JOURNAL OF BALTIC SCIENCE EDUCATION
ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

EXAMINING THE CONNECTION BETWEEN STUDENTS' WORKING MEMORY AND THEIR ABILITIES TO SOLVE OPEN-ENDED CHEMISTRY PROBLEMS

Johnson E. Upahi,
Umesh Ramnarain

Abstract. *Open-ended problem-solving skills have been identified as employable skills, which undergraduate students will need to have in order to cope with real-life problems in their workplaces after graduation. However, the development and assessment of these skills have been inconsistent across courses offered in universities. This research examined undergraduate students' ability to engage with open-ended chemistry problems, and the influence of their working memory space on problem solving. The research is a descriptive research design that employed a survey method for collection data. A purposive sampling technique was used to recruit 665 students from 19 chemistry departments in Nigerian universities. The students' ability to solve open-ended problems was measured in terms of their performance and was found to be below average (< 50). The female students outperformed their male counterparts in the chemistry open-ended problem-solving test (ChemOPST). A strong positive correlation was found to exist between students' working memory capacity and their performance in the ChemOPST. The research concludes on the need for experiential-based learning of chemical concepts which could help students build a knowledge base that is required to engage with problems that have real-life applications.*

Keywords: *open-ended problems, working memory, chemistry problem-solving, university students.*

Johnson E. Upahi
University of Johannesburg, South Africa.
University of Ilorin, Nigeria.
Umesh Ramnarain
University of Johannesburg, South Africa.

Introduction

Problem-solving skill is one of the desirable attributes required by university graduates for employability in professional or occupational environments (Overton & Potter, 2011; Sarkar, Overton, Thompson, & Rayner, 2016). The concepts of graduateness and employability have been described in relation to intellectual or higher-order cognitive development that is characterized by question asking, critical reasoning, decision making, system/lateral thinking and problem solving (Overton & Potter, 2008; Zoller, 2012; Zoller & Pushkin, 2007). The changing professional standards, new workplace demands, and changes in learning theory have informed a plethora of research in problem solving and the consequent revision of science curricula with an intention to create learning environments that would provide learners with opportunities to develop higher-order cognitive skills (HOCS) through problem solving (e.g., Cardellini, 2006). Problem solving is important and plays a vital role in science curricula and classroom practice (Lorenzo, 2005).

Wood (2006) defined problem as "a situation where at present the answer or goal is not known" (p. 98). Generally, problems are of two types: Closed-ended and open-ended. Closed-ended problems are the types with only one correct answer, especially when it requires the application of algorithms to arrive at an answer. These types of problems come in the form of in-chapter or as end-of-chapters questions in textbooks. They serve the purpose of reinforcing concepts already learnt in the corresponding chapter. Open-ended problems are those which have many solutions or no specific solutions for the problem as defined. These are the problems Overton and Potter (2011) described as characteristic of problems encountered in real-life contexts, workplace, and academic research.

The type of problems that are largely encountered within the classroom settings bear the semblance of close-ended problems. While the goal may not immediately appear obvious, the way and manner the problem is structured presumes that a goal has been specified. Such problems begin with, *'find the volume of'; 'how many moles of...?'; 'show that...'* Wood (2006) explained that problems of this type could become routines or practice questions. With such questions, students who are skilled in algorithmic manipulation can substitute one set of data for another, and a solution is immediately reached. Johnstone

https://doi.org/10.33225/jbse/20.19.142

(2006) suggested that for a student who can recollect the strategy to tackle such a problem, there remains no problem.

However, contextual or real-life problems take different forms that are not open to algorithmic manipulation; but may require some level of lateral or divergent thinking to reach solutions (Wood, 2006). Overton and Potter (2011) affirmed that criteria for success in such problems are rather different from the closed-ended problems. Lamentably, the experience is that teachers and students at the different levels of education are so used to working towards 'the correct answer' in problem-solving activities. The consequences of this, create erroneous impression in students to think that for every problem in science; there will always be a single correct answer. Wood (2006) firmly cautioned against the risk of cultivating in students that "all is known" about science–as if it is a discipline to which students cannot make their individual contributions. Oftentimes, this inaccurate conception of a single correct answer is perpetuated across the different levels of education. Stating the obvious, most of the assessments (examinations) at all levels of education reinforce this incorrect nature of science (Bennett, 2004).

For a better understanding of the nature of problems, Johnstone (1993) categorized problems based on three variables that are linked with problem solving. These include the: available data; methods; and the intended outcomes. Furthermore, Johnstone (1993) identified eight (8) problem types based on the amount of information available on each of the variables (see Table 1).

Table 1
Types of problem

Type	Data	Methods	Outcomes	Skills required
1	Given	Familiar	Given	Algorithmic manipulations
2	Given	Unfamiliar	Given	Look out for, and compare alternatives to known methods
3	Incomplete	Familiar	Given	evaluate the problem to determine other data that are required
4	Incomplete	Unfamiliar	Given	consider possible methods and made decision on the data required
5	Given	Familiar	Open	Make appropriate decisions about the outcomes/goals. Explore other networks of knowledge
6	Given	Unfamiliar	Open	Make appropriate decisions about the goals and the methods to apply Explore knowledge networks
7	Incomplete	Familiar	Open	Specify the goals, and determine what data are seen to be incomplete
8	Incomplete	Unfamiliar	Open	Suggest the goals and appropriate methods to arrive at the solution. Think of the need for additional data. All the above skills.

Source. Adapted from A. H. Johnstone (1993). Creative Problem Solving in Chemistry

Problem types 1 and 2 are the problems that students often encounter in their learning of chemistry (Reid & Yang, 2002). They are problems found in textbooks as end-of-chapter questions and examination papers. Johnstone (1993) described them as exercises that are algorithmic in nature. Types 3 and 4 are considered to be more difficult and require seeking data/reasoning to reach a solution. While types 5 to 7 are more open problems, problem type 8 which has incomplete data, and requires unfamiliar methods with ill-defined goals is typical of an open-ended problem.

Problem solving in chemistry combines the features of problems found in mathematics and physics and adds its own distinct chemical characteristics in quantitative chemistry topics such as stoichiometry, chemical reaction and synthesis, and analysis (Cardellini, 2006). Chemistry examination contains a variety of question types. While some questions measure knowledge and recall of chemical facts; others assess students' ability to carry out simple calculations, interpret data, write short explanations or design and report experiments. Regardless of whether the questions require lower/higher-order cognitive skills (L/HOCS), one general characteristic of the prevalent chemistry examination is the close-ended nature of the questions/problems. Unlike closed questions, open-ended problems are relatively new, and the potentials are yet to be fully explored (Scottish Qualification Authority, 2010).

Open-ended problems present challenges that require students to demonstrate their understanding of chemical processes. Reid (2000) noted that when students encounter problems, it is then that they are at the threshold of learning. If this proposition is anything to go by, it is important to provide students with firsthand experience on problem

https://doi.org/10.33225/jbse/20.19.142

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

solving that have real-life applications. Rewarding classroom moments could occur when students are challenged to take ownership of their learning. This active engagement energizes students to take their understanding to an increasingly higher level (Belt, Evans, McCreedy, Overton, & Summerfield, 2002; Overton, Potter, Leng, 2013; Reid, 2000).

The issue of gender differences in problem-solving related research has precipitated a variety of research over time and will no doubt, continue to a strand of research in science education (Al-Ahmadi, 2008; Hindal, 2007; Hindal, Reid, & Whitehead, 2013a; Pomerantz, Altermatt, & Saxon, 2002). In spite of the extensive research on gender differences in mathematics and science, results on students' performance based on their gender has been inconsistent (Beller & Gafni, 2000; Hindal et al., 2013a; Overton et al., 2013). For instance, Beller and Gafni (2000) compared gender differences in open-ended and multiple-choice questions in mathematics tests over a period of two years and reported that boys outperformed the girls. While the findings indicate inconsistent patterns with respect to gender effects and item-type, the researchers posited that item-type alone would be inadequate to make conclusions on gender differences in the mathematics tests. This submission created a research gap for the investigation of cognitive variable(s) associated with high performance in cognitively demanding tasks that are algorithmic and open-ended in nature.

Hindal et al. (2013a) explored how students' performance differs in an examination and a variety of tests that are related to learners' characteristics (e.g., field dependence/independence, convergence/divergence and visual-spatial abilities), as well as working memory capacity. They found out that female students were superior in all the measurements compared to their male counterparts, except for working memory capacity, where there was no significant difference.

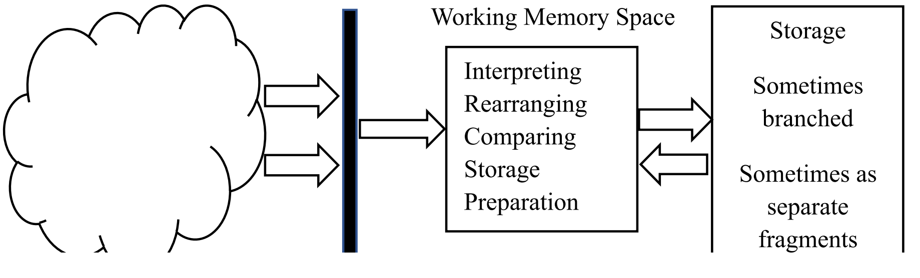
Overton et al. (2013) investigated the different methods that students use in solving rich-context open-ended problems in chemistry and their cognitive abilities, gender, and cultural background, but no result was reported to explain students' performance based on gender. It is therefore, a focus in this research to contribute to the literature by exploring the limiting capacity imposed by the working memory space and the explanations it offers for the individual student to engage with open-ended problems considering their gender.

Theoretical Framework

This research adopted one of the most widely accepted theoretical models–the information processing model by Baddeley and colleagues to describe the function of working memory space that temporarily holds and processes information in relation to problem solving (e.g., Baddeley, 1986, 1999, 2002; Baddeley & Hitch, 1974). The model fits well within the empirical basis for this research and therefore, guides the study in exploring how students' working memory capacity can influence their success or performance in solving open-ended chemistry problems.

Baddeley and Hitch (1974) expanded on the initial multi-store model by Atkinson and Shiffrin's (1968) and developed an alternative model of short-term memory (STM), which they called working memory. The working memory (WM) is the part of human brain that receives and temporarily stores incoming information. It is also described as a mental or thinking-holding space that has a limited capacity (Danili & Reid, 2006). Hindal, Reid and Badgaish (2009) further described working memory as a space where intelligent thinking, information interpretation, understanding and problem solving occurs. While, it is known to have a limited capacity, Johnstone (1997) noted that working memory can have a strong influence on learning.

Figure 1
The information processing model adopted from Atkinson and Shiffrin (1968)



In Figure 1, the information processing model (IPM) suggests a mechanism and control for learning. Information/instruction can be admitted as perception, and it is controlled by what a student already knows. The perception filter is what students can use to filter, control noise and select relevant information. Information that is filtered

https://doi.org/10.33225/jbse/20.19.142

or selected goes through the perception filter. Thereafter, the message of information is accommodated into the students' working memory space to allow for further processing. The processing of incoming information usually requires information from the long-term memory for interaction and sense making (Johnstone, 2006). In other words, if the processed material is to be stored, it looks for previous knowledge and understanding as linchpins in the long-term memory (LTM) to anchor the message/information as new knowledge (Bahar, Johnstone, & Hansell, 1999). This implies that a large interrelated system of knowledge and experience is enriched, from which a learner can draw for effective learning. On the contrary, if sense is made from the processed information through faulty attachment, it gives rise to alternative conceptions that may not be easily debunked, especially in situations where a learner found such faulty knowledge sufficient. Johnstone added that, if the new information accommodated in the working memory space is not linked to the LTM and it becomes necessary to retain it, the new information may however, enter the LTM unattached as rote learning or mere memorization of facts. When such information is needed, a recall is usually difficult. This model unveils some difficulties students encounter and why effective learning may not take place.

First, the IPM reveals that the working memory space of an individual is limited and has a fixed capacity. It can only handle limited information within a particular time (Baddeley, 1986; Johnstone, 1997). In addition, previous research has further confirmed that the working memory space is genetically fixed and limited and has been reported that adults generally have a capacity of accommodating 7 ± 2 units of information (Gathercole, Lamont, Alloway, 2006; Reid, 2009). The working memory space of a student can be measured using some psychological instruments. In literature, the digit-span backward test by Weschler (1997) and figural intersection test (FIT) by Pascual-Leone (1970) have been used to measure students' working memory capacity (Johnstone & El-Banna, 1986). According to Weschler (1955), the amount of information that can be accommodated in the working memory space ranges from four to seven. Consequently, the pieces of information or steps required to solve a problem can be a determining factor to successfully solve problems. Johnstone (2006) noted that in a situation where students do not have the mastery of algorithmic steps to tackle the demand of a problem, they try to manipulate too much information beyond their working memory capacity, and as a result, effective learning is inhibited. This is because conceptual overload has occurred. The resultant effects often manifest in the form of lack of motivation and negative attitude learners' display towards chemistry as they may have shut down on the basis that chemistry requires a lot of information processing with limited working memory space.

Extensive research on cognitive psychology provides further insight into how the STM, alternatively referred to as working memory operates in relation to holding and processing of information (Baddeley, 1986; Engle & Kane, 2004). Specifically, the working memory capacity has been documented as one of the important learners' characteristics that accounts for high academic performance (Hindal et al., 2013a; Hunt, 1999). Nalliah (2012) noted that in disciplines such as mathematics, chemistry and medicine that involves domain-specific learning, the skills and principles of working memory have been adopted as fundamental to experience-based learning (Noble, Miller, & Heckman, 2008).

The working memory space can be reduced to provide space to hold and process information. Researchers suggested the use of schema or chunking of information (e.g., Johnstone, 2006; Reid, 2009). Anderson (1977) describe schema as a mental framework that can be used to organize and process information. For problem solving, students can use schema to break down complex problems into smaller pieces, and then develop a familiar problem-solving procedure to reach an answer. The use of schema as a strategy suggests organizing the working memory for efficient use (Miller, 1956). According to Miller (1956), chunking allows the breaking down of a large amount of information into smaller pieces/chunks to reduce cognitive overload in the problem solvers. Once cognitive overload occurs because of the large amount of data in the working memory space to be processed, problem solving may be inhibited. For students to become successful with open-ended problems, the use of schema and chunking could be good strategies to employ during problem solving. Students' ability to engage successfully with open-ended chemistry problems, putting in perspective the limitations of the working memory space, will inform our interpretations of the results from this research.

Literature Review

One of the dominant research strands in science education focuses on assessment that can help students develop HOCS through question asking, evaluative and lateral thinking, and problem solving (Barak & Dori, 2005; Zoller, 1993, 1999, 2012). However, the types of assessments that are prevalent in typical traditional chemistry

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

classrooms are the conventional algorithmic-based questions that promote LOCS (Bennett, 2004; Johnstone, 1997; Zoller & Tsaparlis, 1997). Usually, these questions have unique correct answers (Surif, Ibrahim, & Dalim, 2014). While such problems certainly provide students with necessary practice to apply the fundamental course concepts, their exclusive use could make students erroneously believe that all chemistry and real-life problems are similarly structured. Reid and Yang (2002) stated that important real-life problems are most times imprecise and open-ended in nature. Hence, the implication of continuously presenting undergraduate students with well-defined or single-right answer questions/problems could leave them unprepared for the more open-ended problems they are likely to come by in real-life contexts and the industry after graduation.

The current economic situation around the world demands that graduates are equipped with academic and special skills required to navigate in fast-changing professional environments and world of work (Overton & Potter, 2011). Similarly, employers have also placed demand on institutions of higher learning to produce graduates who are: equipped to solve new or novel problems; have good communication skills; team players; handle complex data; and have personal skills (Coldstream, 1997; Duch, Groh, & Allen, 2001; Lowden, Hall, Elliot, & Lewin, 2011; Mason, 1998; Zoller & Tsaparlis, 1997). This becomes necessary when Hanson and Overton (2010) reported that, new graduates in their first two years of post-university role, acknowledged that while their education in terms of chemistry learning has been all-inclusive, they felt inadequately prepared in terms of transferable skills (problem solving, critical reasoning, evaluative thinking, decision making, etc.) needed in order to cope at their workplaces (Sarkar et al., 2016). The possibility of engaging students with open-ended problems in problem-based learning has been confirmed to hold potentials for developing an inclusive range of these 21st century learning skills (Duch et al., 2001; Hanson & Overton, 2010). The nature of open-ended problems is such that the data given is incomplete, goals are ill-defined, and it requires the use of unfamiliar methods (Johnstone, 1993; St. Clair-Thompson, Overton, & Bugler, 2012). Open-ended problems require the application of HOCS to arrive at a solution. While there are studies that have reported successful implementations of how students solve chemistry open-ended problems as group work (Belt & Overton, 2007; Grant et al., 2006; Summerfield, Overton, & Belt, 2003; Reid & Yang, 2002), research that has explored individual student's ability to engage with open-ended problem solving are relatively few (e.g., Overton & Potter, 2011; Overton et al., 2013; St. Clair-Thompson et al., 2012).

Recent studies have focused on students' comparative performance in algorithmic, open-ended problems (Overton & Potter, 2011; Surif et al., 2014), and in relation to cognitive variables that are fundamental to successfully engage with open-ended chemistry problems (St. Clair-Thompson et al., 2012). Surif et al. (2014) have compared students' performance in algorithmic, conceptual, and open-ended chemistry problems but the cognitive variable(s) that mediate successful problem-solving were not examined. The findings showed that majority of the students were unable to solve or tackle the conceptual and open-ended problems. In another study, Overton and Potter (2008) reported that students' cognitive styles correlated with their success in problem-solving. Specifically, there was a relationship between field independent students and their open-ended problem-solving ability. With a small sample size, the result of their study cannot be generalized. St. Clair-Thompson et al. (2012) compared students' scores in algorithmic and open-ended chemistry problems and noted some discrepancies. In their study, students' scores in both tests were not significantly linked, and this suggests that students had difficulties with open-ended problems characterized by HOCS (Overton & Potter, 2011).

Research has documented a few cognitive variables (field-dependence/independence, convergent/divergent characteristic, and working memory) that are pertinent to problem solving and also facilitate the achievement of the problem solvers (Solaz-Portolés, & Sanjosé, 2007). This further suggests the existence of a link between the cognitive variables and problem solving. While there are studies that have reported on working memory as a predictor of algorithmic problem solving (Al-Ahmadi & Oraif, 2009; Ali & Reid, 2012; Danili & Reid, 2004; Overton & Potter, 2011; Reid, 2009; Tsaparlis, 2005), others indicated no significant relationship between students' working memory and their ability to solve open-ended problems (e.g., Overton & Potter, 2011). Contrariwise, St. Clair-Thompson et al. (2012) reported that open-ended problem solving partly rely on working memory capacity but noted that a large amount of variance on performance could not be unaccounted for. Since there are inconsistent results in literature, the present research used a baseline assessment to measure students' ability to solve open-ended chemistry problems. Furthermore, it was predicted that students' working memory capacity would influence their ability to solve open-ended chemistry problems. In this research, "ability" is considered as students' high performance in solving open-ended chemistry problems (Hindal, Reid, & Whitehead, 2013b). In clear terms, undergraduates who score high in the ChemOPST will be described as being able to solve the open-ended chemistry problems.

The overall aim of this research was to determine students' ability, and the influence of their working memory

https://doi.org/10.33225/jbse/20.19.142

capacity to solve open-ended chemistry problems. To guide the present research, the following research questions were raised to address the main purpose of the research:

1. What is the performance of undergraduate students in open-ended chemistry problems?
2. Do the male students score higher than their female counterparts in the ChemOPST?
3. Do the male students score higher than their female counterparts in the FIT?
4. Is there any relationship between undergraduate chemistry students' working memory capacity and their ability to solve open-ended chemistry problems?

Research Context

In Nigeria, a Decree of the erstwhile Federal Military Government (amended as Decree No. 48 in 1988) established and empowered the national universities commission (NUC) to prescribe academic standards for all courses offered within the Nigerian universities. As a collaborative endeavor, the Commission in partnership with academic staff of the universities developed what was earlier referred to as the minimum academic standards (MAS) for all the courses in 1989 (NUC, 2007). The document was immediately approved for used in Nigerian universities in 1989.

The MAS documents became major tools to guide the conduct of accreditation exercises of academic programmes offered by Nigerian universities. In 2001, the NUC began the process of revising the MAS documents after a decade of implementation. The review became important as "frontiers of knowledge" in all the science disciplines have advanced in the light of new information generated through research. In addition, the revision was needed to update the documents in terms of integrating entrepreneurship, peace and conflict studies that will equip university graduates with relevant skills and competencies; and to enhance their capability to contribute meaningfully towards the socio-economic growth of the country and global competitiveness.

In 2007, the Commission merged the benchmark standards and the reviewed MAS into new documents, which is now referred to as the benchmark minimum academic standards (BMAS) for the different courses. The BMAS clearly articulates the learning goals/outcomes and skills anticipated from undergraduates at the end of each academic year of their disciplines. The document is not overly prescriptive, but rather flexible and creates room for universities to incorporate emerging course contents that are consistent with international best practice.

In principle, the training of scientists is designed to be thorough, creative, innovative and relevant to graduate employment opportunities. The undergraduate chemistry programme is designed to promote an appreciable knowledge of the centrality of chemical science to human lives, as well as its cross-cutting relevance to other branches of science. The students are also expected to acquire competencies that can be applied in chemical and non-chemical areas; confidence for employment; and fundamental chemical knowledge and skills required to pursue further studies in chemistry-related fields and academic research (NUC, 2007).

In addition, chemistry graduates should be able to apply the knowledge and skills they have acquired to solve academic and real-life practical problems that have relevance for allied industries towards solving societal and national needs (NUC, 2007). However, the development and assessment of these abilities and skills has not been consistent in several courses/programmes offered in Nigeria. Research in open-ended problem-solving and working memory is still in its infancy and not widespread within the context of the study. Therefore, this research aimed at using baseline assessment to measure undergraduate students' competence to solve open-ended chemistry problems, and to determine the influence of their working memory capacity in problem solving.

Research Methodology

Research Sample

This research was a descriptive research that employed a survey method to measure undergraduate students' ability to solve open-ended chemistry problems, and the influence of their working memory capacity. The sample population was purposively selected based on two criteria. One, the universities must have a minimum of 5-year experience in graduating students from the chemistry department; and two, it must be NUC accredited universities with a well-established undergraduate chemistry programme that aligns with NUC benchmarking guidelines. The initial sample of participants enlisted for the research were 830 undergraduate chemistry students drawn from across 19 universities in Nigeria. However, due to voluntary withdrawal and incomplete response to the tests, the final sample consisted of 665 students. The frequency and percentage distribution of participants by gender (i.e.

https://doi.org/10.33225/jbse/20.19.142

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

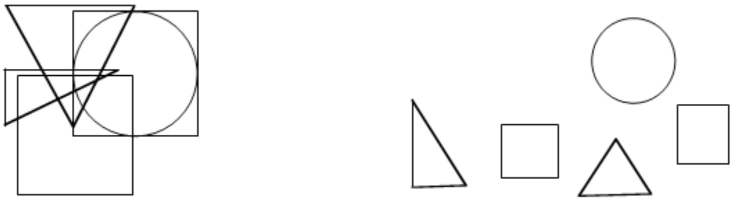
female and male) were 351 (47%) and 314 (53%) respectively. Since, none of the students indicated a different gender identity from their sex at birth, gender is operationally defined as male and female in this research.

Research Instruments

The research instruments consisted of a pre-attitude questionnaire, a FIT, the ChemOPST and a post-attitude questionnaire. The pre-and post-test attitude questionnaire used bipolar statements to measure students' attitude toward chemistry and to solving open-ended chemistry problems. The results on students' attitude before and after the administration of ChemOPST will be reported in another article.

In order to measure students' working memory space, the FIT developed by Pascual-Leone (1970) was adopted and used. In the FIT there are two groups of simple geometric shapes. On one side is the FIT with overlapping shapes that have an intersect inside all the shapes, and on the other side are the same shapes but separated from each other (see example in Figure 2). Altogether, there were 30 overlapping shapes with a common intersect in each item of the FIT. The number of geometric shapes ranges from 2 to 8. The FIT is usually timed, and the intersect of each group of shapes taken as an item must be located and shaded within 20 seconds. The validity and reliability of the FIT has been demonstrated by Johnstone and El-Banna (1986, 1989). Assessing undergraduate students' working memory capacity using the FIT allows to draw relationship between students' performance in FIT and the ChemOPST. Research has shown that scores on working memory task can be a useful predictor of success in cognitively demanding task in science and mathematics (Baddeley, 2002; St. Clair-Thompson & Gathercole, 2006).

Figure 2
An example of a figural intersection test



The validity of the ChemOPST was established using several strategies. To ensure face and content validity of the ChemOPST, experts in teaching chemistry assisted to review the questions and provided feedback. The instrument was given to two professors; a science educator and a chemist. They were requested to provide comments on the content to be assessed, which were discussed between the authors and incorporated into the ChemOPST. In addition, the ChemOPST was administered in paper and pen format to chemistry teachers and postgraduate students enrolled for chemistry programme at master's level. They were requested to take the test, as well as provide their feedback with respect to the chemistry content assessed, the suitability of their answers, and the scope of chemistry content covered. The comments made, especially those from postgraduate students who registered for chemistry programme, were considered in fine-tuning the ChemOPST.

For further validity, the ChemOPST was also administered to 30 students at a different university who were not part of the final sample for the research. They were requested to verify the clarity of problems, appropriateness of language and to also suggest suitable duration or period for the test such that time will not be a constraint for the test takers. The reliability of the ChemOPST was further subjected to a test-retest method within a period of three-week interval. Scores obtained from the first and second administrations of the instrument were correlated using Pearson-product moment correlation statistic to obtain reliability indices for the ChemOPST. A calculated reliability coefficient of 0.76 was obtained and considered adequate for the research.

Data Collection

Having secured the approval of the Faculty of Education Ethical Clearance Committee to conduct this research that involves human subjects, the researcher and research assistants visited participating universities to

https://doi.org/10.33225/jbse/20.19.142

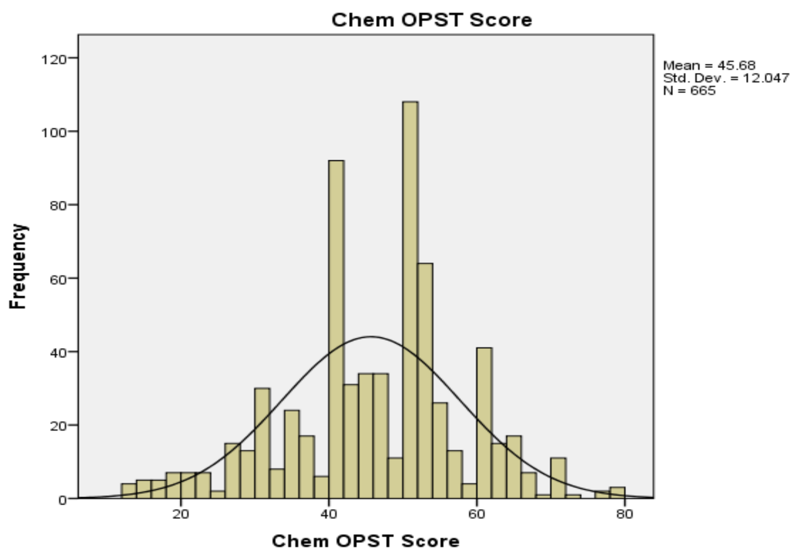
obtain permission to enrol students from chemistry department to participate in the research. The students were requested to indicate their willingness and to fill the consent forms to participate in the research. Thereafter, the research instruments were administered in each of the selected universities with the consent, cooperation and assistance of the chemistry lecturers in those universities. The students were given 1 hour 30 minutes to attempt all the problems and were instructed at the beginning to write down all their thinking in the booklet provided. They could seek clarification if they so wished, but only on the instructions.

Open-ended problems are quite difficult to score compared to close-ended problems. This is because, the problem-solving process or strategy is equally as the outcome. In accordance with established practices in this area, marks were distributed for identifying the goals, the quality of the approach and for the assumptions and estimations made (Overton & Potter, 2011). Each of the open-ended problems was allocated 10 marks. The marks were distributed accordingly to match the designed marking scheme (see supplementary material for samples of open-ended problems and making guides). Only about 665 scripts for each of the FIT and ChemOPST were retrieved and scored. After the test scripts were scored and recorded in MS Word Excel, they were exported into the window version of statistical package for social sciences (SPSS) software 25.0 for analysis.

Results of Research

The results of the research are presented here, in the order in which research questions were raised to guide the study. Research question 1 focused on students' ability to solve open-ended chemistry problems. There were 665 students who consented and participated fully in the chemistry open-ended problem-solving test (ChemOPST). Figure 3 shows the students' scores obtained from the ChemOPST. The mean score for the ChemOPST was 45.68 (SD = 12.05). An examination of the shape of the histogram provides information about the distribution of students' scores.

Figure 3
Mean score of students in the ChemOPST



Do the male students score higher than their female counterparts in the ChemOPST?

Alternative hypothesis (H_A): The scores of male students in the ChemOPST are higher than their female counterparts.

In determining whether the male students score higher than their female counterparts in the ChemOPST, we conducted a Wilcoxon Signed Rank Test, the result of the test in Table 2 revealed a statistically significant difference in the scores of male and female students in the ChemOPST, $Z = -3.476$, $p < .001$, with a small effect size ($\Phi = 0.13$). The median score of the female students (Md = 50.00) was higher than the male students (Md = 44.00). Therefore, the alternative hypothesis was rejected.

https://doi.org/10.33225/jbse/20.19.142

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Table 2
Wilcoxon signed rank test on students' score in the ChemOPST by gender

	Gender	N	Mean Rank	Sum of Ranks
ChemOPST	Female	314	360.33	113145.00
	Male	351	308.55	108300.00
	Total	665		

Test Statistics[a]

	ChemOPST
Mann-Whitney *U*	46524.00
Wilcoxon *W*	108300.00
Z	-3.476
Asymp. Sig. (2-tailed)	.001
Exact Sig. [2*(1-tailed Sig.)]	.0005

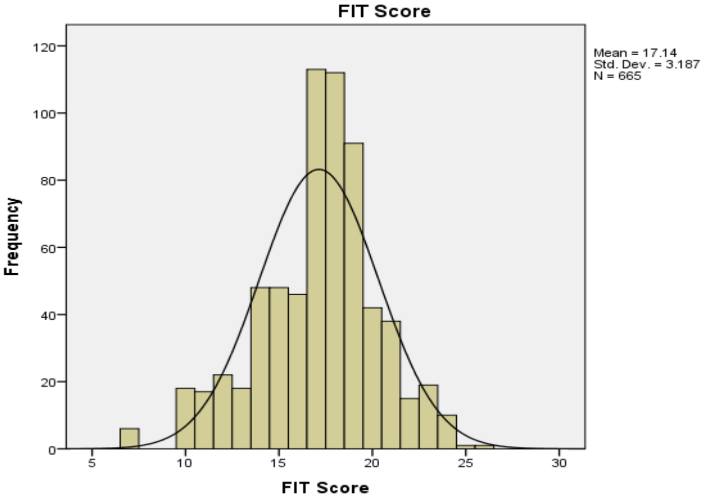
a. Grouping Variable: Gender

Median Score of the ChemOPST by Gender

ChemOPST		
Gender	*N*	Median
Female	314	50.00
Male	351	44.00
Total	665	47.00

The working memory capacity of the students was measured by the FIT. Figure 4 presents students' scores obtained in the FIT. The mean score for the FIT was 17.14 (*SD* = 3.19) skewing fairly to the right. A closer look at the shape of the histogram provides information about the distribution of students' scores.

Figure 4
Mean score of students in the FIT



https://doi.org/10.33225/jbse/20.19.142

Do the male students score higher than their female counterparts in the FIT?

Alternative hypothesis (H_A): The scores of male students in the FIT are higher than their female counterparts.

Table 3 provides a Wilcoxon Signed Rank Test which indicates a statistically significant difference in the scores of male and female students in the FIT, $Z = -5.972$, $p = .000$, with a small effect size ($\Phi = 0.23$). The median score of the female students ($Md = 18.00$) was higher than the male students ($Md = 17.00$). Therefore, the alternative hypothesis was rejected.

Table 3
Wilcoxon signed rank test on students' score in the FIT by gender

	Gender	*N*	Mean Rank	Sum of Ranks
	Female	314	379.71	119229.50
FIT	Male	351	291.21	102215.50
	Total	665		

Test Statistics[a]

	FIT
Mann-Whitney *U*	40439.50
Wilcoxon *W*	102215.50
Z	-5.972
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000

a. Grouping Variable: Gender

Median Score of the FIT by Gender

FIT		
Gender	***N***	**Median**
Female	314	18.00
Male	351	17.00
Total	665	17.00

The correlation between chemistry students' scores in open-ended problems (measured by the ChemOPST) and their working memory capacity measured by the FIT was analysed using Pearson product-moment coefficient correlation. Preliminary investigations were conducted to ensure that there was no violation of the assumptions of normality, linearity and homoscedasticity. The results presented in Table 4 indicate a strong, positive correlation between the two variables, $r = .81$, $n = 665$, $p < .001$, with students' working memory capacity been closely associated with their ability to solve open-ended chemistry problems.

https://doi.org/10.33225/jbse/20.19.142

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Table 4
Correlation of students' scores in the ChemOPST and FIT

		ChemOPST Score	FIT Score
ChemOPST Score	Pearson Correlation	1	.81**
	Sig. (2-tailed)		.000
	Sum of Squares and Cross-products	96362.78	20551.47
	Covariance	145.13	30.95
	N	665	665
FIT Score	Pearson Correlation	.81**	1
	Sig. (2-tailed)	.000	
	Sum of Squares and Cross-products	20551.49	6745.27
	Covariance	30.95	10.16
	N	665	665

*Note. **correlation is significant at the 0.01 (2-tailed)*

Discussion

This research examined students' ability to solve open-ended chemistry problems. Since working memory is known to play an important role in cognitive processes such as problem solving (Danili & Reid, 2006), the research also investigated the correlation between students' working memory capacity (a cognitive variable) and their ability to solve the open-ended chemistry problems. Research findings revealed that students who started out to attempt some of quantitative problems by applying algorithms, soon realized that some of the problems were not opened to algorithmic manipulations. This is because the cognitive skills required to solve open-ended and algorithmic problems are different (Overton & Potter, 2011). The students' ability was measured in terms of their performance in solving chemistry open-ended problems. It was found that majority of the students scored below 50 marks in the ChemOPST. This result is expected, as this may probably be the first-time students are presented with questions that are open-ended. This assumption matches well with Bennett (2004) findings that examination questions from chemistry departments in United Kingdom and Australian universities were algorithmic in nature (Johnstone, 1993).

The analysis of students' score in the ChemOPST based on gender revealed a statistically significant difference with the female students performing better than their male counterparts in the ChemOPST. This result agrees with the findings of those of Hindal et al. (2013a) who explored how students differed in their performance in a range of tests related to learners' cognitive variables based on gender. The female students were found to be superior to male students in all the measurement, except for the working memory capacity, where there was no significant difference related to gender.

To determine students' working memory capacity, the FIT designed by Pascual-Leone (1970) was administered to the students. As shown in Figure 3, the scores obtained from the FIT ranged from 7 to 26, with majority having a score on FIT ranging from 17 to 18. A comparison of students' scores in FIT based on their gender revealed a statistically significant difference between the male and female students at p = .0001 (1-tailed). The females performed better than the males in the FIT. This result probably suggests that female students were able to hold considerable amount of information and have more working memory space to process information, because they appeared to be quick at locating the intersect of geometric shapes within a short time and scoring higher when compared to their male counterparts in the FIT.

The result of the relationship between undergraduates' ability to solve open-ended problems, measured by ChemOPST and their working memory capacity demonstrated a strong, positive correlation between the two variables, $r = .81$, $n = 665$, $p < .01$. The implication of this is that students with relatively high scores in the FIT were the most successful in the open-ended problems. This result is consistent with the findings of (Overton & Potter, 2008, 2011; St. Clair-Thompson et al., 2012). Overton and Potter (2011) examined students' success in open-ended

https://doi.org/10.33225/jbse/20.19.142

chemistry problems that used real-life, rich context, and require the application of HOCS. A positive correlation exists between students' working memory capacity when compared with their ability to solve algorithmic and open-ended problems, with a demonstration of a threshold effect. One important basis for this correlation could be that students who were the most successful in the ChemOPST adopted some more efficient retrieval systems without having to overload the working memory space, and thereby diminished the influence of working memory capacity on their ability to solve open-ended problems.

Conclusions

Open-ended problem-solving ability is one desirable skill that is necessary for students to cope with the challenges in new workplace after graduation. The question of whether undergraduate chemistry students possess the ability to solve chemistry problems that share similar characteristics with open-ended problems in real-life context was the focus of our study. The result shows that undergraduate students' ability to solve chemistry open-ended problems was below average. While it is understandable that the assessments the students are familiar with are not largely open-ended in nature, we believe that exposing university students to this form of assessment early in their university education holds potentials to improving their problem-solving abilities. Therefore, the onus is on academics to employ methods of instruction and assessment that could help students develop higher-order cognition through decision making, system/lateral thinking and problem solving from the first year of their university education. This is important because many students are admitted into the university without these skills.

One way that could help students develop ability in open-ended problem-solving may be the use of myriad of consistent and cumulative teaching-learning activities that involve a large portion of experience-based learning or problem-based learning to reduce overload of the students' WM capacity. It is equally important that modules and courseware materials to which students are being exposed, should reflect the predictions about learnings derived from the information processing model to improve students' ability or performance in context-based learnings.

Working memory capacity as a psychological factor showed relatedness or a positive correlation with students' ability to solve open-ended chemistry problems as evident in this research. Assessment that requires the handling of information will tend to favour students with high working memory capacity. This implies that teaching, learning and assessment of undergraduate chemistry students must operate within the limitations imposed by the working memory. Therefore, for students to be able to cope with problem solving that requires a lot of information, they will need to reduce cognitive overload by making use of schema drawn from the long-term memory or by chunking pieces of information. University teachers could also help students avoid cognitive overload by preparing questions/problems with little or no extraneous information/data that may not be relevant to reach the solution of the problems.

References

Al-Ahmadi, F. M. (2008). *The development of scientific thinking with senior school physics students*. PhD Thesis, University of Glasgow, Glasgow.

Al-Ahmadi, F., & Oraif, F. (2009). Working memory capacity, confidence and scientific thinking. *Research in Science and Technological Education, 27*(2), 225–243. https://eric.ed.gov/?id=EJ857005

Ali, A. A., & Reid, N. (2012). Understanding mathematics: Some key factors. *European Journal of Educational Research, 1*(3), 283–299. https://files.eric.ed.gov/fulltext/EJ1086376.pdf

Anderson, R. C. (1977). The notion of schemata and the educational enterprise: General discussion of the conference. In R. C. Anderson, R. J. Spiro & W. E. Montague (Eds.), *Schooling and the acquisition of knowledge* (pp. 415–431). Lawrence Erlbaum.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In W. K. Spence & J. T. Spence (Eds.), *The psychology of learning and motivation: Advances in research and theory* (pp. 89–195). Academic Press.

Baddeley, A. D. (1986). *Working memory.* Clarendon Press.

Baddeley, A. D. (1999). *Essentials of human memory*. Clarendon Press.

Baddeley, A. D. (2002). Is working memory still working? *European Psychologist, 7*(2), 85–97. https://doi.org/10.1037/0003-066x.56.11.851

Baddeley, A. D., & Hitch, G. J. L. (1974). Working memory. In G. A, Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory (*pp. 47–89). Academic Press.

Bahar, M., Johnstone, A. H., & Hansell, M. H. (1999). Revisiting learning difficulties in biology. *Journal of Biology Education, 3*, 84–87.

Barak, M., & Dori, Y. J. (2005). Enhancing undergraduate students' chemistry understanding through project-based learning in an IT environment. *Science Education, 89*, 117–139.

Beller, M., & Gafni., N. (2000). Can item format (multiple choice vs. open-ended) account for gender differences in mathematics achievement? *Sex Roles, 42*(1-2), 1–21.

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Belt, S. T., & Overton, T. L. (2007). Context-based case studies in analytical chemistry. In P. A. Mabrouk (Ed.), *Active learning: Models from the analytical sciences* (pp. 87–99). ACS Symposium Series 970, Washington, DC.

Belt, S. T., Evans, E. H., McCreedy, T., Overton, T. L., & Summerfield, S. (2002). A problem-based learning approach to analytical and applied chemistry. *University Chemistry Education, 6,* 65–72.

Bennett, S. W. (2004). Assessment in chemistry and the role of examination. *University Chemistry Education, 8,* 52–57.

Cardellini, L. (2006). Fostering creative problem solving in chemistry through group work. *Chemistry Education Research and Practice, 7*(2), 131–140. https://doi.org/10.1039/B5RP90019K

Coldstream, P. (1997). Training minds for tomorrow's world: On independence, curiosity, and effectiveness. *Higher Education in Europe, 22*(4), 507–515.

Danili, E., & Reid, N. (2004). Some strategies to improve performance in school chemistry based on two cognitive factors. *Research in Science and Technological Education, 22*(2), 203–226. https://doi.org/10.1080/0263514042000290903

Danili, E., & Reid, N. (2006). Cognitive factors that can potentially affect pupils' test performance. *Chemistry Education Research and Practice, 7*(2), 64–83. https://doi.org/10.1039/B5RP90016F

Duch, B. J., Groh, S. E., & Allen, D. E. (2001). *The power of problem-based learning: A practical "how to" guide for teaching undergraduate courses in any discipline*. Stylus.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. Ross (Ed.), *The psychology of learning and motivation* (pp. 145–199). Academic Press.

Gathercole, S. E., Lamont, E., & Alloway, T. (2006). Working memory in the classroom. In S. J. Pickering (Ed.), *Working memory and education* (pp. 220–241). Elsevier Press.

Grant, S., Freer, A. A., Winfield, J. M., Gray, C., Overton, T. L., & Lennon, D. (2004). An undergraduate teaching exercise that explores contemporary issues in the manufacture of titanium dioxide on the industrial scale. *Green Chemistry*, *6*(1), 25–32.

Hanson, S., & Overton, T. (2010). *Skills required by new chemistry graduates and their development in degree programmes.* Higher Education Academy UK Physical Sciences Centre.

Hindal, H. S. (2007). *Cognitive characteristics of students in middle schools in state of Kuwait, with emphasis on high achievement.* PhD Thesis, University of Glasgow, Glasgow.

Hindal, H., Reid, N., & Badgaish, M. (2009). Working memory, performance and learner characteristics. *Research in Science and Technological Education, 27*(2), 187–204. https://doi.org/10.1080/02635140902853640

Hindal, H., Reid, N., & R. Whitehead. (2013b). High ability and learner characteristics. *International Journal of Instruction, 6*(1), 59–76. https://files.eric.ed.gov/fulltext/EJ1085379.pdf

Hindal, H., Reid, N., & Whitehead, R. (2013a). Gender and learner characteristics. *European Journal of Educational Research, 2*(2), 83–95. https://files.eric.ed.gov/fulltext/EJ1086328.pdf

Hunt, E. (1999). What is a theory of thought? In J. R. Sternberg (Ed.), *The nature of cognition.* MIT Press.

Johnstone, A. H. (1993). Introduction. In C. Wood & R. Sleet (Eds.), C*reative problem solving in chemistry* (pp. 4–6). The Royal Society of Chemistry.

Johnstone, A. H. (1997). Chemistry teaching-science or alchemy? *Journal of Chemical Education, 74*(3), 262–268.

Johnstone, A. H. (2006). Chemical education research in Glasgow in perspective. *Chemistry Education Research and Practice, 7*(2), 49–63.

Johnstone, A. H., & El-Banna, H. (1986). Capacities, demands and processes: A predictive model for science education. *Education in Chemistry, 23*(3), 80–84.

Johnstone, A. H., & El-Banna, H. (1989). Understanding learning difficulties – a predictive research model. *Studies in Higher Education, 14*(2), 159–168.

Lorenzo, M. (2005). The development, implementation and evaluation of a problem-solving heuristic. *International Journal of Science and Mathematics Education, 3,* 33–58.

Lowden, K., Hall, S., Elliot, D., & Lewin, J. (2011). *Employers' perceptions of the employability skills of new graduates*. Edge Foundation.

Mason, G. (1998). *Change and diversity: The challenges facing chemistry higher education*. The Royal Society of Chemistry and the Council of Industry and Higher Education.

Miller, G. A. (1956). The magic number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63*(2), 81–91.

Nalliah, S. (2012). The influence of working memory capacity on academic achievement of final year medical students. *International e-Journal of Science, Medicine and Education, 6*(1), 87–102.

National Universities Commission (NUC). (2017). *Benchmark minimum academic standards (BMAS) for undergraduate programmes in Nigerian universities*. NUC Press.

Noble, K. A., Miller, S. M., & Heckman, J. (2008). The cognitive style of nursing students: educational implications for teaching and learning. *Journal of Nursing Education, 47*(6), 245–253.

Overton, T. L., & Potter, N. M. (2008). Solving open-ended problems, and the influence of cognitive factors on student success. *Chemistry Education Research and Practice, 9*(1), 65–69.

Overton, T. L., & Potter, N. M. (2011). Investigating students' success in solving attitudes towards context-rich open-ended problems. *Chemistry Education Research and Practice, 12*(3), 294–302.

Overton, T. L., Potter, N. M., & Leng, C. (2013). A study of approaches to solving open-ended problems in chemistry. *Chemistry Education Research and Practice*, *14*(4), 468–475.

Pallant, J. (2013). *SPSS survival manual*. McGraw-Hill Education.

Pascual-Leone, J. (1970). A mathematical model for the transition rule in Piaget's developmental stages. *Acta Psychologica, 32*, 301–345.

https://doi.org/10.33225/jbse/20.19.142

Pomerantz, E. M., Altermatt, E. R., & Saxon, J. L. (2002). Making the grade but feeling distressed: Gender differences in academic performance and internal distress. *Journal of Educational Psychology, 94*(2), 396–404.
Reid, N. (2000). The presentation of chemistry: Logically driven or applications led? *Chemistry Education Research and Practice, 1,* 381–392.
Reid, N. (2009). The concept of working memory. *Research in Science and Technological Education, 27*(2), 131–138.
Reid, N., & Yang, M. (2002). The solving of problems in chemistry: The more open-ended problems. *Research in Science and Technological Education, 20,* 83–98.
Sarkar, M., Overton, T., Thompson, C., & Rayner, G. (2016). Graduate employability: Views of recent science graduates and employers. *International Journal of Innovation in Science and Mathematics Education, 24*(3), 31–48.
Scottish Qualifications Authority (2010). *Chemistry open-ended questions support materials.* Learning and Teaching Scotland.
Solaz Portolés, J. J., & Sanjosé López, V. (2007). Cognitive variables in science problem solving: A review of research. *Journal of Physics Teacher Education Online, 4*(2), 25–32.
St. Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition, and working memory. *Quarterly Journal of Experimental Psychology, 59,* 745–759.
St. Clair-Thompson, H. L., Overton, T., & Bugler, M. (2012). Mental capacity and working memory in chemistry: Algorithmic versus open-ended problem solving. *Chemistry Education Research and Practice, 13*(4), 484–489. https://doi.org/10.1039/C2RP20084H
Summerfield, S., Overton, T., & Belt, S. (2003). Problem solving case studies. *Analytical Chemistry, 75*(7), 181–182.
Surif, J., Ibrahim, N. H., & Dalim, S. F. (2014). Problem solving: Algorithms and conceptual and open-ended problems in chemistry. *Procedia-Social and Behavioral Sciences*, *116*, 4955–4963. https://doi.org/10.1016/j.sbspro.2014.01.1055
Tsaparlis, G. (2005). Non-algorithmic quantitative problem solving in university physical chemistry: A correlation study of the role of selective cognitive factors. *Research in Science and Technological Education, 23,* 125–148.
Wechsler, D. (1955). *Wechsler adult intelligence scale manual*. Psychological Corporation.
Wechsler, D. (1997). *The Wechsler adult intelligence scale-III.* Psychological Corporation.
Wood, C. (2006). The development of creative problem solving in chemistry. *Chemistry Education Research and Practice, 7,* 96–113. https://doi.org/10.1039/B6RP90003H
Zoller, U. (1993). Lecture and learning: Are they compatible? Maybe for LOCS, unlikely for HOCS. *Journal of Chemical Education, 70*(3), 195–197.
Zoller, U. (1999). Teaching tomorrow's science courses–are we getting it right? *Journal of College Science Teaching, 29,* 409–414.
Zoller, U. (2012). Science education for global sustainability: What is necessary for teaching, learning, and assessment strategies. *Journal of Chemical Education, 89*, 297–300. https://doi.org/10.1021/ed300047v
Zoller, U., & Pushkin, D. (2007). Matching higher-order cognitive skills (HOCS) promotion goals with problem-based laboratory practice in a freshman organic chemistry course. *Educational Research, 8*(2), 153–171.
Zoller, U., & Tsaparlis, G. (1997). Higher and lower-order cognitive skills: The case of chemistry. *Research in Science Education, 27,* 117–130.

Appendix

A sample of the Chemistry open-ended problem-solving test (ChemOPST).

The Chewing Gum Problem

People have chewed gum-like substances to freshen their breath and clean their teeth for centuries. Some people think that chewing gum does not only freshens the breath, but also cleans the teeth and helps to free them from decay.

Let's look at tooth decay. Does gum-chewing really help to keep teeth healthy?

Here's a list of what is in chewing gum:

i. **Chewing gum base:** a synthetic rubber-like substance;
ii. **Sweeteners:** sugar (sucrose) or sugar substitutes (like those used in diet coke);
iii. **Softeners:** vegetable oil products like glycerine (glycerol); and
iv. **Flavourings:** spearmint and peppermint oils.

Discuss the possible answers to the problems below:

1. What do you think is the difference between ordinary gum and "sugar-free" gum?
2. After eating, bacteria will attack and break down carbohydrates like starch and sucrose (sugarcane). Try to write down as much as you can, about the process in which carbohydrate is broken down in the mouth.
3. We want to find out if the practice of using chewing gum helps to fight tooth decay or not. Discuss what information you need to reach an answer, based on your knowledge of the way carbohydrates are broken down. Make a list of what you need to know.

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Marking Scheme for the ChemOPST

Activity		Mark
Identifying data	Separating relevant from irrelevant	1
	Making assumptions or estimations	1
Method	Applying known methods or strategies	2
	Developing new methods or strategies	2
Goals	Defining the goal	1
	Working towards the goal	1
	Reaching the goal	1
	Checking the goal	1

Received: *June 15, 2019*　　Accepted: *January 15, 2020*

Cite as: Upahi, J. E., & Ramnarain, U. (2020). Examining the connection between students' working memory and their abilities to solve open-ended chemistry problems. *Journal of Baltic Science Education*, *19*(1), 142-156. https://doi.org/10.33225/jbse/20.19.142

Johnson E. Upahi
(Corresponding author)
PhD, Postdoctoral Research Fellow, Department of Science and Technology Education, Faculty of Education, University of Johannesburg, Kingsway Avenue, Auckland Park, Johannesburg, South Africa.
Lecturer, Department of Science Education, University of Ilorin, Ilorin, Nigeria.
E-mail: johnsonenero@yahoo.com, upahie@uj.ac.za
ORCID: http://orcid.org/0000-0002-8332-1285

Umesh Ramnarain
PhD, Professor, Department of Science and Technology Education, Faculty of Education, University of Johannesburg, Kingsway Avenue, Auckland Park, Johannesburg, South Africa.
E-mail: uramnarain@uj.ac.za
ORCID: http://orcid.org/0000-0003-4548-5913