THE IMPACT OF PHYSICAL MOLECULAR MODELS ON STUDENTS' VISUO-SEMIOTIC REASONING SKILLS RELATED TO THE LEWIS STRUCTURE AND BALL & STICK MODEL OF AMMONIA

Abstract. *Visuo-semiotic models, such as Lewis structures and ball & stick models, are widely used to enhance students' learning. However, there is limited research about the impact of these models on specific visuo-semiotic reasoning skills. In the current research, we aimed to determine the extent to which physical molecular models could enhance specific visuo-semiotic reasoning skills among students. The research question that we explored was, "what is the impact of physical molecular models on Grade 11 students' visuo-semiotic reasoning skills related to Lewis structures and ball & stick models of ammonia?" In this mixed-methods research, we collected data from purposively selected Grade 11 chemistry students aged between 15 and 18 from an under-resourced school in South Africa. Through a quasi-experimental design, participants in the experimental group (n = 101) used physical molecular models to learn about Lewis structure and ball & stick models of ammonia while participants in the control group (n = 100) did not. We subsequently tested students' visuo-semiotic reasoning skills. Results show that using physical molecular models significantly improved students' visuo-semiotic reasoning skills and reduced associated learning difficulties. We, therefore, recommend that these models should be used as an instructional tool to enhance learning.*

Keywords: *ball & stick models, Lewis structures, physical models, visuo-semiotic reasoning.*

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Introduction

Research in science education attempts to ensure that teaching and learning are regularly revised through reflective practice. This reflection is driven by various theoretical, philosophical, and practical questions that inform research. Schunk (2012) suggested that there are some critical questions about learning that must be asked by teachers, curriculum, and instructional designers for teaching and learning to be effective. Among these, two questions that are relevant to the current paper are, "how does learning occur, and what factors influence learning" (Ertmer & Newby, 1993, p. 53). While Schunk first raised these questions almost three decades ago (in Schunk, 1991), their relevance to curriculum and instructional design is still essential. For example, the rise of technology-enhanced classrooms means researchers in the 21st century must revisit these questions to ensure that technology supports teaching and learning rather than impede it. Ertmer and Newby (1993, p. 53) suggested that based on answers to the above questions, an added question must be asked, i.e., "how should instruction be structured in order to effectively facilitate learning"? Considering the poor student performance in science subjects in countries such as South Africa, one wonders whether these questions have been answered to inform instructional design. For example, South Africa continues to be ranked low compared to other countries on education and skills, quality of primary education, and the quality of mathematics and science education (Mnguni et al., 2019; Schwab, 2016). In this regard, researchers have explored factors that affect student performance extensively (e.g., Jama et al., 2019). However, not much has been done to interrogate teaching methods and tools used by teachers concerning modern theories of teaching and learning. We, therefore, explored the use of physical molecular models in teaching within the context of cognitivism. The findings of this research could expand our understanding of learning and factors that affect it.

Learning as a Cognitive Phenomenon

Learning in science education, including chemistry education, could be understood through several theoretical perspectives, including cognitivism. According to cognitivism, learning involves cognitive processes through which knowledge is transformed into discrete forms (Ertmer & Newby, 1993). Such learning involves transformation, rehearsing, storage, and retrieval of information, which leads to changes in the state of knowledge as it is being coded and decoded in the cognitive structures. Cognitivism attempts to explain what students do during learning in addition to what they can do because of learning and the learning environment in which learning takes place. In this instance, the learning environment, which also facilitates learning, includes the "instructional explanations, demonstrations, illustrative examples and matched non-examples which are all considered to be instrumental in guiding student learning" (Ertmer & Newby, 1993, p. 58). Teaching and learning models, such as physical molecular models, therefore, form part of the learning environment.

The significance of physical molecular models in science education can be understood through embodied cognitivism. According to embodied cognitivism, learning occurs in the cognitive structures, including various parts of the body, such as the integrated motor and perceptual systems, which are intricately connected to the matrix of cognitive, affective, and psychomotor domains (Thelen et al., 2001). It follows that effective learning should involve various parts of the body both for assimilation and dissemination of information. For example, Sternberg (2003) suggested that information is cognitively coded in at least two forms, namely, as analogue and symbolic codes. The analogue codes are used to process and store information as mental representations of images, while the symbolic codes are used to store information as mental representations of words (Sternberg, 2003). Related to this, Clark and Paivio (1991) suggested that learning is the process of creating associative networks of verbal (analogue) and imaginal (symbolic) representations. Learning in this regard leads to the creation of links between verbal and imaginal mental representations as well as within these representations to create and continuously develop a complex network of verbal and imaginal mental representations. The effectiveness of learning can be determined through the assessment of the extent to which students can construct and express these networks of verbal and imaginal mental representations.

The Role of Visuo-Semiotic Models in Learning

To facilitate the creation and development of verbal and imaginal mental representations, researchers (e.g., Mayer & Mayer, 2005) recommend the use of multimedia learning resources for teaching and learning. These resources could include visuo-semiotic models, which are defined "as visual models that use discipline-specific semiotics to represent scientific phenomena for research, teaching, and learning" (Mnguni, 2019, p. 1). They include a wide variety of models, such as physical models, paper-based 2D models, printed 3D models, or computer and virtual models. By nature, some of these are static, while others are dynamic, such as computer animations and simulations. These models could be used to represent phenomena that exist at multiple macroscopic levels (e.g., the universe), microscopic level (e.g., bacteria), or molecular level (e.g., genetic materials).

Recent research has shown that visuo-semiotic models, such as physical molecular models, can enhance learning. For example, Newman et al. (2018) showed that physical molecular models could improve student learning because they engage various receptor sense organs through which information is internalized. This includes internalizing information through visual perception, aural perception, as well as haptic perception. Terrell et al. (2019), also suggested that physical molecular models, such as 3D printed models, could enhance students' ability to construct mental models as well as their conceptual and visual development. Bareither et al. (2013) showed that using physical models, such as clay models, could enhance learning as it accommodates students with learning styles that may not be accommodated through traditional teaching methods such as paper-based teaching methods. They argue that "multiple teaching modalities may accommodate learning preferences and improve understanding" (Bareither et al., 2013, p. 170). This research supports earlier research, which showed that pedagogical strategies that involve "active-engagement learning strategies result in higher learning gains and reduce the chance of failure compared with lecture-only approaches" (Newman et al., 2018, p. 436).

Multiple teaching modalities, however, bring about the challenge of representational competence, which may be deficient in some students. Representational competence refers to the ability to understand and use diverse representations of a scientific concept (Hinze et al., 2013; Kozma & Russell, 1997). "Representational competence requires, among other skills, the ability to differentiate the purposes of different representations and to understand

when and why to use one representation over another" (Hinze et al., 2013, p. 13). Students' visuo-semiotic reasoning, as a form of representational competence related to multiple representations, therefore, is a critical part of cognitive learning which students must have to learn with visuo-semiotic models effectively.

Research Problem

While research shows that physical molecular models improve learning, as discussed above, based on the overall student performance in related assessment tests, there is a dearth of knowledge about the impact of these models on specific reasoning skills. For example, within the context of the dual coding theory, there is limited research to explain the extent to which physical molecular models could facilitate the development of "networks of verbal and imaginal representations" (Clark & Paivio, 1991, p. 151). Clark and Paivio (1991) argued, for example, that effective learning involves the creation of referential connections between visual symbolic imagery and verbal analogue codes, as well as associative connections between and within the verbal and nonverbal systems. There is also limited research to explain the extent to which physical molecular models could enhance students' visuo-semiotic reasoning. Mnguni (2019, p. 4) defined visuo-semiotic reasoning as the "ability to internalize, conceptualize, and externalize scientific knowledge through the use of visuo-semiotic models and discipline-specific semiotics representing" discipline-specific content (Mnguni, 2019, p. 4). It includes various cognitive skills, such as analyzing, interpreting, and generating visuo-semiotic models. Research is, therefore, necessary to determine the impact of learning models, such as physical molecular models, on specific aspects of reasoning skills. Such research could help teachers in developing learning environments that could enhance cognitive development among students.

Research Aim and Research Question

In the current research, we aimed to determine the extent to which the use of physical molecular models could impact specific visuo-semiotic reasoning skills among students. In this instance, we were not concerned with the overall performance of students in a content knowledge test, but we were interested in their ability to perform specific visuo-semiotic skills. These skills were interpreting and drawing Lewis structure as well as ball & stick structure of ammonia. These structures are used as a teaching aid as they represent atoms, bonds, lone pairs, unpaired electrons, and a formal charge of molecules that would otherwise be difficult to visualize with an unaided eye (Cooper et al., 2010). In the current research, we explored the visuo-semiotic reasoning skills (drawing and interpreting visuo-semiotic models) as a preliminary effort to understanding the impact of physical molecular models on visuo-semiotic reasoning, as findings would inform future research in this context. The research question framing the current research asked, "*what is the impact of physical molecular models on Grade 11 students' visuo-semiotic reasoning skills related to Lewis structure and ball & stick model of ammonia*?"

Theoretical Framework

Mnguni's (2019) framework for the development of a visuo-semiotic reasoning test instrument framed the current research. Mnguni (2014) suggested that learning from visuo-semiotic models occurs in three interrelated stages, which may occur simultaneously. The first stage is concerned with the "inputting of information from the external world into the cognitive structures." The internalization of visuo-semiotic information is characterized by feature extraction, target detection, region tracking, and counting, which could require minimal cognitive effort. Some researchers suggest that the internalization of visuo-semiotic information requires first-order stimuli and second-order stimuli (e.g., Baloch et al., 1999). In the first-order stimuli, feature extraction is based on luminance, while contrast and texture characterize feature extraction. This suggests that less cognitive resources may be used to process visuo-semiotic models in the case of first-order stimuli. Second-order stimuli play a significant role in the processing of 2D and 3D models where the relative depth of overlapping surfaces is essential to determine the position of objects, such as when a model depicts different molecular geometry of molecules. Mnguni (2014) defines the second stage as the conceptualization of visuo-semiotic information, where students make sense of visuo-semiotic information. In the conceptualization stage, cognitive effort and cognitive resources are used to interpret the external stimuli as the information pass through the sensory memory into the working memory (van Schoren, 2005). At this stage, information extracted from the visuo-semiotic model is selected and organized into mental representations (Chalmers et al., 1992). The third stage is the externalization of visuo-semiotic information.

Here information stored in the long-term memory is retrieved and externally expressed as external visuo-semiotic models verbally or visually. In this instance, students may use spoken and written words, or produce graphical representation to express information stored in the memory.

Other researchers (e.g., Mnguni et al., 2016; Schönborn & Anderson, 2010) have found various skills that may be used in the distinct stages of visuo-semiotic reasoning. For example, Schönborn and Anderson (2010) showed various broad visualization skills that are used by students in molecular biology. These include decoding the symbolic language composing a representation, interpreting, and using a representation to solve a problem, spatially manipulating a representation to interpret and explain a concept, constructing a representation to explain a concept or solve a problem, and, translating across multiple representations of a concept (Schönborn & Anderson, 2010). Mnguni (2018) identified individual skills that may be used by students when learning biological concepts. These include analyzing, interpreting, and drawing visuo-semiotic models.

In the current research, our focus was on assessing students visuo-semiotic reasoning with specific reference to two visuo-semiotic reasoning skills, namely, interpreting and drawing visuo-semiotic models. Using Mnguni's (2018) definitions, 'interpreting visuo-semiotic models' was defined as systematically breaking down a visuo-semiotic model into its essential features to translate its discipline-specific visual cues and make sense of its characteristics. 'Drawing visuo-semiotic models' was defined as generating visuo-semiotic illustrations that correctly depict scientific concepts using discipline-specific semiotics. Within the current research, the focus was on Lewis structures as well as ball & stick models of ammonia. We wanted the students to either interpret or draw these visuo-semiotic models.

Research Methodology

General Background

Creswell (2014) suggested that research methodology refers to the philosophical and theoretical perspectives that frame research methods, techniques, paradigms, approaches, and design of a research study. This view is supported by Somekh and Lewin (2005, p. 346) who stated that research methodology is "the collection of methods or rules by which a particular piece of research is undertaken" as well as the "principles, theories, and values that underpin a particular approach to research." Similarly, Mackenzie and Knipe (2006, p. 5), posited that research "methodology is the overall approach to research linked to the paradigm or theoretical framework while the method refers to systematic modes, procedures or tools used for collection and analysis of data." The current researchers followed the research design described below and were guided by the theoretical framework described above.

Research Design

The current researchers adopted a realism research paradigm described by Creswell (2014), where knowledge is generated through mixed methods to enhance the validity and reliability of the research findings. With regards to the quantitative methods aspect of the research, phenomena are described within a sampled population from which inferences to a larger population are made. In this instance, we used a quasi-experimental research design that utilized a content knowledge test as an instrument for data collection from a purposively selected sample of participants. Data analysis was guided by the classical test theory, which suggests that a respondents' observed score on a test is equal to the sum of their true score and error score. It, therefore, relies on the measure of reliability and validity to generate logical findings. Qualitative data, from the interviews, were not used to confirm quantitative data, but to explain them through an explanatory mixed method format. In this instance, the items in the interview protocol asked participants to explain their responses to the quantitative responses concerning learning difficulties associated with visuo-semiotic reasoning.

Research Context and Sampling

Data were collected from a purposively selected group of Grade 11 chemistry students from two township schools in Witbank, South Africa, in 2019. The schools were purposively selected because they are under-resourced government township schools that did not have teaching resources such as science laboratories, smart boards, or mobile computers for teaching and learning. The underlying assumption, therefore, was that, within the context of formal education, students from these schools had not been exposed to teaching and learning aids such as

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computer-based models or physical molecular models. Participants were all aged between 15 and 18. The participants were randomly assigned to the experimental group ($n = 101$) and the control group ($n = 100$). The sample sizes reflect the total number of learners who were doing chemistry in Grade 11 in the selected school and thus purposively selected. However, we considered Gogtay's (2010, p. 518) formula ($n = [(Z_\alpha + Z_\beta)^2 \times \sigma^2]/d_2$) for estimating the minimum sample size required for two means in quantitative data in determining the suitable minimum sample size. In this regard, we wanted to determine the number of students required at 80% power and 5% significance with an effect size of 0.2, to detect an average difference with a standard deviation of 30%. Using Gogtay's (2010) formula, we calculated the minimum sample size required to be 24. Therefore, the sampled sizes of 100 and 101 were considered adequate. The 100 and 101 participants responded to the quantitative content knowledge test. Of these, we randomly selected 10% from either group to take part in the interviews.

Data Collection and Analysis

During the research, the two groups of students were taught the characteristics of molecules, and chemical bonds related to geometric shapes by the same teacher, who was not a researcher in the current research. Ammonia was used as an example, specifically, the Lewis structure and ball & stick model of ammonia. In the control group, students were taught using summary notes, a textbook, and worksheets accredited by the Department of Basic Education. These resources had written text, pictures, and diagrams that were used to explain and describe concepts. In the experimental group, students were taught using physical molecular models as an added teaching resource. These models depicted both the three-dimensional position of the atoms and the bonds between them. They used distinct colors to depict different atoms and bonds. Students who worked with these models worked in pairs, with each pair having its own set of models. The same teacher taught in both groups.

After the lessons, students in both groups were given a content knowledge test assessing their ability to interpret and draw a Lewis structure and ball & stick model of ammonia. The teacher administered the test. However, we developed and validated it through a panel of experts and a pilot group. The purpose here was to enhance the face, content, and criterion-related validity of the instrument. From the nine experts who validated the instruments, a content validity index of 87% was obtained, which suggested that the instrument was 'fit for purpose.' The pilot group was also able to complete the test within 30 minutes, and no technical or content related concerns were raised. Given the content validity index from the panel of experts and the fact that the students in the pilot group were able to complete the tests, the researchers were, therefore, satisfied that the instrument was valid. We used the pilot data to calculate the reliability coefficient. Here a Cronbach alpha coefficient of .782 was obtained, suggesting that the instrument was statistically reliable. All data were then analyzed quantitatively using SPSS and qualitatively to determine the impact of the physical molecular models on students' visuo-semiotic reasoning skills related to the Lewis structure and ball & stick model of ammonia. After the analysis of the data from the test, an interview protocol was developed through which participants would explain their responses in the test and discuss learning challenges related to interpreting and drawing a Lewis structure and ball & stick model of ammonia. We validated the interview protocol in the same way as the test.

Research Results

Impact of the Physical Model on Visuo-Semiotic Reasoning Skills

Results showed that in the control group, students performed poorly in all items (Table 1). The average visuo-semiotic reasoning score in this test was 27.44 ($SD = 21.42$). Students scored the lowest on the items asking them to interpret Lewis structures ($M = 16.5$, $SD = 15.73$) as well as ball & stick structures ($M = 19.75$, $SD = 26.42$). The performance was best on items that asked students to draw a Lewis structure of ammonia. In the experimental group, the students' average visuo-semiotic reasoning score was 61.51 ($SD = 23.83$). Here the performance was highest in the items that asked the students to interpret a Lewis structure of ammonia.

Table 1

Summary of scores obtained by students

Group		*n*	*M*	*SD*	*SEM*
Drawing a Lewis structure of ammonia	Control group	100	40.00	45.51	4.55
	Experimental group	101	62.87	43.39	4.32
Drawing a Ball & stick structure of ammonia	Control group	100	33.50	43.84	4.38
	Experimental group	101	60.89	46.69	4.65
Interpreting Ball & stick structure of ammonia	Control group	100	19.75	26.42	2.64
	Experimental group	101	58.91	29.07	2.89
Interpreting the Lewis structure of ammonia	Control group	100	16.50	15.74	1.57
	Experimental group	101	63.37	32.70	3.25
Average visuo-semiotic reasoning	Control group	100	27.44	21.42	2.14
	Experimental group	101	61.51	23.83	2.37

Results of a t-test analysis of the students' performance showed that there was a significant difference in the students' average visuo-semiotic reasoning scores when comparing the control group and experimental group scores ($t(199) = -11.439$, $p < .001$) (Table 2). Cohen's d in this regard was -1.6145, and the effect size r was -0.6281, confirming that the difference between the means was statistically significant. A similar observation was made in all the variables tested in the present research. However, the Levene's Test for Equality of Variances showed that the difference between the variances was not significant ($p > .05$). Levene's Test for Equality of Variances, however, showed that the difference between the variances was significant on the items that asked students to interpret Lewis structures ($p > .001$).

Table 2

A comparison of students' performance on their visuo-semiotic reasoning related to structures of ammonia

		Levene's Test for Equality of Variances		t-test for Equality of Means					95% Confidence Interval of the Difference	
		F	*p*	*t*	*df*	*p*	Mean Difference	Std. Error Difference	Lower	Upper
Drawing a Lewis structure of ammonia	Equal variances assumed	1.341	.248	-3.647	199	< .001	-22.871	6.271	-35.23794	-10.50464
	Equal variances not assumed			-3.646	198.343	< .001	-22.871	6.273	-35.24113	-10.50144
Drawing a Ball & stick structure of ammonia	Equal variances assumed	3.116	.079	-4.287	199	< .001	-27.391	6.390	-39.99180	-14.79038
	Equal variances not assumed			-4.288	198.443	< .001	-27.391	6.388	-39.98805	-14.79413
Interpreting Ball & stick structure of ammonia	Equal variances assumed	.028	.867	-9.992	199	< .001	-39.161	3.919	-46.88952	-31.43227
	Equal variances not assumed			-9.997	197.570	< .001	-39.161	3.917	-46.88619	-31.43560

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

| | | Levene's Test for Equality of Variances | | t-test for Equality of Means | | | | | | | |
| | | F | p | t | df | p | Mean Difference | Std. Error Difference | 95% Confidence Interval of the Difference | |
									Lower	Upper
Interpreting the Lewis structure of ammonia	Equal variances assumed	77.070	< .001	-15.682	199	< .001	-46.866	3.626	-64.01687	-49.71580
	Equal variances not assumed			-15.731	144.284	< .001	-46.866	3.615	-64.01118	-49.72149
Average visuo-semiotic reasoning	Equal variances assumed	1.644	.201	-11.439	199	< .001	-36.572	3.197	-42.87682	-30.26799
	Equal variances not assumed			-11.446	197,179	< .001	-36.572	3.195	-42.87383	-30.27097

The results also showed that in both the control group and the experimental group, students' ability to draw Lewis structures correlated significantly with their ability to draw geometric structures of ammonia (Table 3). In the control group, there was a significant correlation between drawing geometric shapes of ammonia and interpreting ball & stick structure of ammonia. However, there was no significant correlation between drawing a Lewis structure of ammonia and Interpreting the Ball & stick structure of ammonia or Interpreting the Lewis structure of ammonia. The correlation between Interpreting Ball & stick structure of ammonia and Interpreting the Lewis structure of ammonia was also significant.

Table 3
Correlation between different visuo-semiotic reasoning skills

Group			Drawing a Lewis structure of ammonia	Interpreting Ball & stick structure of ammonia	Interpreting Ball & stick structure of ammonia
Control group	Drawing a Ball & stick structure of ammonia	Pearson Correlation	.359**		
		Sig. (2-tailed)	< .001		
	Interpreting Ball & stick structure of ammonia	Pearson Correlation	- .065	.241*	
		Sig. (2-tailed)	.520	.016	
	Interpreting the Lewis structure of ammonia	Pearson Correlation	.092	.175	.235*
		Sig. (2-tailed)	.364	.081	.019
Experimental group	Drawing a Ball & stick structure of ammonia	Pearson Correlation	.424**		
		Sig. (2-tailed)	< .001		
	Interpreting Ball & stick structure of ammonia	Pearson Correlation	.126	.315**	
		Sig. (2-tailed)	.209	.001	
	Interpreting the Lewis structure of ammonia	Pearson Correlation	- .158	.117	.163
		Sig. (2-tailed)	.115	.246	.104

In the experimental group, we observed a significant correlation between Drawing a Lewis structure of ammonia and Drawing a geometric shape of ammonia. Interpreting Ball & stick structure of ammonia and correlated significantly with Drawing a geometric shape of ammonia. Interpreting the Lewis structure of ammonia did not correlate significantly with any other abilities.

Learning Difficulties Associated with Geometric Shapes

Based on the results, a sample of participants from both groups was asked, in an interview, to explain factors that affect their learning of geometric shapes. Students were, however, allowed to present ideas on other topics in chemistry should they wished to. The significant factor related to the abstractness of chemistry concepts. Students suggested that conceptualizing chemistry concepts is a difficulty as they cannot see these concepts and must rely on imagination. For example, participants said the following:

- Tebogo: "We have problems with the chapter on VSEPR and struggles to *see* the shape of the molecule."
- Nonhlanhla: "I understand electronegativity and the periodic table trends because I cannot *see* these elements."
- Linda: "Teaching polar and non-polar bonds intermolecular forces is important when having to draw the shapes, and that is not emphasized. Being able to *watch* a video on how electronegativity attracts the elements leaving one more positive and the other one more negative can help. As a result, we *imagine* these things. However, if we can *see* it happen, we can have a better understanding of this chapter."
- Mbali: "In grade 10, we are taught that when we move to the right towards Helium, atoms get smaller. We understand why and so forth, but it would be good to get *to make* these atoms and their shapes or watch videos because now we are working on imagination."
- Participant 14: "In grade 11, we are told to apply those concepts, meaning we continue applying imagination."
- Lerato: "the challenge is having to imagine that one of the other bonds is actually at the back. In an exam when you have to draw methane or prove why it is tetrahedral, we cram it from textbooks that the one bond is in actual fact at the back and not on the right of the carbon atom."

To resolve the issue of abstractness, the participants suggested the use of visuo-semiotic models. These could include physical molecular models and computer-based models. For example, the participants said the following:

- John: "We could make atoms out of clay or jelly tots before learning about them."
- Zipho: "Before every lesson, it would make things easier if we could watch a video on the topic."
- Lerato: "actually making and creating the atoms can assist us to remember when writing exams."
- Nonhlanhla: "We went to Sci-Bono last year, and it was fun having to see real dry ice; it made it exciting to see something they have learned about."
- Mbali: "If we could get the opportunity to go to real science labs and do experiments with all these elements. Because when we do experiments, our teacher allows us to help and take part but not with sulfuric acid, all she says is 'it is dangerous.' But we need a platform that allows us to see how dangerous it is. In exams, we need to state it corrosive and eats through flesh, but we have never seen that. Watching a video where we see sulphuric acid eats through flesh can help. If we could get to see and feel the molecules and their shapes, it can assist us when answering questions."
- Ntando: I wish we could do practicals for every topic because I would perform better. Chemistry has a lot of theory that requires realistic practicals."
- Tebogo: "Watching videos can help with the naming of molecules as much as it can help with the understanding of the geometric shapes because it falls under the same topic."
- Amahle: "I wish we had our own box of molecules and not have to share with others."

Discussion

Earlier research found that students could have learning difficulties associated with the use of visuo-semiotic models, including ball & stick models (e.g., Masonjones et al., 2014), as well as Lewis structures (e.g., Cooper et al., 2010). However, the nature of these learning difficulties within the context of visuo-semiotic reasoning has not been reported widely. In the current research, we, therefore, attempted to determine the extent to which the use of physical molecular models could enhance specific visuo-semiotic reasoning skills among students.

The current research has shown that students may have difficulties with the visuo-semiotic reasoning skills

such as drawing and interpreting both Lewis structures and ball and still structures of ammonia. Cooper et al. (2010, p. 869) suggested that ordinarily, students could have difficulties performing these skills because they "require a complex interplay between prior knowledge and previously worked examples." For example, assigning scientific meaning to the semiotic models and symbols used in Lewis structures and ball & stick models without any prior knowledge is unlikely to be successful unless students have relevant prior knowledge (Cooper et al., 2010). Taber (2001, p. 125) suggested that learning chemistry without any prior knowledge is a form of "'bootstrapping' (a term borrowed from the paradoxical image of having to 'pull oneself up by one's own boot-laces': intended to imply a ridiculous plan or fantastic achievement)." Even with some prior knowledge, Taber (2001) argued that it would still be difficult for students to learn chemistry knowledge. This is because even though chemistry may be a "logical subject, many chemical concepts cannot be learned in an entirely logical manner, at least not in terms of clearly following deductively from previously accepted ideas and/or interpretation of empirical evidence" (Taber, 2001, p. 125). Taber's (2001) argument in this regard was corroborated by our findings in the current research as the participating students found it challenging to interpret or draw chemical models unless they had prior knowledge and relevant experience.

The current research has also revealed that students may have learning difficulties associated with visuo-semiotic reasoning if they lack prior knowledge and adequate experience. Experience in this regard refers to representational competence, which is the ability to derive meaning from visuo-semiotic models based on the previous encounter with them (Daniel et al., 2018). We found that without prior knowledge and representational competence, students may not be able to learn effectively from visuo-semiotic models. For example, participants in the current research said that they could not "see" chemical phenomena and therefore had to rely on "imagination" to visualize them. Imagining chemical phenomena that you have not previously encountered could be a form of 'bootstrapping' described by Taber (2001). We argue that 'bootstrapping' during visuo-semiotic reasoning may compromise learning. For example, the dual coding theory describes learning as a creation of "networks of verbal and imaginal representations" (Clark & Paivio, 1991, p. 151). Likewise, the Cognitive Theory of Multimedia Learning describes how new knowledge is integrated with prior knowledge (Mayer & Mayer, 2005). These theories, however, do not explain the phenomena mentioned by students in the current research of how they could "imagine" knowledge of phenomena they have not previously "seen." The findings in the current research, therefore, suggest that visuo-semiotic reasoning may require students to first internalize knowledge to be able to conceptualize and externalize it, as suggested in Mnguni's (2014) theoretical cognitive process of visualization. Alternatively, students may need to have prior knowledge and representational competence to reason with visuo-semiotic models effectively without bootstrapping.

Results in the experimental group suggest that interacting with physical molecular models could enhance students' ability to interpret and draw related visuo-semiotic models, as this enhances their representational competence. Essentially, interacting with these physical molecular models is a form of internalization, in which knowledge is assimilated through visual perception and haptic perception. As suggested by Terrell et al. (2019), this enhances students' ability to construct mental models. A critical finding in the current research in this regard is that physical molecular models were internalized through visual perception and haptic perception in addition to the aural perception of knowledge, which was presented by the teacher through narrated summary notes, a textbook, and worksheets. This finding is related to Newman et al.'s (2018) claim that physical molecular models improve student learning because they engage various receptor sense organs. The findings in the current research suggest that increasing modes of perception may enhance students' visuo-semiotic reasoning in molecular sciences. This may be because using haptic models in addition to the aural and visual perception increases the form and number of referential and associative connections that students can construct. It is for this reason that participants in the current research recommended more visual models (e.g., videos) and haptic models (e.g., clay and jelly tots) as learning tools. Consequently, findings in the current research show that moderately increasing forms of perception may improve visuo-semiotic reasoning among students.

Conclusions

The current research has shown that physical molecular models as an added learning tool enhanced students' visuo-semiotic reasoning related to interpreting and drawing physical molecular models. Based on our findings, this may be attributed to haptic perception through which knowledge is internalized. This haptic perception was afforded by interacting with physical models. The research has also shown that increasing modes of internalization

of knowledge, including haptic perception, enhances visuo-semiotic reasoning in molecular sciences and overall students' understanding of scientific phenomena. This finding also proves that cognitive learning is not limited to dual processing of information, which is limited to sight and hearing. Instead, our research has shown that cognitive learning is embodied to include various perceptual systems through which information can be internalized. When these perceptual systems are used, learning is enhanced, as found in the current research.

The current researcher, however, recommend further research to determine the cognitive effect of physical molecular models on learning. Researchers in this regard may consider exploring the role of haptic internalization of scientific knowledge, particularly given the increasing use of smart devices in science teaching and learning. Researchers may also explore the nature and significance of other internalization modes in science education, including olfactory perception, and how these could aid teaching and learning. While further research is needed in this field, we conclude, in response to the research question, that physical molecular models have a positive impact on Grade 11 students' visuo-semiotic reasoning skills related to Lewis structure and ball & stick model of ammonia when used as we described in the current research.

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