Chapter 13
Working Memory Capacity and Teaching and Learning of Stoichiometry

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Abstract Cognitive neuroscience education is a new trend in educational psychology research. In the context of science education, research performed from the perspective of neuroscience is gaining incremental importance. The findings of studies on neuro-cognitivism have significant implications in designing classroom teaching and learning strategies. Notably, the studies on neuroscience education suggested investigating the role of working memory (WM) in teaching and learning of specific science concepts that deal with solving problem such as stoichiometry. This study investigated the level of working memory capacity (WMC) of 80 Form Four science stream students (16–17 years old). At the same time, the study also explored how working memory was considered in teaching and learning of stoichiometry from students' and teachers' perspectives. The findings revealed that the level of WMC among the students appeared generally low and from the students' and teachers' perspective, WMC was frequently ignored in the stoichiometry lessons. The findings of this study offer revisiting the research on WMC in science education from the perspective of teaching and learning of stoichiometry.

Keywords Neuroscience education · Secondary students · Stoichiometry · Working memory capacity

Introduction

Cognitive neuroscience education is a new trend in educational psychology research. Particularly in the context of science education, many available studies have investigated teaching and learning of science from the neurocognitive perspective (Anderson, 1992, 1997; Anderson & Kunin-Batson, 2009; Immordino-Yang & Damasio, 2007). Immordino-Yang and Damasio (2007) investigated the attention, memory, decision-making, and social functioning as neurobiological evidence that affects the

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learning in schools. According to Immordino-Yang and Damasio (2007) when students engaged in decision-making about the real-world, transformation of knowledge and skills learned in the classroom to the real-world context takes place. The brain controls the transformation process, and cognitive neuroscience research reveals that the idea (*knowledge*) or information is encoded onto the working memory (D'esposito & Postle, 2015). Working memory is a mental workspace that stores and processes information in translating the classroom knowledge to the real-world context. The information stored on working memory was later retrieved and translated into specific behaviors while executing the task (St Clair-Thompson, Overton, & Bugler, 2012). The ability to hold, retrieve, and manipulate information varies among individuals. This ability is referred to as working memory capacity (WMC) (Wilhelm, Hildebrant, & Oberauer, 2013). In other words, WMC determines the specific behaviors executed in completing the task.

WMC is one of the factors that influence the cognitive performance of students (Gathercole, Pickering, Knight, & Stegmann, 2004). Mainly WMC is highly correlated to students' performance in subject matter that focuses on problem-solving such as Mathematics and Sciences (St Clair-Thompson et al., 2012). This is because in science lessons students required to generate information, recognize, analyze and transfer information in solving the problems. According to St Clair-Thompson et al. (2012) due to the differences in WMC, the readiness to learn a topic, concept, skills, and ideas vary among the students in the same age group. During any teaching and learning session, students need to retrieve the stored information and manipulate the information in completing the given task. Students who lack the ability to hold and manipulate the information omit crucial information that guides their actions and encounter difficulties in completing the task. This group of students is identified to have low WMC (Gathercole et al., 2004; Yuan, Steedle, Shavelson, Alonzo, & Oppezzo, 2006).

Among various science concepts stoichiometry is one of the abstract and most difficult topics in chemistry for students to comprehend (Dahsah & Coll, 2007). This is because, in stoichiometry, students learn concepts that are invisible to human eyes such as mole, chemical formulae, and equations (Hafsah, Rosnani, Zurida, Kamuruzaman, & Yin, 2014). These fundamental chemistry concepts are essential for students to further their study in chemistry (Dahsah & Coll, 2007). In learning stoichiometry, students are required to understand the definition of mole and utilize higher-level thinking skills in solving stoichiometry task (Dahsah & Coll, 2008; Gulacar, Damkaci, & Bowman, 2013). For example, students need to acquire the knowledge mole as a unit of measurement that describes the number of atoms, molecules, and ions in any substances. Students learn to integrate their understanding of mole in writing the chemical formula using subscripts and understand that the chemical equation is a symbolic representation of the chemical reaction. Later this knowledge is applied in solving problems that require conversion of mole-mass-mole and balancing equations. As such ability of the students to retrieve and manipulate information delivered in the classroom teaching is paramount importance. In other words, WMC determines the ability of the students in solving stoichiometry problems.

Solaz-Portales and Sanjose-Lopez (2009) asserted that students successfully solve the problems when the mental demand (steps involved in solving the problem) is lesser than the WMC. Overloading of WMC happens when the demand to solve the problem is above the students' abilities to hold, retrieve, and manipulate information (Smith, Sáez, & Doabler, 2016). In such situations, students' information processing capacity declines. Subsequently problem-solving capacity of the students' decreases. This happens because, in the case of overloading WMC, the brain loses the efficacy to maintain critical information and inhibit irrelevant or misleading information (Solaz-Portales & Sanjose-Lopez, 2009).

Hafsah et al. (2014) reported Malaysian students having difficulties to understand stoichiometry concepts because the students lack problem-solving ability. The learners encounter difficulties in solving problems dealing with conversions of mole-to-mass, the role of limiting reactant, writing a chemical equation, and identifying the composition of stoichiometry. Solving problems on stoichiometry requires students to know chemical formulae of the substances, writing a balanced chemical reaction, knowing the mass and moles of the substances. Hence, solving stoichiometry problems involves processing a large amount of information (Gulacar et al., 2013). Probably, the students have inadequate ability to hold, retrieve, and manipulate large amount of information. In other words, the mental demand of the stoichiometry problems is higher than the WMC of the students. The overloading of WMC explain the difficulties faced by Malaysian students in solving stoichiometry problems.

Teaching methods that heavily relies on delivering facts frequently result in overloading of WMC. This is because a huge amount of information is given during the short duration of the lessons. Working memory with limited space unable to store the large amount of information, although the attentional priority and saliency of the subject affect WMC (Li, He, Wang, Hu, & Guo, 2017). This results in the loss of valuable information, and at the same time, the working memory loses processing power (Smith et al., 2016). When the processing power is depleted students tend to be confused (Solaz-Portales & Sanjose-Lopez, 2009).

On the contrary, the processing power of the working memory is enhanced if the information is acquired in a meaningful way (Li et al., 2017). When the students are provided with opportunities to analyze, evaluate critically, and synthesize, the information is organized in a coherent manner that is intelligible to the learners (Smith et al., 2016). As such, teaching strategy determines the storage of information in the working memory and the ability to hold, retrieve, and manipulate the information.

Association between working memory and learning is well established (Baddeley, 2017). Specifically, in science education, working memory is referred to as a constructive operator for problem-solving and predictor for academic achievement (St Clair-Thompson et al., 2012). Stoichiometry is one of the challenging topics in chemistry among secondary school students as stoichiometry profoundly involves a problem-solving task that requires high mental demand. This study used the lens of WMC to "research" students' learning of stoichiometry with the intention that the findings of the study informs the teachers in planning their lessons.

Aim

Review of the literature depicts that students' WMC has paramount importance in learning, particularly in solving problems that require the use of thinking skills. Studies also proposed that it is essential for the teachers to use strategies that encourage the building of WMC specifically in teaching scientific concepts such as stoichiometry. This is because stoichiometry inherently deals with solving problems. Hence, this study is aimed at investigating Form Four science stream students' WMC and exploring the consideration of working memory in the current teaching and learning of stoichiometry. The findings of this study would be informative in planning for teaching considering the students' WMC.

Methodology

Research Design

The mixed method research design was used in this study. The quantitative method was implemented to collect numerical data on the level of students' working memory using The Cambridge Neuropsychological Test Automated Battery (CANTAB). Qualitative interview data were collected individually from two teachers and six students to explore whether working memory forms an integral part of current teaching and learning of stoichiometry concepts in the classroom.

Sample

The targeted population of this study was the Form Four (16–17 years old) Science stream students in the state of Penang, Malaysia. A total of 80 students from three classes from one government funded secondary school participated in this study. Government funded secondary schools located in urban areas throughout the country share many commonalities. These include the availability of teaching and learning facilities, enrollment of students, training of the teachers, and the school environment. For this reason, a conveniently located school was identified to participate in the study. As the researcher does not have the authority to choose the participating classes, all three Form Four science stream classes in the school participated in the study. As such, intact group sampling was used in this study (Gay, Mills, & Airasian, 2009). For the interview, six students were purposefully selected. From each class, two students who were able to clearly describe the teaching that executed during the lessons and how the teaching impacted their learning were interviewed. The two chemistry teachers teaching chemistry for the three classes were interviewed.

Instruments

The Cambridge Neuropsychological Test Automated Battery (CANTAB) is a cognitive assessment tool used for measuring the role of specific brain functions across a range of disorders and syndromes (Atkinson, 2015). The CANTAB was administered immediately after completing the lessons on stoichiometry prior to the interview to ensure that WMC reflects on the stoichiometry lessons. Beattiea, Schutteb, and Cortesa (2018) measured the WMC immediately after completing mathematic tasks to avoid interference from other factors. Similarly, in this study, following Beattiea's et al. (2018) strategy CANTAB was administered after the lessons on stoichiometry to avoid interferences from other factors that possibly influence the WMC of the students.

CANTAB has been widely used and reported reliable to be used to measure the working memory capacity of an individual (Luciana, Conklin, Hooper, & Yarger, 2005). There are eight memory tests included in CANTAB, but only the Spatial Working Memory test (SWM) was used in this study. This is because SWM measures delayed responses to the tasks in retaining and manipulating information regarding the task (Beattiea et al., 2018). The ability to retain, retrieve, and manipulate information implies on the WMC of the individual (Constantinidis & Klingberg, 2016). Hence, SWM measures portray the WMC of the student. As the SWM test was administered immediately after the lessons on stoichiometry and students were informed to refer to the lessons on stoichiometry in responding to the test, the ability of the students to hold, retrieve, and manipulate the information or WMC displayed infers on the stoichiometry.

SWM measures students' ability in using strategies to hold and manipulate the displayed information. The lowest level of difficulty involves 4 boxes, and the highest level involves 8 boxes. In solving the problem, students will be shifting from the lowest to the highest level. For the purpose of this study, the lowest is 4 and the highest is 8 boxes. The errors made in solving the problem reflected from SWM values. SWM between error score depicts the errors made in solving the problem involving 4 boxes. SWM's total error score portrays the accumulation of the errors in solving 4, 6, and 8 boxes problems.

The test began with the screen showing several colored square boxes as in Fig. 13.1. The participants should find the colored box with blue "token" and drag them to fill up an empty column on the right-hand side of the screen (Fig. 13.1). The test starts with four colored boxes and progressively increased to eight colored boxes. The number of blue "token" that should be found is parallel to the number of the colored box. The students need to find the blue "token" and drag it to the corner. For instance, in the 4 boxes problem, after trial and error, when one blue "token" was found, the students dragged the identified blue "token" to the side. Now the screen will be showing three boxes. Blue "tokens" are available in one of the three boxes. When the blue "token" was successfully found it will be again dragged to the corner. As two blue "token" have been dragged to the side, the left two colored boxes will appear on the screen. The students repeated the same strategy (trial and error) as

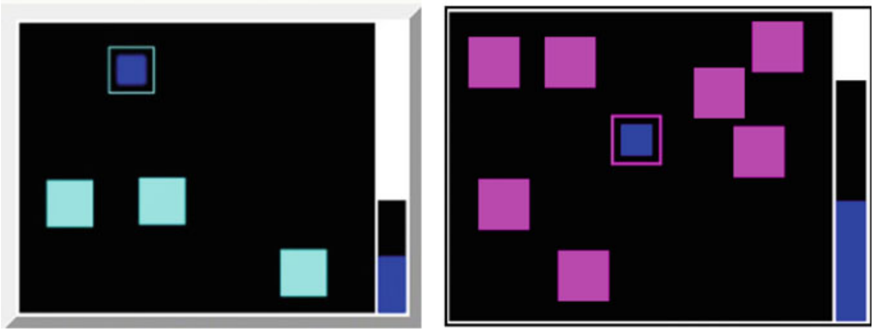

Fig. 13.1 The SWM test screen with 4 boxes and 8 boxes

earlier until all the four blue "tokens" were found. Then the problem will be shifted to the next level involving 6 boxes problems subsequently to 8 boxes. In the attempt to locate the blue "token", revisiting the same box indicates an error. It shows that the student unable to remember that they have visited the box. SWM between error score indicates a number of errors made or the number of time revisiting happen in solving the problem at the same level. SWM total error score indicates the sum of SWM between error scores obtained from 4, 6, and 8 boxes. SWM's total error score indicates the total number of times the boxes are revisited throughout solving the problem. The high scores and mean values for SWM between errors and SWM total errors represent poor memory (Beattiea et al., 2018; Schutte et al., 2017). Beattiea et al. (2018) mentioned that the presence of distractors and attention influence the SWM scores. The SWM between and total error scores will be lower if the students were trained to ignore distractors, and focused on the targeted location (Schutte, Keiser, & Beattie, 2017).

Interview Question

Semi-structured face-to-face interviews were conducted with teachers and students. Interview session with each person lasted for 20 min. First, a general question was posted. The teachers were asked to describe how they usually teach stoichiometry lessons and the students were asked to explain how the lessons on stoichiometry were usually taught. The teachers were further prompted with questions like what kind of activities they usually integrate into stoichiometry lessons, the depth of the syllabus and the time allocated to complete the lessons on stoichiometry. The students were prompted with questions like asking them to specify the activities used, whether the activities motivated them to learn and the depth of content covered. The questions mainly derived from suggestions to measure working memory from Kaufman (2010).

Pilot Study

A pilot study was conducted to validate the CANTAB and interview questions. For this purpose, a total of 30 students and 3 teachers from a neighboring school participated. A brief instruction was given to the students on how to perform the task using CANTAB. The students one by one were later asked to complete the task. The students said that the instruction provided by the researcher is explicit and they were able to perform the task in CANTAB. Initial testing of interview questions revealed that the questions appeared general. The three teachers were of the opinion in order to identify WMC; interview questions are required to provide detailed information. Based on the teachers' suggestions in the pilot study, the interview questions were revised.

Data Analysis

Spatial Working Memory (SWM)

SPSS (Statistical Packages for Social Science) version 22 was used to measure the frequency distributions, the standard measures of central tendency (mean), and the standard measures of dispersion (standard deviation) of the scores from CANTAB. SWM between errors and total errors for each participant was automatically calculated by CANTAB and transferred to SPSS to calculate the mean value for the SWM between errors and SWM total errors.

Interview Analysis

Guideline on thematic analysis as proposed by Braun and Clarke (2006) was used to analyze the interview responses obtained from the teachers and students. The definition for WMC provided by Gathercole and Alloway (2008) guided the thematic analysis conducted according to six steps as proposed by Braun and Clarke (2006). A total of three chemistry teachers were involved in all the six steps during the analysis. The first step of the analyses is transcribing and familiarizing the data. For this purpose, the data was re-read many times, and the response that implies on WMC was extracted from the transcripts. In the second step, the responses that render WMC were assigned to codes. In the third step, the codes were merged into subcategories and later into categories. The theme generated was reviewed to ensure the codes and categories match the themes in the fourth step. In the fifth step, the categories were given specific names, and finally, the thematic maps were produced in the sixth step. From the analysis performed in the six steps, the theme "overloading of WMC" emerged. Figure 13.2 illustrates the thematic map produced from the analysis of interview responses.

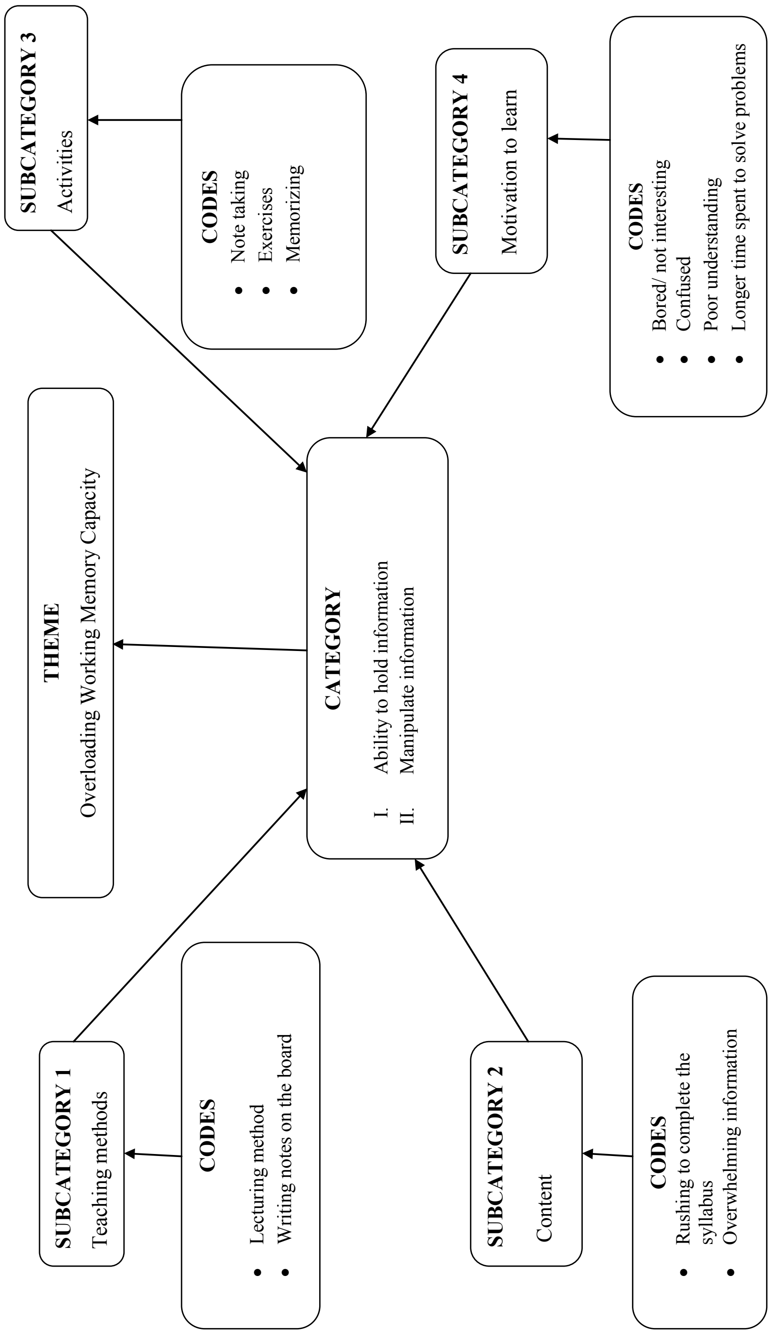

Fig. 13.2 Thematic map obtained from the analysis of interview responses

The transcript with interview responses was provided to the teachers. The teachers worked individually in assigning the codes into subcategories and categories. The teachers later met and compared their analysis. Decisions at each stage were made after the teachers reached an agreement over their discussion. For instance, as shown in Fig. 13.2, the codes such as "lecturing method" and "writing notes on the board" emerged from the transcript were grouped into teaching methods, i.e., subcategory-1. The codes "rushing to complete the syllabus" and "overwhelming content" identified from the transcript constitute subcategory-2. For subcategory-3, the code that implies the activities performed in the classroom includes "note taking", "exercises", and "memorization". In subcategory-4, motivation to learn is exemplified by the codes "bored", "confused", "poor understanding", and "longer time spent on problem-solving". The four subcategories cumulatively explain the categories (ability to hold and manipulate the information) which constitute the theme "overloading of WMC".

Results

Data presentation begins by presenting 80 participants' working memory capacity as "SWM between errors (4 boxes)" and "SWM total errors (8 boxes)". The high scores of "SWM between errors (4 boxes)" and "SWM total errors (8 boxes)" represent poorer use of the strategy to solve the task (Atkinson, 2015).

Table 13.1 presents the findings of the descriptive analysis of SWM between errors and SWM total errors. For SWM between errors involving 4 boxes, the lowest score obtained was 0, and the highest score is 10. A low mean score (M = 1.04; SD = 1.965) was obtained for SWM between errors. A lower mean score indicates the students made fewer errors and used effective strategies to solve the task. For SWM total errors involving 8 boxes, the lowest score obtained was 0, and the highest score is 75. The mean score for SWM total errors (M = 26.93; SD 16.03) indicates that most students have committed many errors and used poor solving problem strategies.

Figure 13.3 shows that data is not uniformly distributed and positively skewed. The data reveals that more than 40 students scored 0 errors in solving the task involving four boxes. This means that many of them have used an effective strategy in completing the task. According to Atkinson (2015), if the distribution is positively skewed, as in the case of Fig. 13.3, this implies an effective use of strategy in solving problems. Lower errors score also indicates that participants' working memory capacity

Table 13.1 Descriptive statistics of "SWM between errors" and "SWM total errors"

	SWM between errors (4 boxes)	SWM total errors (8 boxes)
Low score	0	0
High score	10	75
Mean	1.04	26.93
Std. deviation	1.97	16.03

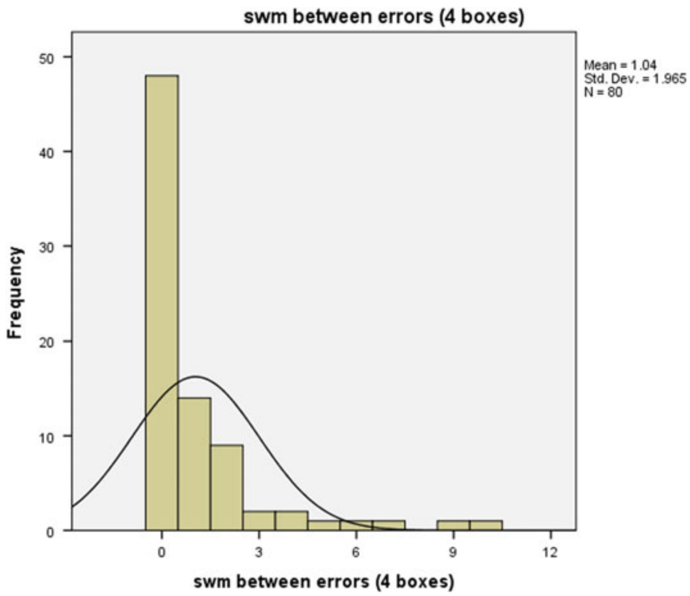

Fig. 13.3 Bar chart of SWM between errors (4 boxes)

is generally high (Atkinson, 2015). As such the students possess the ability to retain and manipulate more information.

When the number of boxes was increased to eight (Fig. 13.4), it was observed that many students committed more errors. From Fig. 13.4, it is noticed that the data presented in the bar chart is normally distributed. The data in Fig. 13.4 reveals that the majority of students committed 20–40 total errors with 12 students committing most errors (the tallest bar). This indicates that the students frequently attempted the "trial and error" approach to find the blue box and the students' working memory capacity was considered as average (Beattiea et al., 2018; Schutte et al., 2017).

Interview Findings

From the analysis of both students' and teachers' responses, the theme "low and overloading of working memory capacity" emerged. T1 and T2 refers to teacher 1 and teacher 2 respectively. T1 claimed that she frequently explains the concepts in detail first and then she provides examples reflecting the application of the definition. For instance, she provides the definition for a mole, followed by explaining the definition with some examples. T1 further said that students would be taking note of the important points. She will also write down the crucial points on the whiteboard to ensure students do not miss any information and pay more attention to the points that she has highlighted. Similar to T1, T2 also said that the lecturing method

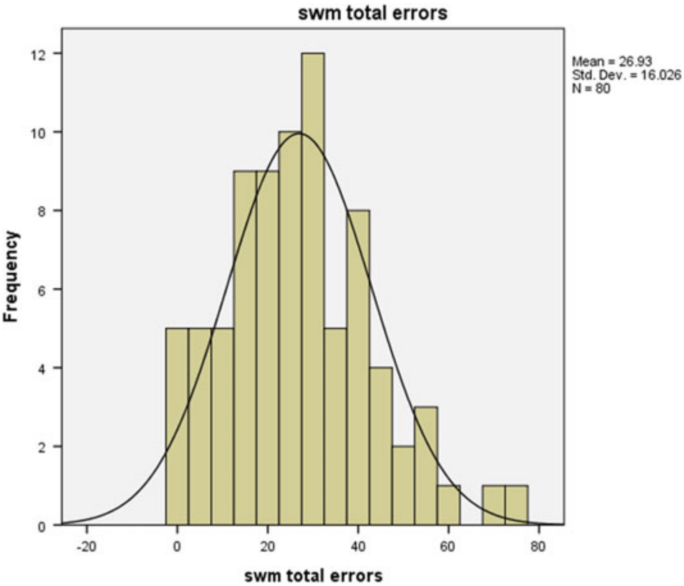

Fig. 13.4 Bar chart of SWM total errors (for 8 boxes)

dominates her class. T2 asserted she would begin the lesson explaining what a mole is. She explains mole in terms of ions, atoms, and molecules. Then she provides some examples and exercises. The teacher-centered approach used by T1 and T2 does not permit students to hold information in working memory. This explains the overloading of WMC occurs during the teaching.

T1 justified her claim for using lecturing method saying designing and implementing classroom activities takes more time. This will further delay completing the syllabus as she needs to cover mole concepts, relating mole and mass and linking mole with ions, molecules, and atoms. T2 reflected similarly and said time does not permit for having activities as she will be in a rush to complete the syllabus in time to prepare the students for the examination. Responses of T1 and T2 depict that time constraint is the reason for having teacher dominated teaching strategies and the need to cover the wider range of content results in opting for short ways of teaching the lessons. Addressing the overwhelming amount of content in a stipulated time apparently does not provide space for the students to manipulate the information. This is another factor that contributes to the lower and overloading of WMC.

The analysis of responses also revealed that note taking, and simple exercises are some of the activities given by T1 and T2 in the class. These kinds of activities are simple and less demanding. Hence, engaging in these activities does not require retrieving and manipulating the stored information. Simultaneously, T1 and T2 said that the students passively engaged in learning and students take a longer time to solve the given problem. Passive engagement portrays that students' motivation to learn the content is minimal.

From the students' viewpoint, all the six students were of the opinion sitting passively and taking notes is boring and these are the activities they normally performed during stoichiometry lessons. S3 particularly said that he is less motivated to learn because the lessons are boring and S4 and S5 added they are bored as well because the lessons are not interesting. S2 and S6 further added saying the teacher teaches very fast and most of the time we are confused. From the students' responses it could be postulated that they appeared less motivated to learn the content, the activities are less interesting, the strategy used failed to engage them in learning, and vast content coverage in a shorter duration contributes to the poor ability to hold and manipulate information (Holmes, Gathercole, & Dunning, 2010). Subsequently, this leads to lower or overloading of WMC.

Discussion

This study documents WMC of Form Four science students and how working memory is reflected in current teaching and learning of stoichiometry from students' and teachers' perspective. The lessons on stoichiometry were focused in this study mainly because stoichiometry is an abstract concept. Stoichiometry involves learning about moles, conversion of moles of ions, atom, and molecules to mass. Particularly, solving stoichiometry problems would not be successful if the concepts were understood in a compartmentalized manner. The students should have the analytical, critical, and creative skills in solving the problems (Gulacar et al., 2013). For the students to apply these skills, the teaching and learning activities in the stoichiometry lessons should consider students' WMC. The information should be presented in a logical sequence, for the knowledge to be easily extracted to use in solving problems that require different thinking skills (Raghubar et al., 2010).

The quantitative finding of this study shows that students tend to commit more errors in solving complex tasks. This is reflected from the higher SWM total errors involving eight boxes than the lower errors identified in the task with 4 boxes. The findings indicate that when the difficulty level of the task increases the students unable to retrieve and manipulate the stored information effectively. This circumstance relates to lower WMC (Gathercole & Alloway, 2008). The WMC of the students appears lower when the complexity and the difficulty of the task increases. The notion that more errors are committed in complex task corroborates with Solaz-Portales and Sanjose-lopez (2009) assertion that students were unsuccessful in solving complex questions (involving more steps) because the mental demand of the task is higher than the WMC.

The interview responses revealed the shreds of evidence that the lessons contribute to the overloading of WMC. The dominating teacher-centered strategy to deliver overwhelming content in a shorter duration affects the information processing capacity when the working memory is overloaded (Opdenacker et al., 1990). The unstructured way of note taking results in failing to retain information and possibly losing valuable information in working memory (Klingberg, 2009). As reviewed in the literature, large amount of content leads to demanding information processing. When this happens, students are unable to capture and retain the entire information. Consequently, students fail to hold and manipulate information during the learning process. This situation is parallel with Ashcraft and Kirk's (2001) assertion that exceeded information lays heavy demand on the capacity of working memory and disrupts working memory sufficiently to recall the existing knowledge.

Conclusion

Previous studies have evaluated students' WMC (Redick, Broadway, Meier, Kuriakose, Unsworth, Kane, & Engle, 2012) and highlighted the importance of WMC in teaching abstract subjects like mathematics (Raghubar, Barnes, & Hecht, 2010) and problem-solving ability of the students (Alloway & Alloway, 2010; Constantinidis & Klingberg, 2016). In this study, an attempt was made to revisit the role of WMC in teaching and learning of stoichiometry. This is because stoichiometry involves learning a highly abstract concept. In teaching the concept, a mere teacher-centered approach will result in students facing greater difficulty as reported in some studies (Osman & Sukor, 2013; Wright, 2011). The findings of this study inform that the teachers to some extent ignored the WMC of the students in learning stoichiometry concepts. The strategy used by the teacher should permit easy processing of information to order for the students to solve the problem. Easy processing depicts that students are able to use many skills at a time (Raghubar et al., 2010). For this to happen, teachers should avoid overloading of WMC which subsequently results in the students having lower ability to process the information in working memory (Alloway & Alloway, 2010; Gatherole & Alloway, 2008).

The SWM scores reported through this study reveals that students have committed many errors in completing the task. As the SWM scores depict the ability of the students to hold, retain, and manipulate information, the low score exhibits low WMC of the students. The lower WMC explains the reasons for the difficulty students encounter in solving the stoichiometry problems (Dunning, Holmes, & Gathercole, 2013). The teachers' intention to complete the syllabus and prepare the students for examination refrained them from using strategies that allow students to hold, retain, and manipulate the information. The teachers' action subsequently results in the students having lower WMC.

The study exhibits several limitations. Since the students and teachers participated in the study were from one school, the findings lack generalization. For the findings to generalize to a wider range of population the study is recommended to be repeated with students and teachers from more schools. Additionally, Onwuegbuzie and Teddlie (2003), suggested including more schools and students to have better control of the external variables and improve the internal validity to yield the same result. Challenges were also encountered in quantitative data collection due to the limited availability of CANTAB. For this reason, the researchers had to collect data after the formal schooling hours to ensure the data collection was performed promptly after the lessons on stoichiometry to avoid other interferences.

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