumentation that lead to formation and modification of concepts and theories about the natural and social world.

Furthermore, expectations of the outcomes of education in the 21^{st} century increasingly focus on higher order thinking of synthesis, analysis and evaluation (Osborne, 2013), yet school science education is still dominated by lower level cognitive demands - in particular recall. Failure to transform science education for the needs of the 21^{st}

century is a consequence of a lack of a good model of scientific reasoning, scientific literacy and a body of expertise about how to assess such higher order cognitive competencies (Osborne, 2013). The main purpose of this paper is to review literature on scientific reasoning skills with the view to understand the theoretical backgrounds on science education. At the end of this paper, suggestions for future research are identified.

Research findings are synthesized to address the following review question; what does literature say about scientific reasoning skills of learners? In addition, this review contributes to finding out what specific effects does the assessment of scientific reasoning has on learners' learning and growth.

Methodology

In this section, we briefly introduce the indexes of selecting literature and its outcomes, to give an overview of related studies on scientific reasoning skills and its impact on learning of science education. Different methods were used to select and identify studies for this review. First, the multi-dimensional reviews of studies were based on publications from the late 1990s to March 2016. Second, the publications were searched from different academic databases, such as, but not limited to; EBSCO, Science Direct, Web of Science, ERIC, ProQuest, and the search engine Google Scholar. Third, a wide range of search terms were employed in searching for diversified studies. During the screening and searching of literature, studies were included based on the following:

- *they were about the assessment of scientific reasoning and thinking skills in science lessons;*
- *they involved students from elementary (Primary) school;*
- *their outcomes reported on students' scientific reasoning skills and impacts on science education;*
- *they were empirical studies: descriptions, explorations of relationships or assessment;*
- *they were carried out during the period 1990-2016; and*
- *they were published in the English language.*

We also had to hand-search target journals, such as Studies in Science Education from Southern Africa, and from Namibia in particular. Finally, these terms match flexibly but thematically. For example, we mixed "scientific reasoning skills of primary school children" "assessment" "thinking skills" whether from the title, abstract, or both, in order to identify the information strongly related to the review topic as available.

Results

Synthesis of the findings of the studies in the review

Importance of science education

Current thinking about the desired outcomes of science education is rooted strongly in a belief that an understanding of science is so important that it should be a feature of every young person's education (OECD, 2013). Indeed, in many countries science is a foregrounded element of the school curriculum from kindergarten until the completion of compulsory education. The emphasis on the curricula and its frameworks should not rely on producing individuals who will be producers of scientific knowledge, but rather it should be on educating young people to become informed critical consumers of scientific knowledge, a competency that all individuals are expected to need during their lifetimes (OECD, 2013).

Amongst others, literature reveals that science education is vital as it i) promotes a culture of scientific thinking and inspires citizens to use evidence-based reasoning for decision making, ii) ensures that citizens have the confidence, knowledge and skills to participate actively in an increasingly complex scientific and technological world (Zhou et al., 2016). Further, Turiman, Omar, Daud, and Osman (2012) recommend that, to overcome the challenges of the 21st century in science and technology education, students need to be equipped with the 21st century skills to ensure their competitiveness in the globalization era. Tytler echoed the same sentiment whether debate about the role of school science education hinges on the question of whether the aim is to (i) prepare students for tertiary science studies and careers in science, or (ii) raise the scientific literacy of the community as a whole (Tytler, 2007).

The 21st century skills in science education that are expected to be mastered by students comprise four main domains, digital age literacy, inventive thinking (reasoning), effective communication and high productivity (Turiman et al., 2012). In their report, (OECD, 2013) affirms that many of the challenges of the 21st century will require innovative solutions that have a basis in scientific thinking and scientific discovery. Elsewhere, developers of Australia's national science curriculum identify three possible pathways for students' need to be prepared for; to make personal decisions on the basis of a scientific view of the world; to become the future research scientists and engineers; and to become analysts and entrepreneurs in the diverse fields of business, technology and economics (National Curriculum Board, 2009).

Although in Namibia, secondary school teachers historically tend to enact a view that they are preparing students for university as Kapenda, Kandjeo-Marenga, Kasanda, and Lubben (2002, p. 60) argued, "teachers rarely used practical work in science education to develop skills in planning an investigation, in processing experimental data, or in communicating results of experimental work". International educational plans, like the Australian School Science Education plan 2008-2012, (Goodrum & Rennie, 2007) identify the fundamental purpose of school science education as among others, promoting scientific reasoning and scientific literacy. They further extend these views by stating that science not only prepares students for citizenship but "provides firm basis for more specialized, discipline-based subjects in upper secondary school that lead to science courses at university, and prepares students for technical education courses that lead to science-related careers" (Goodrum & Rennie, 2007, p. 70), thus bringing together both sides of the debate. This focus is in line with NIED's (2014) views that scientific and technological literacy are the key purposes for science education for all students, not just those destined for careers in science and engineering, while the National Core Curriculum (2012) for Hungary, proposed that scientific literacy should enable individuals to navigate their way through life, rather than focusing on tertiary studies only.

Furthermore, science education has always been considered one of the best tools for cultivating students' minds. Scientific activities such as conducting empirical research, designing and executing experiments, gaining results from observations and building theories are seen as those in need of the most systematic forms of reasoning (Adey & Csapo, 2012). Elementary science education introduces young children to the basic facts about objects, materials, and organisms as well as the activities involved in designing and conducting a scientific investigation (Lazonder & Kamp, 2012). By engaging in these activities, children can start to develop proficiency in the scientific reasoning skills as well as scientific literacy.

Importance of scientific reasoning skills

Science and mathematics education is emphasized worldwide. Reports from large-scale international studies such as Trends in International Mathematics and Science Study (TIMSS) and Programme for International Students' Assessment (PISA), PIRLS (the Progress in International Reading Literacy Study) and National Assessment of Educational Progress (NAEP) continually make use of science, mathematics and reading contents within their question items. As a result, many countries in the world are advocating for the increase and implementation of a more extensive basic education curriculum in science, technology, engineering, and mathematics (STEM) education. Educational reforms worldwide stress the need for a prepared 21st century workforce, which translates into students learning not only science contents, but also acquiring advanced transferable reasoning skills (Kuhn, 2011). The development of these skills will better enable students to handle open-ended novel situations and design their own investigations to solve scientific, engineering, and social problems in the real world (Bao et al., 2009).

As science education continues to become fundamental to modern society, there is a growing need to pass on the essential aspects of scientific inquiry and with it the need to better impart such knowledge. The current style of the content rich STEM education, even when carried out at a rigorous level, has little impact on the development of students' scientific reasoning abilities (Bao et al., 2009). The findings from their comparative study (Bao, et al., 2009) between American and Chinese students indicate that it is not *what we teach*, but rather *how we teach it*, that makes a difference in student learning of higher-order abilities in science reasoning. They further indicate that students ideally need to develop both content knowledge and transferable reasoning skills (Bao et al., 2009). The onus is upon researchers and educators to invest more time in the development of a balanced method of education, such as incorporating more inquiry based learning that targets both goals. Previous studies have indicated that scientific reasoning is critical in enabling the successful management of real-world situations in professions beyond the classroom (Han, 2013). For example, in the K-12 education in the United States of America (USA), the development of scientific reasoning skills has been shown to have a long-term impact on students' academic achievement (Adey & Shayer, 1994). Positive correlations between students' scientific reasoning abilities and measures of students' gains in learning science content have been reported (Coletta & Phillips, 2005), and reasoning ability has been shown to be a better predictor of success in Biology courses (Lawson, 2000).

The above findings support the consensus of the science education community on the need for the basic education (Grade1-12) students to develop an adequate level of scientific reasoning skills along with a solid foundation of content knowledge. Zimmerman (2007) claims that investigation skills and content knowledge bootstrap one another, creating a relationship that underlies the development of scientific thinking. Research has been conducted to determine how these scientific thinking skills can best be fostered and which teaching strategies contribute most to learning, retention, and transfer of these skills (Osborne, 2013). For instance, Zimmerman (2007) in her research conducted in Illinois, United States of America (USA), found that, children are more capable in scientific thinking than was originally thought, and that adults are less so. She also states that scientific thinking requires a complex set of cognitive skills, the development of which require much more practice and patience. It is therefore important for educators to understand that scientific reasoning ability is best developed through science inquiry based education.

Scientific reasoning in school-children

Traditionally, developmental psychologists have considered the thinking and reasoning of elementary school children as deficient and have argued that scientific reasoning skills emerge only during adolescence (Inhelder & Piaget, 1958). However, in the last 20 years, developmental research has brought forth evidence for early competencies (Mayer et al., 2014). In his research, conducted in Southern Africa, Libienberg (2013) found that San people use scientific reasoning skills when they are tracking down animals in the veld. He further posits, "An example of inductive-deductive reasoning in tracking would be the way tracks are identified as that of an animal belonging to a particular species, such as the porcupine. Footprints may vary according to the softness or hardness of the ground" (p. 9) and this will guide the San people on the direction of where the animals are. It is also further argued that if the required foundations are not constructed, serious difficulties may rise at later stages of learning, as failures suffered during the first years of schooling will delimit children's attitudes towards education for the rest of their lives (Csapo & Szabo, 2012). The development of concepts related to science begins before the start of formal education and the first years of schooling, and play a decisive role in steering conceptual development in the right direction. Early science education shapes children's thinking, their approach to the world and their attitudes toward empirical discovery (Csapo & Szabo, 2012).

Moreover, research has also found that, even pre-school children understand the relationship between covariation data and causal belief, when only potential causal factor (e.g., red or green food) covaried partially or perfectly with outcomes (good or bad teeth) (Osborne, 2013). When the effects of more than two variables must be taken into account, young children often fail to interpret patterns of empirical evidence (Kuhn, 2011). Unlike adolescents or adults, children tend to neglect or distort data, when covariation evidence does not agree with their prior beliefs or knowledge (Molnar, Greiff, & Csapo, 2013). Therefore, research findings indicate that basic experimentation and evidence evaluation skills in pre-school and primary school children do exist (Mayer et al., 2014). The onus is upon teachers and researchers to develop and assess the scientific reasoning in children while at an early stage in their schooling with the view to enhance learning. When children's scientific reasoning and thinking skills are assessed, it would inform the teachers and parents on the best possible ways on how to help the children in their education.

Assessment of scientific reasoning

In a review of the relevant research conducted for the US department of Education, Hannaway and Hamilton (2008) in Osborne (2013), found that standards and accountability policies lead teachers to focus on particular subject areas and types of instructional practices. In addition, they found that teachers focused on competencies specific to assessment and testing procedures (Osborne, 2013). Thus, a shift in the nature of assessment is important if science education is to transform itself from an emphasis on knowledge and the lower order cognitive demands of recall and comprehension to the higher order cognitive demands of evaluation and synthesis. One of the aims of diagnostic assessment of reasoning within science amongst others, is to monitor students' cognitive development, to make sure they possess the reasoning skills necessary for them to understand and master the science learning material in a meaningful way on the one hand, and to check if science education stimulates students' cognitive development as much as it can be expected, on the other hand (Csapo, 2012). This idea is echoed by Adey and Csapo (2012), Adey and Shayer (1994) and Csapo and Szabo (2012), who assert that the content-based methods of enhancing cognition by applying science material for stimulating development provide rich resources for identifying reasoning processes which can be relevant in learning science and which can be developed through science education.

Furthermore, tests in scientific reasoning can provide valuable information at various levels as alluded to earlier. Teachers will be able to evaluate and reflect on their teaching styles should the results of the test bring no satisfaction. Both teachers and children may be motivated if the results of the test are good. Adey and Csapo (2012) argue that once teachers overcome the urge to teach the reasoning skills directly, they (teachers) will find the results of reasoning test useful to inform them of where children are now so that they can; (a) map out the long road of cognitive stimulation ahead, (b) better judge what type of activities are likely to cause useful cognitive conflict - both for a class as a whole and for individual children. Moreover, a diagnostic assessment programme should support the renewal of primary education. This programme has a dual purpose (Nagy, 2009), it assists individual development by providing learner-level feedback and its aggregated results can be used to establish various reference norms. It is further explained that, diagnostic assessment as a direct tool of criterion-referenced education is a method of learner-level evaluation by definition (Nagy, 2009), as such, it is reliant on the longitudinal documentation of individual progress.

Assessment tools of scientific reasoning skills

What are the possible mechanisms of assessing and testing scientific reasoning? Adey and Csapo (2012) suggest a way of assessing scientific reasoning. They argue that computerized testing could be much closer to the ideal individual interview than a paper-and-pencil assessment. Furthermore, administering the same test to every subject improves the objectivity of the assessment (Adey & Csapo, 2012). Mayer et al. (2014) suggest that a variety of task formats that can be used to explore scientific reasoning competencies in young children. Apart from self-directed experimentation tasks in which participants may be involved in hands-on physical activities, tasks using story problems are common measures of scientific reasoning. Additionally, contextual support (abstract vs. concrete), task complexity (single - vs. multi-variable), plausibility of factors, response format (choice vs. production), strength of prior belief or prior content knowledge in scientific domains (e.g., Physics, Chemistry and Biology) have been shown to influence performance on scientific reasoning tasks (Lazonder & Kamp, 2012; Adey & Csapo, 2012). Predict-Observe-Explain (POE) items ask children to make informed predictions about a presented situation (Fu, Raizen, &

Shavelson, 2009), and following an observation or summary of what happens, and asking students to provide explanations. For example, students might be asked to predict whether a given object sinks or floats in water. Once they find out that the object sinks or floats, they must explain why this occurred. This provides opportunities to reliably capture how students reason through and justify their predictions and explanations (Fu et al., 2009).

From a more operational perspective, scientific reasoning is assessed and operationally explained in terms of a set of basic reasoning skills that are researched thoroughly and found to be needed for students to successfully carry out scientific inquiry. This includes problem exploration, formulating and testing hypotheses, manipulating and isolation of variables as well as observing and evaluating of consequences. To that end, the Lawson's Test of Scientific Reasoning (LTSR, 1978) and Lawson's Classroom Test of Scientific Reasoning (LCTSR, 2000), provide a solid starting point for assessing scientific reasoning skills (Lawson, 1978, 2000). The tests are designed to examine skills such as; conservation of matter and volume, proportional reasoning, control of variables, probabilistic reasoning, correlation reasoning and hypothetical-deductive reasoning. These skills are deemed important concrete components of the broadly defined scientific reasoning ability.

The popular version of Lawson's Classroom Test of Scientific Reasoning (LCTSR, 2000) has been used and it is still being used to assess scientific reasoning among students. Many science education researchers have been using the Lawson test to study the relationships between students' scientific reasoning abilities and science subjects (e.g. Physics, Biology or Chemistry). It is a 24 item two tier, multiple-choice test. Osborne (2013) describes a two-tier item as a question with some possible answers followed by a second question giving possible reasons to the first question. The reasoning options are based on students' misconceptions and that are discovered through free response tests, interviews and the literature. Furthermore, guided by Piagetian tasks, a number of researchers have developed measurement tools and instruments to assess scientific reasoning skills. These are the Group Assessment of Logical Thinking Test (GALT) by (Roadrangka, Yeany, & Padilla, 1982) and the Test of Logical Thinking (TOLT) by (Tobin & Capie, 1981).

Development of scientific reasoning

What mechanisms can be used to stimulate and enhance students' scientific reasoning and by extension all of their reasoning skills? The development of scientific reasoning, as with the development of any reasoning, must necessarily be slow and organic process in which the students construct the reasoning for themselves (Adey & Csapo, 2012). Morris et al. (2015) concurred with them that effective scientific reasoning requires both deductive and inductive skills. Individuals must understand how to assess what is currently known or believed, develop testable questions, test hypotheses, and draw appropriate conclusions by coordinating empirical evidence and theory.

Furthermore, lessons which promote scientific reasoning provide plenty of opportunities for social construction (Adey & Csapo, 2012), that is to say, students are encouraged to talk meaningfully to one another, to propose ideas, to justify them and to challenge others in reasonable manners. Research (Harlen, 2013) has shown that the adoption and the use of inquiry based science learning has the potential to inculcate scientific reasoning and thinking skills required in the 21st century. Harlen (2013) further posits that embracing inquiry based science education recognises its potential to enable students to develop the understandings, competencies, attitudes and interests needed by everyone for life in societies increasingly dependent on application of science.

Notwithstanding that inquiry leads to knowledge of the particular objects or phenomena investigated, but more importantly, it helps build broad concepts that have wide explanatory power, enabling new objects or events to be understood (Harlen, 2013). A stimulating classroom environment is characterized by high quality dialogue, modelled and organised by the teacher, meaning that students will be working within the Zone of Proximal Development (ZPD) as proposed by Vygotsky (1978). The more knowledgeable students will be able to help their peers without the peer feeling less important (Vygotsky, 1978). However, despite the over-whelming evidence that asking higher-level, open ended questions has the potential to promote students' higher level reasoning and problem-solving abilities, teachers still struggle to use these types of questions when interacting with their students (Gillies, Nichols, Burg, & Haynes, 2014). Therefore, the development of general scientific abilities is crucial to enable science students to successfully handle open-ended real world tasks in future careers (Bao et al., 2009). Bao et al. (2009), further state that teaching goals in science education include fostering content knowledge and developing general scientific abilities. One such ability, scientific reasoning is related to cognitive abilities such as critical thinking and reasoning. Moreover, scientific reasoning can then be developed through training and can be transferred (Adey & Csapo, 2012; Bao et al., 2009). Training in scientific reasoning may also have a long term impact on students' academic achievement.

Conclusion

Although there exists a number of understandings on what constitutes scientific reasoning, the literature seem to generally agree that scientific reasoning represents an important component of science inquiry. Therefore, a better understanding of the nature of scientific reasoning requires extended knowledge of science inquiry. Scientific inquiry is embedded in the early research on constructivism and reasoning (Vygotsky, 1978; Inhelder & Piaget, 1958). Vygotsky (1978) posits that children learn constructively when new tasks fall within their Zone of Proximal Development (ZPD). That is, if a task is one that a child can do with a more knowledgeable knower's help, then the children will eventually learn to perform this task on their own by modelling the more knowledgeable person. The idea that children build on existing knowledge is also reflected in Inhelder and Piaget's (1958) work with formal reasoning development. Their model articulates clearly the levels through which children develop from birth (sensorimotor stage) to adulthood (formal operational stage).

On developing scientific reasoning, research has shown that inquiry based science instruction can promote scientific reasoning abilities (Adey & Csapo, 2012; Lawson, 2001). Controlled studies have shown that students had higher gains on scientific reasoning abilities in inquiry classrooms over non-inquiry classrooms (Bao et al., 2009). On the other hand, students and teachers' levels of reasoning skills can significantly influence the effectiveness of using inquiry methods in teaching and learning science courses (Lawson, 2001). Therefore, in order to effectively implement inquiry based curricula, improving scientific reasoning abilities need to be highly emphasized in basic education curriculum for both students and teachers. We are of the opinion that if children are to be diagnostically assessed before any progression to the next level in their schooling, it will enhance their performance in subject areas, especially in Science, Technology, Engineering and Mathematics (STEM). Teaching goals in STEM education include fostering content knowledge and developing general scientific abilities such as scientific reasoning skills.

With these findings from the reviewed literature, Namibia could learn a thing or two to improve the reasoning skills and learning content of the students. In China, it is traditionally often expected that rigorous content learning in science and mathematics will help develop students' scientific reasoning abilities. This is proven by Chinese students' performance in PISA and TIMSS regularly. According to the results of PISA in 2012 and 2015, Chinese students had high-level science literacy (OECD, 2014; OECD, 2016). In PISA 2012, Shanghai-China ranked as number 1 in the science and mathematics assessment, and number 6 in the problem solving assessment (OECD, 2014); and in PISA 2015, China (Beijing, Shanghai, Jiangsu, Guangdong) ranked as number 10 in science and number 6 in mathematics. This performance is still much higher than the average level of OECD (OECD, 2016). However, studies have shown that the traditional style of STEM education has little impact on the development of students' scientific reasoning abilities (Bao et al., 2009). It is not what we teach but rather how we teach it that makes a difference in student learning of higher order abilities such as scientific reasoning.

Therefore, a synthesis of the findings from literature reveals that, OECD countries have been carrying out research on the effectiveness of their educational system on a regular basis (PISA, TIMSS and NAEP). Results from these studies provide valuable feedback as to whether their education systems were sufficient in preparing students to thrive in future (OECD, 2013). Amongst other components, scientific literacy has always been part and parcel of these studies and to a lesser extent scientific reasoning. Equally, there have been also many researches on scientific reasoning (Bao et al., 2009; Kuhn, 2011; Adey & Csapo, 2012; Osborne, 2013; Zhou et al., 2016). However, all the above research were conducted mostly in developed countries. Research of these kinds are hardly carried out in Namibia, and currently we do not have empirical data on Namibian students' scientific reasoning abilities as well as on scientific literacy. This presents an opportunity for research in this field of scientific reasoning skills for both upcoming and established researchers.

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