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COMPARING THE EFFECTS OF MODELLING AND ANALOGY ON HIGH SCHOOL STUDENTS' CONTENT UNDERSTANDING AND TRANSFERABILITY: THE CASE OF ATOMIC STRUCTURE

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Abstract. *Analogies and modelling have been developed and applied in learning and teaching science to facilitate students' understanding of abstract concepts, such as atomic structure. Considering few studies focus on comparing the effects of two teaching strategies—analogy-based teaching (ABT) and modelling-based teaching (MBT)—this study aims to compare the effects of ABT and MBT on high school students' content understanding and transferability of atomic concepts in science. Implementing a quasi-experimental design with pre-post-delayed tests, the study compared learning outcomes achieved by the MBT group (N = 68) and the ABT group (N = 69). The results showed both MBT and ABT could improve students' content understanding and promote transferability. However, the MBT group significantly outperformed the ABT group in terms of generating initial models and overall transferability. Although there was no difference in content understanding, or near or far transferability, at post-test between the two groups, the MBT group maintained more extended memory of atomic structure on the delayed post-test. Moreover, qualitative analysis of students' drawings of atomic models revealed that both groups were able to develop and transfer their models, but inadequate scientific knowledge affected the quality of the transfer product. These findings have implications for designing and implementing instructional approaches that leverage analogy and modelling in the science class.*

Keywords: *analogy-based teaching, atomic concepts, modelling-based teaching, science education*

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Introduction

Atomic concepts have been one of the core concepts in science curricula (Muştu & Özkan, 2019). The concept of atomic structure, in particular, is considered fundamental for understanding the nature of matter at secondary and university levels (McKagan et al., 2008; Park & Light, 2009; Taber, 2003). However, many studies have revealed that students usually find the concept of atomic structure difficult to attain, and instead, they develop alternative conceptions, as the atom is a kind of matter in the sub-microscopic world whose structure cannot be observed directly. Moreover, students only receive limited opportunities to explore atomic structures at the sub-microscopic level, and few strategies have been adopted to help them learn the characteristics of atomic models (Sunyono & Sudjarwo, 2018).

Among the existing teaching strategies, analogy-based teaching (ABT) and modelling-based teaching (MBT) are two effective instructional approaches for facilitating students' understanding of abstract and intangible concepts, recommended by numerous empirical studies (e.g., Brown & Salter, 2010; Khan, 2007). However, there were observations that ABT and MBT were sometimes inappropriately designed and implemented without achieving the intended outcomes. For example, analogies were presented statically and didactically to students as textbook or lecture content that failed to engage the students, or were used uncritically and thus led to a less accurate understanding (Cin, 2007; May et al., 2006). Additionally, MBT was criticised as it was "too challenging" for learners and teachers in the classroom (Settlage, 2007). To further unfold the mechanisms behind these contradictions, further research is needed to explore the effects of ABT and MBT on students' learning.

Since analogies and modelling can transform knowledge and provide predictive and explanatory capability for making sense of the familiar and unfamiliar (Khan, 2007), it is intriguing to investigate how teaching strate-

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gies can reinforce such transferability effectively. According to Dori and Sasson (2013), there is a gap between theoretical and empirical studies, due to a lack of emphasis on the importance of near and far transfer in educational processes. Particularly, although far transfer is more associated with deep learning and long-term retention than near transfer, it is much more difficult to achieve (Kassai et al., 2019; Sala et al., 2019). Accordingly, the main purpose of the present study is to explore how to improve high school students' transferability through the use of two teaching strategies: ABT and MBT.

Analogies in the Teaching of Atomic Concepts

According to the assumption of Sarantopoulos and Tsaparlis (2004), an analogy is a system of relations between parts of two particular domains: the analogue (the familiar domain) and the target (the unfamiliar one). An analogy involves the identification and conversion of relational information from the analogue to the target, which consists of finding the similarities between the two domains (Vosniadou, 1988). According to related studies (Buckley et al., 2004; Else et al., 2008; Gobert & Buckley, 2000), ABT is a teaching approach in which teachers help students conduct analogies for understanding the specific content by recognising the analogy's coherence with the target concept. ABT often assists students in comprehending perplexing concepts and visualising abstractions by representations in different forms, such as texts, pictures, videos, verbal examples, and computer simulations (Trey & Khan, 2008).

The commonly used analogy of the atomic structure is the solar system. In this case, the spatial and dynamic features of the sun and the surrounding planets are analogous to the atomic nucleus and electrons (Taber, 2013). Goh et al. (1994) proposed other useful analogies of atomic structure. For example, determining the location of a student based on his or her schedule is comparable to the identification of an atomic orbital; the way passengers occupy seats on a bus provides a good analogy of Hund's rule; and an analogy is drawn between one's address (that includes the name, unit number, house number, and street name together), and the four quantum numbers (that include the spin quantum number, magnetic quantum number, subsidiary quantum number, and principal quantum number). These analogies illustrate and visualise the key features of atomic concepts with reference to real-world scenarios (Devecioglu-Kaymakci, 2016), and draw on students' prior knowledge and experience to enable their understanding. Inverse analogies can be productive, too: using atomic structure as the familiar domain, Slabin (2017) applied valence bond and molecular orbital theories to explain formation of educationally valuable chemical eponyms (the unfamiliar domain). As confirmed by Dangur et al. (2014), engaging diverse analogies and encouraging connections between scientific concepts and daily life experiences can improve students' understanding of complex concepts (e.g., quantum mechanical concepts).

Leveraging analogies may improve the instruction of abstract and sub-microscopic concepts. However, it should be noted that there are no perfect analogies that could completely represent the target concepts (Taber, 2001), and stopping at a literal understanding of an analogy may result in limited comprehension. Taber (2005) reported that students are likely to equate quantum mechanical spin to the spinning of a basketball or a planet. Such a superficial interpretation may lead to misconceptions. The generation of mixed/hybrid atomic models (e.g., a localised electron included in the "surface" of the electron cloud) also indicated inadequate understanding of the target concept (Dangur et al., 2014; Tsaparlis & Papaphotis, 2009). To eliminate these misunderstandings and maximise the efficacy of analogies, a more precise design of ABT is needed.

Modelling-based Teaching

Modelling builds knowledge through an ensemble of processes involving building, critiquing, and modifying models (Campbell et al., 2012; Gobert & Buckley, 2000; Schwarz et al., 2009). Modelling-based teaching (MBT) provides an effective way for learning key scientific concepts and unobservable phenomena through modelling processes (Al-Balushi & Al-Hajri, 2014; Chittleborough & Treagust, 2007; Maia & Justi, 2009; Nakiboglu, 2008). Having students develop integrated mental models that they can employ in a dynamic and recursive process of model development is the objective of MBT (Gilbert & Justi, 2016, p.58).

An MBT framework comprised of multiple and complex stages (involving elaboration, testing, reformulation, and discussion of the proposed models) was proposed for advancing students' learning about the main qualitative aspects of chemical equilibrium in Maia's study (Maia & Justi, 2009). In this framework, modelling was considered a non-linear process. Khan (2007) introduced a productive modelling cycle that contains model generation, evaluation, and modification (GRM). Translating GEM modelling cycle into the university chemistry classroom has contributed to students' understanding of molecular structure and intermolecular forces.

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In addition, several studies revealed students' outstanding performance on assessments in relation to their non-modelling counterparts (Campbell et al., 2011; Dukerich, 2015; Settlage, 2007). However, teachers were uneasy about controlling MBT in their classes as it was too time demanding (Campbell et al., 2011; 2012). Since MBT is a complex approach that can be manifested in many disparate forms and processes, it is beneficial to establish a diverse set of cases and clarify how MBT is implemented in chemistry classrooms to support teachers who incorporate modelling pedagogies in their classrooms.

Transferability in ABT and MBT Classes

To learn from an analogy, learners must first understand why the analogue (the familiar domain) behaves the way it does, and then transfer that understanding to the unfamiliar domain (Gray & Holyoak, 2021). Most analogies relate to empirical phenomena, including the key functional relations that involve causes and their consequences (Gray & Holyoak, 2021). The analogy presents a new explanation of why various phenomena occur by transferring knowledge about causal relations, which enables further transfers to new situations. MBT is a constructivist teaching approach, and learners construct mental models during their interaction with environments, artefacts, technology, and communities (Johnson-Laird, 1983). According to mental model theory, a mental model is defined as an internal cognitive representation or an interconnected concept that correlates in some way to the external structure that it represents (Gentner & Stevens, 1983). Mental models are incomplete and unstable, and they can also be analogical, partial, and fragmentary (Greca & Moreira, 2000; Norman, 1983). In a dynamic situation, learners often construct mental models to understand the world and solve problems (Seel, 2017). Successful and unsuccessful comprehension involves processes relevant to mental model development or transfer (Rapp, 2005).

Further, educators intend to pass on knowledge and skills, which will apply in future and unknown contexts to the students (Sasson & Dori, 2015). Regarding this, transferability takes an essential role in ABT and MBT classes. Transferability refers to the ability of learners to retain knowledge and skills and apply them in a new learning environment (Dori & Sasson, 2013; Salomon & Globerson, 1987). Dori and Sasson (2013) proposed a framework of transferability and indicated that near transfer occurs when the learning situation is comparable to the previous learning situation; far transfer, on the other hand, occurs when a student is required to perform in a new and unfamiliar learning context. They further defined three main characteristics of a transfer task: (a) task distance [TD], (b) interdisciplinarity [I], and (c) skill set [S] (detailed explanations of these terms can be found in Dori and Sasson's study in 2015). However, near and far transfers are ambiguous, and the term "closeness" is vaguely defined and very subjective (Perkins & Salomon, 1992). Whether near or far, the assessment of transfer heavily depends on one's understanding of learning (Lave, 1988; Marton, 2006) and the assessment instruments used (Bransford & Schwartz, 1999; Schwartz et al., 2005). In addition, Sasson and Dori (2015) constructed assignments and evaluated ninth-grade students' transfer skills, finding that boys' near transferability was much higher than for girls. It was suggested that effective teaching intentions should be further explored to develop learners' transferability in the science classroom.

Several studies have explored transferability between different external representations, the effect of hypothesis-testing skills on the transfer of learning, and the impact of learning models on the development of transferability in different contexts. However, few empirical studies have optimally explored how students transfer their mental model in the chemistry class. This study helps to fill this gap, by demonstrating the effect of two different teaching strategies (ABT and MBT) on students' transferability in science.

Research Purpose and Questions

This study examined the effects of two teaching strategies ABT and MBT on high school students' content understanding of atomic structure and transferability. The study seeks to answer the following questions:

(1) Which teaching strategy enhances students' content understanding and transferability in the context of the atomic structure?
(2) Are there significant differences in students' content understanding and transferability between the two groups after experiencing the teaching interventions?
(3) How do both groups develop and transfer their mental models after receiving different teaching strategies?

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Research Methodology

Context

Curricular Context: The lessons designed and implemented were from the same module of atomic structure prescribed in the local chemistry curriculum. According to the learning objectives, the students were expected to learn about the history of atom discovery and understand the concepts of atomic structure, spectrum, atomic orbital, electronic configuration, the periodic table, and chemical bond formation. In the local context, educational policymakers and practitioners advocated the development of the students' modelling skills. The National Academy for Educational Research (Ministry of Education in Taiwan, 2018) had specific requirements for modelling at the high school level. Taking the chemistry subject as an example, 10th graders should have the ability to "build models based on scientific problems or through group discussions and be able to use, for example, 'analogous or abstract' representations to describe a systematic scientific phenomenon, and then understand the limitations of the model" (p.32).

The design and implementation of ABT and MBT: Both ABT and MBT groups were engaged in the same analogical activities guided by a common set of instructional worksheets, a feature for ensuring common practice between conditions. The analogical examples consisted of a set of forms presenting the different atomic concepts, in the form of text, pictures, verbal examples, and computer simulations. There were two main differences between the two teaching strategies. One was that analogies were provided by the teacher in the ABT group (teacher generates analogy for students), while the students in the MBT group (teacher and student co-construct analogy) also had to recall analogies based on the teachers' enquiries. Another difference was the modelling process was integrated into analogical activities in the MBT group, while there was no modelling process in analogical activities in the ABT group.

Referring to the principles of the analogical approach which were proposed by Gray and Holyoak (2021), the teacher selected analogies (solar system) to describe scientific concepts (the atomic structure) based on their prior knowledge. The students then engaged in interactive dialogue with their teacher, explaining the corresponding relations between the analogy and the target concepts. After a comparison between analogy and target concepts, the students realised the limitations of the previous analogies and the teacher promoted a new analogy (climbing ladders) for better representing the target. Finally, the students summarised all of the analogies and clarified the relationships between the analogies and the atomic concepts. The teacher encouraged the students to generate inferences founded on basic knowledge of the atomic structure, for example, a question was asked: do you think that two different atoms and their structure can be combined to form a molecule? The ABT was derived from the students' existing ideas and the teacher further developed the efficacy of analogies, but the students learned with analogies and generated models without the process of modelling. In this way, the students did not have ownership of the analogies.

In the MBT group, the students and the teacher contributed the ideas, and the analogies were generated building on the students' existing knowledge, which were guided by the scientific modelling GEM (Generate, Evaluate, and Modify) approach (Khan, 2007). It is important to make the distinction that not all analogies are models; analogies are the medium through which a model is expressed (Lee et al., 2017). In this study, the GEM indicated that students were able to develop mental models (understanding of atomic concepts). These mental models were represented by analogies or drawings which showed aspects of scientific objects. Below are illustrations of GEM approach.

In the model generation stage (*Generate*), the teacher helped the students develop an initial model of atomic structure. The basic concept that "An atom is composed of a nucleus and extra-nuclear electrons, and that electrons run around and surround the nucleus" was first introduced. The students were then guided to recall their prior knowledge and experiences that could relate to this concept through questioning. Then, the teacher guided the students to select the most appropriate analogy and asked them to explain the reason for this selection. The solar system was considered as a plausible analogy for this concept, the Rutherford Atomic Model. An explanation that the sun represented the atomic nuclei, the encircling planets represented electrons, and their orbits represented the atomic orbital was made after teacher-and-student discussion.

In the model evaluation stage (*Evaluate*), more advanced knowledge was introduced, that was critical to understanding the concept of the atomic structure (e.g., electron movement, energy change in electronic transition), and the students were encouraged to evaluate whether the initial solar system analogy could accommodate such additional information. They thought about how energy would change when an electron moved from a layer

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of lower electronic energy to the one of higher electronic energy. With a revised understanding, students would consider looking for a new analogy to compare with the initial model that had been deemed inadequate.

During the model modification stage (*Modify*), the initial model was modified and improved based on the limitations identified in the evaluating phase. Then the students applied the elaborated model, the Bohr atomic model (with a new analogy if possible), to accommodate new situations (e.g., energy change as electrons move from atomic orbital K to L). The new scenario would provoke another round of model evaluation and modification, and thus build up the students' mental models and conceptual understanding.

Research Design

This study adopted a quasi-experimental design (Plomp, 2013), with a pre-post-delayed test design. In total, there were eight instructional sessions for the ABT class and nine for the MBT class. To guarantee that both groups had the same class time, the ABT group had one more session to review atomic structure concepts and related tasks (eight teaching sessions and one session for review). The implementation of these two instructional methods continued for three weeks. There were three 55-min lessons each week. The total time for teaching intervention was 8 hr 25 min hr. The pre-test and post-test were administered to examine the students' content understanding and transferability. Two weeks after the post-test, a delayed post-test was conducted to evaluate the sustainability of the students' understanding of the target concepts and compare the two groups in retention of content understanding of atomic structure (Mauro & Furman, 2016). The time interval of two weeks was to avoid the effects of another chapter in the local curriculum, Molecular, on the students' content understanding of atomic structure. To explore the students' transferability, a qualitative analysis of student-generated drawings of atomic models was performed, to reflect how mental models were developed and transferred based on different transfer scenarios (Gobert & Pallant, 2004; Sun & Looi, 2013). This was intended to provide a more comprehensive, detailed description of the level of content understanding and model development achieved by the two groups.

Participants

Altogether, four classes of 10th graders (n = 137, age 15-16 years old) from a school in Taiwan participated in this study (35% male and 65% female). The four classes were assigned randomly to the MBT group (*N* = 68, 2 classes) and the ABT group (*N* = 69, 2 classes). To ensure the sample size was appropriate, G*Power 3 was used (Mayr et al., 2007). Given an effect size of 0.4 with 80% power in a one-way ANCOVA (2 groups, $\alpha = 0.05$, df = 1, and 1 covariate), the suggested a total sample size of 52. Therefore, the sample size of this study was satisfactory. This study followed the ethical considerations outlined by Taber (Taber, 2014). The administrators and teachers of the selected classes were contacted, and consent was gained. Students were informed about the purpose of the study before the intervention, but participation was voluntary and anonymous. By the end of the study, no students had refused to participate.

In the study, two participating teachers discussed, designed, and implemented the lesson plans in close collaboration with the researchers, to control interference from teacher variables such as the competence of the teachers (Cumming & De Miranda, 2012). Specifically, a male teacher A with six years of teaching experience in chemistry taught the MBT group, and a female teacher B with eight years of teaching experience in chemistry implemented ABT in another group.

Instruments

The test items were developed in relation to the local chemistry curriculum for secondary schooling (Ministry of Education of Taiwan, 2018). The pre-test and post-test were composed of two parts, including Part I true/false questions and Part II open-ended questions. Pre and post-test had the same questions, but the post-test had a minor difference in the description and the order of items. A total of eight items with a true or false question format were designed for Part I, which tested the students' content understanding of atom composition, the electronic and structural properties of an atom, electronic cloud, and the element periodic law. In addition, the students were requested to provide justifications for their choices. Regarding Part II, the three items of mental model transferability, based on the transfer framework (Dori & Sasson, 2013), were defined as an initial mental model, for near transfer and far transfer. In this part, the students were required to respond to three transfer items by drawing.

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The students' illustrations could make their mental models explicit and provide an assessment indicator for model development and content understanding (Larkin & Simon, 1987). Samples of Part I and II are presented in Tables 1 and 2. A delayed post-test with twenty multiple-choice questions for evaluating the students' retention of content understanding of the atomic structure was administered two weeks later.

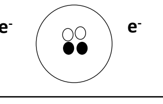
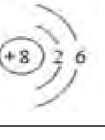
Table 1
Example Items for Evaluating Content Understanding

Test	Item	
Pre-test	As shown in the figure, the outermost electrons have higher energy than the innermost electrons. • True. Please provide the reason: ____ • False. Please provide the reason: ____	
Post-test	As shown in the figure, the outermost electrons have lower energy than the innermost electrons. • True. Please provide the reason: ____ • False. Please provide the reason: ____	
Delayed post-test	As shown in the figure, which is the most stable layer? • Left • Middle • Right • Not sure	

Note: These items were used for evaluating students' content understanding of the electron orbitals energy such that: the innermost electron, near the nucleus, has the lowest energy and is also the most stable. On the contrary, the higher the energy (farther away from the nucleus) the outermost electron has, the more unstable and the easier for electronic transitions.

Table 2 demonstrates examples of transfer items. These three items dealt with how students applied their initial model (the atomic structure of a general atom) to a near transfer question (atomic structure with specific elements) and a far transfer question about a molecular structure. Referring to the three transfer attributes framework (Dori & Sasson, 2013), the first item was designed to assess if students could recognise the qualitative features of the atomic structure (e.g., the composition of an atom). Regarding the near transfer item, it instructed students to apply knowledge of atomic structure to a specific element's atomic structure and to identify the correct connections between protons, neutrons, and electrons. It was similar to the first mental model item based on the same scientific concept, and this question featured a low degree of all three transfer framework attributes (TD, I, and S). The far transfer items required students to apply knowledge from the atomic structure to a different concept, molecular structure, and to distinguish how the orbitals overlapped and how the valence electrons were shared across the hydrogen and oxygen atoms. Hence, this item featured all three transfer framework attributes to a high degree (TD, I, and S).

Table 2
Pre/Post-test Part 2 Model Development Items and Sample Responses

Question	Learning objective	Sample response
1. Please draw a schematic diagram of the atomic structure	Students were expected to recognise the qualitative features of atomic structure (e.g., the composition of an atom).	
2. Considering the drawing you created in the last item, please draw a schematic diagram of the distribution of electrons in an oxygen atom ($^{16}_{8}O$)	Students were expected to acknowledge the quantitative features of the atomic structure (e.g., the exact number of electrons in each energy layer)	

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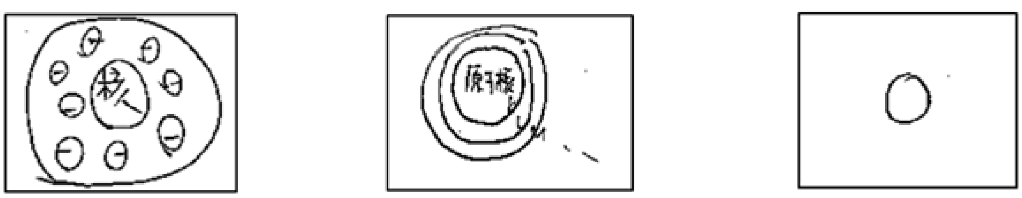
Question	Learning objective	Sample response
3. Considering the drawings you created in the last two items, please draw the electron arrangement in an H2O molecule	Students were expected to apply the model developed to new situations and evaluate its fitness (e.g., designing a model for the compound of H2O based on the atomic structures developed for the elements of H and O)	H :Ö: H

Scoring for content understanding. The students' understanding of the target concept was reflected in their test scores. The full score for each "true or false" question in the pre-test and post-test was 3 points, and a student's answer would be awarded 1, 2, or 3 points based on their selections and justification. If a student selected the correct answer and justified it well, 3 points would be awarded; If only partial explanations were provided, 2 points would be awarded; and for incorrect or correct answers, without explanations or with wrong explanations, only 1 point would be awarded. For multiple-choice questions in the delayed post-test, the full score was 5 points. No points would be awarded if the response was wrong or missing. The test papers were marked by two chemistry teachers who achieved 99% consistency in scoring. The student test scores were analysed using SPSS 24.0.

Scoring for transferability. The scoring rubric stemmed from Supasorn and Promarak (2015), who used it to classify three categories of student conceptions (good conception, alternate conception, and misconception) in comparison to the scientific consensus. The answers to the three open-ended questions were graded on a scale of one-to-three, where one meant "wrong answer", two meant "partially correct answer", and three meant "correct answer". If the illustration was provided correctly and displayed the relevant components (the nucleus and electrons), relations (situationally or mathematically), and numerical features (e.g., the number of electrons) of an atomic model, 3 points would be given. If the illustration only showed a partially accurate model, correctly displaying the relevant components and relations, but with numerical features missing or being incorrect, 2 points would be given. Only 1 point would be given if the illustration noted an inaccurate model, or the question was left unanswered. For examples of student illustrations that were awarded 3 points, 2 points, and 1 point respectively, please refer to Fig. 1. The scoring rubric of this item only focused on whether students could draw an accurate atomic model including the essential elements of electrons and nuclei (protons or neutrons), without consideration if it was a scientific model. This is the reason for giving 3 points in Fig. 1. Although this student did not provide a scientific model (the Electronic Cloud Model), the drawing includes the required atomic components, and so it was given 3 points. All of the students' models were reviewed by a chemistry educator who coded 10% (n = 14) of the data to establish intercoder reliability with the first author. Intercoder reliability was calculated as 95% and reached 100% after discussion (Patton, 2002).

Figure 1

Examples of Student Illustrations of an Atom in the First Item of the Initial Model



3-point illustration (correctly displayed the relevant components).	2-point illustration (Only partial components are presented. Electrons are missing.	1-point illustration (no relevant components).

Two researchers designed and administered the pre-and post-tests. A pilot of the pre- and post-tests was carried out involving a class of 39 students who had learnt the topic. This was intended to potentially modify the instrument. The test items and questions were revised based on the students' responses. The delayed post-test was generated collectively by three experienced chemistry teachers who had taught chemistry for 10 years in this school. All of the test items were peer-reviewed by two chemistry teachers and two professors in science education to ensure their validity and legitimacy. The Cronbach Alpha coefficient of the pre-test was 0.81, the post-test

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was 0.84, and the delayed post-test was 0.90. The results of the pilot study indicated a good degree of reliability in the instruments (Taber, 2018).

Data Analysis

Before conducting paired sample *t*-tests and an ANOVA analysis, the Shapiro–Wilk test had demonstrated normal distribution of the pre-, post-, and delayed-tests results ($p > 0.05$). There was no significant variance between the two groups in terms of pre-test scores ($F = 1.202$, $p = 0.275$). For exploring the differences between the variables of students' content understanding and transferability before and after teaching interventions, a two-way ANOVA analysis comparing the two different methods (ABT and MBT) and the time of assessment (pre-test and post-test) was performed. Then paired sample *t*-tests were carried out to examine whether the students' content understanding, and transferability had improved significantly between the groups. Regarding transferability, it was categorised according to three scales: initial model, near transfer, and far transfer.

The paired sample t-test generated Cohen's d effect size, suggesting small, medium, and large effect sizes would be 0.20, 0.50, and 0.80 respectively. The effect size when the ANOVA analysis was conducted generated partial eta squared, considering values of 0.01 as a small effect, 0.06 as a medium effect, and 0.14 as a large effect (Bryman & Cramer, 2009).

The qualitative method for analysing the students' drawings was in three transfer items, by using classical content analysis for a priori codes of correct, partial-accurate, and inaccurate models (Patton, 2001). Data were analysed for patterns within the two conditions, for how the students developed and transferred their models. The qualitative analysis involved a continual process of data coding, displaying, and verification to identify themes within the drawings and their comments that revealed the characteristics of their mental model (Patton, 2001). Two independent ratters coded three items in the pre- and post-tests. The inter-rater reliability was 92% and Cohen's Kappa was 0.84. Inconsistent codes were discussed and resolved.

Research Results

Students' Performance on Content Understanding

First, a paired-sample *t*-test was administered to examine whether the two groups of students had improved their learning outcomes after the instruction. The results revealed that students, in both the MBT group and the ABT group, performed significantly better in the post-test (Table 3). The effect sizes (Cohen's d) ranged from 0.34 to 1.51, indicating that while the two instructional conditions showed large positive effects on the students' content understanding, the initial model and overall transferability had a medium effect on near transfer and had a small effect on far transfer. This provided evidence for the effectiveness of the two instructional approaches.

Table 3
Paired Sample t-test Results: Pre-test and Post-test

		MBT Group			ABT Group		
	Test	*t*	*p*	*Cohen's d*	*t*	*p*	*Cohen's d*
Content understanding	Pre-test / Post-test	-1.339	<.001	0.92	-.889	< . 001	0.84
Initial models	Pre-test / Post-test	-8.492	< .001	1.51	- 8.804	< . 001	0.89
Near transfer	Pre-test / Post-test	-3.780	< .001	0.62	-4.331	< . 001	0.51
Far transfer	Pre-test / Post-test	-2.711	< .001	0.43	-2.815	< . 001	0.34

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		MBT Group			ABT Group		
	Test	*t*	*p*	*Cohen's d*	*t*	*p*	*Cohen's d*
Overall	Pre-test / Post-test	-8.496	< .001	1.28	-6.682	< . 001	1.06

ANOVA revealed no significant differences in the students' post-test scores of content understanding between the two groups (F (1,135) = 2.5, p = .12). However, Table 4 shows a significant statistical difference between the two groups (F (1,135) = 3.09, p = .00 < .001, partial eta squared η^2 = .022) in terms of overall transferability. Regarding the comparison of the two groups' performance on the model transferability test, students in the MBT group, in general, obtained higher scores than their counterparts, but these differences were not statistically significant in terms of near transfer and far transfer. The only significant distinction between the two groups in the post-test was in the item about the initial model, where the MBT group obtained higher scores than the ABT group (F (1,136) = 8.34, p = .01 < .05, η^2 = .06). Even though the average scores that the MBT group achieved in other items were slightly higher than the ABT group, these differences were not statistically different.

For further investigation of the retention impact of MBT and ABT, ANOVA was performed on the student scores on content understanding in the follow-up test. The results further confirmed the positive effect of the MBT approach. Students in the MBT group outperformed the ABT group F (1,136) = 1.83, p = .04. Compared to ABT, it appeared MBT facilitated knowledge retention and long-term memory of the target concept.

Table 4
ANOVA Analysis Results for the Post-test and Delayed Post-test of the Two Groups

	MAI Group		AI Group		*F*	*p*	η^2
	M	*SD*	*M*	*SD*			
Content understanding	17.49	2.22	16.21	2.13	2.50	.12	.03
Initial model	2.41	0.82	2.02	0.93	8.34	.01	.06
Near transfer	1.80	0.74	1.78	0.69	0.06	.81	.00
Far transfer	1.28	0.67	1.23	0.46	1.83	.17	.01
Overall	5.56	1.33	5.30	1.41	3.09	.00	.02
Delayed post-test							
Content understanding	71.36	12.44	66.99	15.36	1.83	.04	.03

The Students' Performance on Transfer Tasks

The qualitative analysis identified correct models, partial-accurate models, and inaccurate models from students' drawings in the post-test, by one-to-three scores respectively. Since it was found that the students had very limited prior knowledge of model transferability in the given questions, the students' drawings in the post-test were mainly for assessing how the students' models had progressed. Based on the scoring method introduced above, the scores from the two groups, calculated in percentages, are presented in Fig. 2.

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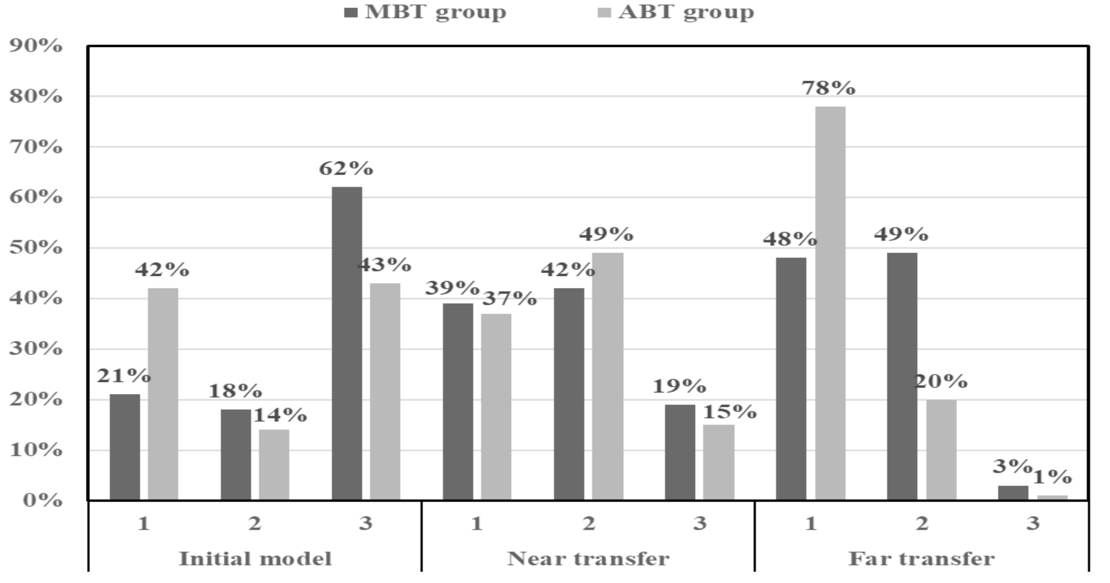
Figure 2

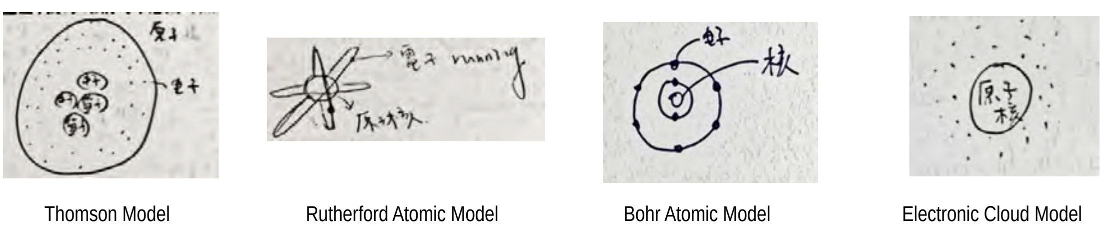
Transfer Scores in Post-test



Initial model. For the first item, the students were expected to generate an initial model of atomic structure that included all the necessary components such as the nucleus and electrons. It was not necessary for the students to manage to draw the scientific position between the nucleus and the electrons at this item. For example, the students who wrote a Bohr model should get more points than the ones with the Dalton model. The quality of the Bohr or quantum models of the atom, the most frequently accepted models, were examined from the students' drawings. Examples of student illustrations in the post-test for generating initial models are provided in Fig. 3. As observed, the students' developed models at this stage were very similar, with most being of the Bohr atomic model (n = 54 for MBT group, n = 37 for ABT group). This result showed that the students gained an enriched content understanding of the atomic structure from the MBT.

Figure 3

Examples of the Student Illustrations in the Post-test: Generating Models



Thomson Model | Rutherford Atomic Model | Bohr Atomic Model | Electronic Cloud Model

The solar system was the most frequently adopted analogy. Overall, students in the MBT group outperformed the ABT group. They generated more accurate models (62% vs. 43%) and more diverse types of mental models. Besides the Bohr atomic model (the predominant model provided by the ABT group), the MBT group illustrated the Rutherford atomic model, the Thomson atomic model, the Dalton atomic model, as well as the Electron cloud model. The illustrations also unveiled the problems students encountered in understanding the target concept. There were instances of alternative conceptions and misconceptions. Many students failed to grasp the idea of electronic movement, and the positions of the electrons in the nucleus. Also, some of the students were not able to identify the relationship between the number of electrons and protons.

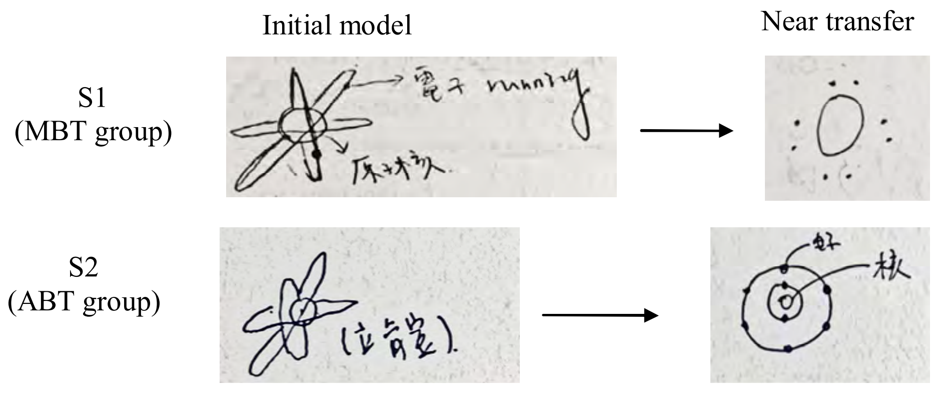
Near transfer. In the second item, students were expected to transfer the model they had developed in the

https://doi.org/10.33225/jbse/22.21.325

first item to a new context (the specific atom), evaluating whether the model accurately depicted the quantitative relationship between protons, neutrons, and electrons. In the pre-test responses, most students were unable to describe the atomic model of a specific element (Oxygen - O_2). Only 15% of the students generated a partially correct model of O_2. Most of the students had difficulties in understanding the relationships between the number and location of protons and electrons.

In the post-test, 19% of students in the MBT group and 15% of students in the ABT group generated correct models. Students in the MBT group preferred to apply and adapt the initial model constructed to the new situation. Yet in the ABT group, the students preferred to drop the initial model and provide a new one in the new scenario. Figure 4 displays two atomic models developed by Student 1 (S1) in the MBT group and S2 in the ABT group. In the first item of the initial model, S1 developed a Bohr atomic model. When he noted the model was not suitable for the new situation, he kept the original model but adapted the way the electrons were arranged. In contrast, S2 dropped the Bohr atomic model which was developed in the first item and proposed a Rutherford atomic model to accommodate the situation.

Figure 4
Examples of Student Illustrations in the Post-test: Near Transfer



In the post-test, most models provided were still partially correct. Among the different kinds of models generated, the Rutherford atomic model was the most common. This indicated the overall accessibility and acceptability of the "solar system" analogy. Compared to the pre-test, the illustrations of the Rutherford atomic model provided in the post-test were more accurate. Based on the student responses collected, the areas that would require further instructional efforts were identified. Some students failed to visualise the electronic structures and Lewis structures; some hesitated to interpret numerical symbols of an atomic sign (e.g., 16 and 8 in $^{16}_{8}O$), and some students had difficulty in figuring out the correct number of electrons of an atom.

Far transfer. The third item was more challenging as the students were expected to consider different structures of atomic models and combine them. Only 3% of the students in the MBT group generated correct models. And in the ABT group, the percentage was even lower (1%). Students who could come up with a partially correct model were very limited as well. Almost half of the MBT group (49%) and one-third of the ABT group (29%) illustrated a partially correct model in the post-test. This observation echoed the frustrations the students expressed in their written reflections. For the majority of the students, it was indeed difficult for them to develop a model as required. A lot of them failed to distinguish between electronic structures and Lewis structures. And even though some students could figure out the atomic structure of the elements of oxygen and hydrogen respectively, structuring a water molecule was still beyond them.

Based on the illustrations provided at this stage, the trajectory of model transferability could be outlined. Taking the modelling practices of Student S3 in the MBT group and Student S4 in the ABT group as an example (see Fig. 5), S3 provided an initial model based on the analogy of the "solar system". In this model, the components of the nucleus, electrons, and atomic orbital were provided and correctly positioned. In the following stage of the near transfer, S3 further shifted to a Rutherford atomic model, with each component quantitatively specified. At the 3rd stage of the far transfer, S3 correctly illustrated the basic structure of a water molecule that included the

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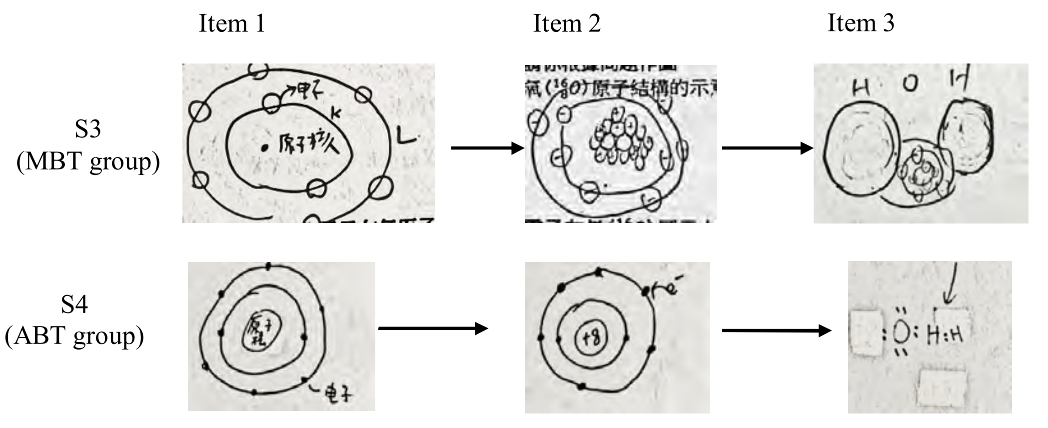
elements of hydrogen and oxygen. She also tried to combine the two elements and structured them together, however, as she did not include valence shell electrons, the model she generated was still only partially correct.

Similarly, S4 of the ABT group provided an initial model based on the "solar system" analogy that incorporated most of the essential elements, with only the atomic orbital missing. In the near transfer item, S4 visualised the main structure of an oxygen atom and labelled the components (e.g., electrons, protons, and the electronic charge). As for far transfer, the illustration provided by S4 included the key elements but with other components missing. The processes of model transferability depicted above were typical. Such observations reflected the challenges and difficulties the students encountered as they tried to develop and further elaborate their mental models of the atomic structure.

Figure 5

Examples of the Student Illustrations in the Post-test: Far Transfer



Discussion

The first two research questions in this study were to examine the difference between the MBT and ABT on the students' learning outcomes, including content understanding and transferability. A quantitative analysis between pre- and post-test results showed that generally, both instructional approaches could significantly facilitate a student's content understanding and transferability of sub-microscopic concepts, with a large effect size. This finding revealed the value of the two teaching strategies for facilitating the understanding of abstract concepts (Çalik & Ayas, 2005; Dilber, 2012; Orgill et al., 2015). When comparing the post-test results between the two groups, there was a difference in performance of generating initial models and overall transferability with a small effect in favour of the MBT group, but no noticeable difference was found in content understanding and the other two transfer items. This might imply that MBT benefits students' transferability more than analogical activities without modelling. It was noted earlier that far transfer is difficult to achieve, so this study contributes significantly to the literature.

Following the GEM cycle of modelling instruction, the students in the MBT group developed an enriched understanding of the atomic structure model, and their modelling practices resulted in more accurate and complete models, This finding is consistent with the established literature that modelling-based instruction is a more effective way of promoting the development of scientific process skills, such as reasoning and explanation (e.g., Aktamis & Ergin, 2008; Baze, 2017; Liguori, 2014; Wen et al., 2020). However, these results do not seem to be aligned with previous studies that noted that scaffolded modelling conditions could support students in developing a better conceptual understanding of science (Al-Balushi & Al-Hajri, 2014; Chittleborough & Treagust, 2007; Maia & Justi, 2009; Nakiboglu, 2008;).

Although there was no significant difference in content understanding at post-test, the delayed post-test results affirmed the significance of integrated modelling in terms of facilitating content knowledge retention. The MBT group remembered and recalled the atomic concepts thoroughly and did better in the delayed post-test. Involving the modelling process in teaching sequences may enable students to store concepts in long-term memory. This finding may add to the value of incorporating modelling-based instructional activities to further assist the retention of scientific knowledge.

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Modelling-based teaching (MBT), in essence, is processed by students making information meaningful to them personally by using various models to enable the comprehension of contents and contexts (Windschitl et al., 2008). In the MBT group, the drawings that students developed in the previous stage were considered, critiqued, and leveraged upon. Student modelling processes were connected. However, in the ABT group, analogies were proposed independently, the teacher did not provide a "bridge" between them, and students did not explore the connections between the proposed models. Compared to the ABT, the MBT provided a more conducive environment for content understanding and long-term memory of concepts.

The results also indicated that two teaching strategies had the same effect on promoting students' performance of near transfer and far transfer. Modelling has often been considered as a significant factor, meaning that notable changes occurred when compared to non-modelling conditions, but this did not always mean that learning was occurring. Campbell et al. (2011) compared the difference between two instructional conditions, model-based inquiry and traditional demonstration and lecture on student outcomes (science content, scientific process/reasoning, nature of science, and attitudes toward science) in physics classrooms. There were no significant differences in the results between groups. This seemed to suggest that appropriate analogical activities benefit students' transferability, as both groups implemented teaching materials with the same analogy. This finding is consistent with a previous study by Schönborn and Bögeholz (2009), whose study focused on the nature and role of transfer and translation in biology, which required moving across more than one external representation that delivered the same or different biological ideas. In this study, multiple forms of analogy were used such as computer simulations, pictures, and verbal representations, which may support the linkage and integration of information for fostering content understanding and transferability. On the other hand, it seems to suggest that incorporating modelling processes has no additional learning effect regarding students' near and far transfer.

The qualitative analysis demonstrated how two groups of students developed their models over different transfer distances. It was found that the MBT group built more correct models, which included a more accurate element of the atomic structure such as electrons and nucleus. Even though the MBT group outperformed the ABT group in the generation of initial models, they had a similar product in the near and far transfer items. Successful cases in both groups showed that students had the ability and awareness to apply their initial models to another model. Students in the MBT group were able to transform a stable mental model (such as the Bohr atomic model) to a similar situation with a little revision by giving required quantitative information. In comparison with the ABT group, although students were able to develop an atomic model for near transfer, they seemed to rather choose a new model than reference their initial models. In far transfer items, both groups favoured changing their models to find a proper way to satisfy the given question. This finding could indicate that both groups decontextualised the model and reorganised it in a new context in such a way that it helped them make accurate decisions (Sampson et al., 2011; Schwarz et al., 2009). During the near transfer process, while utilising and evaluating the model in the new context, students could decide to reject the model or restart the process from the beginning (Galbraith & Stillman, 2006; Louca & Zacharia, 2012). Therefore, it was found that both instructional activities in this study could foster students' modelling practice in the model transfer process (Bamberger & Davis, 2013; Justi & Gilbert, 2002; Louca & Zacharia, 2015).

Transfer tasks are still relatively rare in educational studies (Sasson & Dori, 2015). The empirical literature has reported difficulty in achieving transfer (De Corte, 2003). The ability to read and draw sub-micro representation phenomena is related to one's reasoning abilities. The ability to transfer is closely aligned to reasoning, which has a correlation with the students' scientific knowledge (Devetak & Glažar, 2010). The qualitative analysis of the student models revealed the difficulties the students had in transferring understanding of the concept of atomic structure, especially at the nanoscale, which is compatible with previous studies on learning the atomic structure (Sunyono & Sudjarwo, 2018; Wang & Barrow, 2013). In both groups, a considerable proportion of the students failed to identify the quantitative relationship of atomic structure. They were unable to figure out the number of electrons of each orbital. For most students, combining atomic structures to develop a molecular model was unattainable, and it required additional support and experience.

Conclusions and Implications

This study adds to the ongoing conversation about analogy and modelling in science education and contributes empirical evidence to justify the use of analogies and modelling in improving content understanding and transferability. To address the first two research questions, the quantitative analysis found that with the appropriate

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implementation of two instructions, MBT and ABT, both ways could significantly increase students' content understanding and transferability in the context of the atomic structure. Particularly, MBT could better support students with longer knowledge retention. The students' ability to transfer in both groups showed the same increase in near and far transfer items, but the MBT group could develop better initial models than the ABT group. This suggested that the transfer changes made in the two groups are related to the use of analogy, but the use of modelling has little or no added effect. The qualitative analysis responded to the third research question. The results indicated that both of the groups could be competent with transfer tasks after experiencing instructions, but challenges and difficulties in the accuracy of near and far transfer still exist because of students' inadequate scientific knowledge. This result emphasized the relationship between the mastery of scientific knowledge and transfer level.

These results have practical implications for science education. Modelling-based teaching (MBT) may be more effective for enhancing and retaining students' content understanding, but there is no evidence for increasing short-term transferability in comparison with analogy-based instruction. Moreover, appropriate implementation with analogy can enable a better understanding of the concepts of the atomic structure and students' transferability. Instructors should keep in mind how and what kind of analogies are favourable for teaching specific science knowledge, such as multiple forms of analogy, critical use of analogies, comparing the unshared features between analogy and target concept, based on a student-centred environment, and emphasising the limitation of analogy. This study provides an insight into how two educational interventions in the content of atomic structure are implemented for promoting students' learning outcomes. Further research could focus on analogy with other pedagogical support to explore which method can generate substantial learning effects when compared to analogy activities without support.

References

Al-Balushi, S. M., & Al-Hajri, S. H. (2014). Associating animations with concrete models to enhance students' comprehension of different visual representations in organic chemistry. *Chemistry Education Research and Practice*, *15*(1), 47–58. https://doi.org/10.1039/C3RP00074E

Bamberger, Y. M., & Davis, E. A. (2013). Middle school science students' scientific modelling performances across content areas and within a learning progression. *International Journal of Science Education*, *35*(2), 213–238. https://doi.org/10.1080/09500693.2011.624133

Boo, H. K., & Toh, K. A. (1997). Use of analogy in teaching the particulate theory of matter. *Teaching and Learning*, *17*(2), 79-85. https://repository.nie.edu.sg/bitstream/10497/417/1/TL-17-2-79.pdf

Bransford, J. D., & Schwartz, D. L. (1999). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education*, *24*(1), 61–100. https://doi.org/10.2307/1167267

Brown, S., & Salter, S. (2010). Analogies in science and science teaching. *American Journal of Physiology- Advances in Physiology Education*, *34*(4), 167–169. https://journals.physiology.org/doi/full/10.1152/advan.00022.2010

Bryman, A., & Cramer, D. (2009). Quantitative data analysis with SPSS 14, 15 & 16: A guide for social scientists. Routledge.

Buckley, B. C., Gobert, J. D., Kindfield, A. C. H., Horwitz, P., Tinker, R. F., Gerlits, B., Wilensky, U., Dede, C., & Willett, J. (2004). Model-based teaching and learning with BioLogica™: What do they learn? How do they learn? How do we know? *Journal of Science Education and Technology*, *13*(1), 23–41. https://doi.org/10.1023/b:jost.0000019636.06814.e3

Çalik, M., & Ayas, A. (2005). An analogy activity for incorporating students' conceptions of types of solutions. *Asia-Pacific Forum on Science Learning and Teaching*, *6*(2), 1–3.

Campbell, T., Oh, P. S., & Neilson, D. (2012). Discursive modes and their pedagogical functions in model-based inquiry (MBI) classrooms. *International Journal of Science Education*, *34*(15), 2393–2419. https://doi.org/10.1080/09500693.2012.704552

Campbell, T., Zhang, D., & Neilson, D. (2011). Model based inquiry in the high school physics classroom: An exploratory study of implementation and outcomes. *Journal of Science Education and Technology*, *20*(3), 258–269. https://doi.org/10.1007/s10956-010-9251-6

Chittleborough, G., & Treagust, D. F. (2007). The modelling ability of non-major chemistry students and their understanding of the sub-microscopic level. *Chemistry Education Research and Practice*, *8*(3), 274–292. https://doi.org/10.1039/B6RP90035F

Chiu, M., & Lin, J. (2005). Promoting fourth graders' conceptual change of their understanding of electric current via multiple analogies. *Journal of Research in Science Teaching*, *42*(4), 429–464. https://doi.org/10.1002/tea.20062

Cin, M. (2007). Alternative views of the solar system among Turkish students. *International Review of Education*, *53*(1), 39–53. https://doi.org/10.1007/s11159-006-9029-5

Cumming, J. M., & De Miranda, M. A. (2012). Reducing retroactive interference through the use of different encoding techniques: An exploration of pre-test/post-test analyses. *International Journal of Higher Education*, *1*(1), 22–31. https://doi.org/10.5430/ijhe.v1n1p22

Dagher, Z. R. (1994). Does the use of analogies contribute to conceptual change? *Science Education*, *78*(6), 601–614. https://doi.org/10.1002/sce.3730780605

https://doi.org/10.33225/jbse/22.21.325

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

Dangur, V., Avargil, S., Peskin, U., & Dori, Y. J. (2014). Learning quantum chemistry via a visual-conceptual approach: Students' bidirectional textual and visual understanding. *Chemistry Education Research and Practice*, *15*(3), 297–310. https://doi.org/10.1039/c4rp00025k

Devecioglu-Kaymakci, Y. (2016). Embedding analogical reasoning into 5E learning model: A study of the solar system. *Eurasia Journal of Mathematics, Science and Technology Education*, *12*(4), 881–911. https://doi.org/10.12973/eurasia.2016.1266a

Devetak, I., & Glažar, S. A. (2010). The influence of 16-year-old students' gender, mental abilities, and motivation on their reading and drawing sub-microrepresentations achievements. *International Journal of Science Education*, *32*(12), 1561–1593. https://doi.org/10.1080/09500690903150609

Dilber, R. (2012). The effects of analogy on students' understanding of direct current circuits and attitudes towards physics lessons. *European Journal of Educational Research*, *1*(3), 211–223. https://doi.org/10.12973/eu-jer.1.3.211

Dori, Y. J., & Sasson, I. (2013). A three-attribute transfer skills framework-part I: Establishing the model and its relation to chemical education. *Chemistry Education Research and Practice*, *14*(4), 363–375. https://doi.org/10.1039/c3rp20093k

Dukerich, L. (2015). Applying modeling instruction to high school chemistry to improve students' conceptual understanding. *Journal of Chemical Education*, *92*(8), 1315–1319. https://doi.org/10.1021/ed500909w

Else, M. J., Clement, J., & Rea-Ramirez, M. A. (2008). Using analogies in science teaching and curriculum design: Some guidelines. *Model Based Learning and Instruction in Science*, (pp. 215-231). Dordrecht: Springer.

Eryilmaz Muştu, Ö., & Özkan, E. B. (2019). Determining the pre-service teachers' perceptions of atom and atomic structure through word association test. *Asia-Pacific Forum on Science Learning and Teaching*, *20*(1), 1–30. https://eric.ed.gov/?id=EJ1233471

Galbraith, P., & Stillman, G. (2006). A framework for identifying student blockages during transitions in the modelling process. *ZDM-International Journal on Mathematics Education*, *38*(2), 143–162.

Gentner, D., & Stevens, A. L. (1983). *Mental models*. Psychology Press.

Gilbert, J. K., & Justi, R. (2016). *Modeling based teaching in Science education*. Springer.

Gobert, J. D., & Buckley, C. (2000). Introduction to model-based teaching and learning in science education. *International Journal of Science Education*, *22*(9), 891–894. https://doi.org/10.1080/095006900416839

Gobert, J. D., & Pallant, A. (2004). Fostering students' epistemologies of models via authentic model-based tasks. *Journal of Science Education and Technology*, *13*(1), 7–22. https://doi.org/10.1023/B:JOST.0000019635.70068.6f

Goh, N. K., Chia, L. S., & Tan, D. (1994). Applications and analogies: Some analogies for teaching atomic structure at the high school level. *Journal of Chemical Education*, *71*(9), 733–734. https://doi.org/10.1021/ed071p733

Gray, M. E., & Holyoak, K. J. (2021). Teaching by analogy: From theory to practice. *Mind, Brain, and Education*, *15*(3), 250–263. https://doi.org/10.1111/mbe.12288

Greca, I. M., & Moreira, M. A. (2000). Mental models, conceptual models, and modelling. *International Journal of Science Education*, *22*(1), 1–11. https://doi.org/10.1080/095006900289976

Heng, C. K., & Karpudewan, M. (2017). Facilitating primary school students' understanding of water cycle through guided inquiry-based learning. *Overcoming Students' Misconceptions in Science* (pp. 29-49). Springer. https://doi.org/10.1007/978-981-10-3437-4_3

Johnson-Laird, P. N. (1983). *Mental models: Towards a cognitive science of language, inference, and consciousness*. Harvard University Press.

Justi, R. S., & Gilbert, J. K. (2002). Modelling, teachers' views on the nature of modelling, and implications for the education of modellers. *International Journal of Science Education*, *24*(4), 369–387. https://doi.org/10.1080/09500690110110142

Kassai, R., Futo, J., Demetrovics, Z., & Takacs, Z. K. (2019). A meta-analysis of the experimental evidence on the near-and far-transfer effects among children's executive function skills. *Psychological Bulletin*, *145*(2), 165. http://dx.doi.org/10.1037/bul0000180

Khan, S. (2007). Model-based inquiries in chemistry. *Science Education*, *91*(6), 877–905. http://dx.doi.org/10.1002/sce.20226

Lave, J. (1988). *Cognition in practice: Mind, mathematics and culture in everyday life*. Cambridge University Press.

Lee, S. W. Y., Chang, H. Y., & Wu, H. K. (2017). Students' views of scientific models and modeling: Do representational characteristics of models and students' educational levels matter? *Research in Science Education*, *47*(2), 305–328. https://doi.org/10.1007/s11165-015-9502-x

Louca, L. T., & Zacharia, Z. C. (2012). Modeling-based learning in science education: cognitive, metacognitive, social, material and epistemological contributions. *Educational Review*, *64*(4), 471–492. https://doi.org/10.1080/00131911.2011.628748

Louca, L. T., & Zacharia, Z. C. (2015). Examining learning through modeling in K-6 science education. *Journal of Science Education and Technology*, *24*(2–3), 192–215. https://doi.org/10.1007/s10956-014-9533-5

Maia, P. F., & Justi, R. (2009). Learning of chemical equilibrium through modelling-based teaching. *International Journal of Science Education*, *31*(5), 603–630. https://doi.org/10.1080/09500690802538045

Marton, F. (2006). Sameness and difference in transfer. *The Journal of the Learning Sciences*, *15*(4), 499–535. https://doi.org/10.1207/s15327809jls1504_3

Mauro, M. F. D., & Furman, M. (2016). Impact of an inquiry unit on grade 4 students' science learning. *International Journal of Science Education*, 38(14), 2239-2258. https://doi.org/10.1080/09500693.2016.1234085

May, D. B., Hammer, D., & Roy, P. (2006). Children's analogical reasoning in a third-grade science discussion. *Science Education*, *90*(2), 316–330. https://doi.org/10.1002/sce.20116

Mayr, S., Erdfelder, E., Buchner, A., & Faul, F. (2007). A short tutorial of GPower. *Tutorials in Quantitative Methods for Psychology*, *3*(2), 51–59.

McKagan, S. B., Perkins, K. K., & Wieman, C. E. (2008). Why we should teach the Bohr model and how to teach it effectively. *Physical Review Special Topics-Physics Education Research*, *4*(1), 10103. https://doi.org/10.1103/PhysRevSTPER.4.010103

https://doi.org/10.33225/jbse/22.21.325

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

Ministry of Education in Taiwan (2018). *Curriculum standards for grades 1–12*. Taipei: Ministry of Education.

Nakiboglu, C. (2008). Using word associations for assessing non major science students' knowledge structure before and after general chemistry instruction: The case of atomic structure. *Chemistry Education Research and Practice*, *9*(4), 309–322. https://doi.org/10.1039/B818466F

Norman, D. A. (1983). Some observations on mental models. *Mental Models*. Psychology Press, pp. 15–22, Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers. https://doi.org/10.1039/b818466f

Orgill, M., Bussey, T. J., & Bodner, G. M. (2015). Biochemistry instructors' perceptions of analogies and their classroom use. *Chemistry Education Research and Practice*, *16*(4), 731–746. https://doi.org/10.1039/c4rp00256c

Park, E. J., & Light, G. (2009). Identifying atomic structure as a threshold concept: Student mental models and troublesomeness. *International Journal of Science Education*, *31*(2), 233–258. https://doi.org/10.1080/09500690701675880

Patton, M. Q. (2002). *Qualitative research & evaluation methods: Integrating theory and practice*. Sage Publications.

Perkins, D. N., & Salomon, G. (1992). Transfer of learning. *International Encyclopedia of Education*, *2*, 6452–6457.

Plomp, T. (2013). Educational design research: An introduction. *Educational Design Research*, 11–50. London: Routledge.

Rapp, D. N. (2005). Mental models: Theoretical issues for visualizations in science education. In *Visualization in science education* (pp. 43-60). Springer. https://doi.org/10.1007/1-4020-3613-2_4

Sala, G., Aksayli, N. D., Tatlidil, K. S., Tatsumi, T., Gondo, Y., Gobet, F., Zwaan, R., & Verkoeijen, P. (2019). Near and far transfer in cognitive training: A second-order meta-analysis. *Collabra: Psychology*, *5*(1). https://doi.org/10.1525/collabra.203

Salomon, G., & Globerson, T. (1987). Skill may not be enough: The role of mindfulness in learning and transfer. *International Journal of Educational Research*, *11*(6), 623–637. https://doi.org/10.1016/0883-0355(87)90006-1

Sampson, V., Grooms, J., & Walker, J. P. (2011). Argument-driven inquiry as a way to help students learn how to participate in scientific argumentation and craft written arguments: An exploratory study. *Science Education*, *95*(2), 217–257. https://doi.org/10.1002/sce.20421

Sarantopoulous, P., & Tsaparlis, G. (2004). Analogies in chemistry teaching as a means of attainment of cognitive and affective objectives: A longitudinal study in a naturalistic setting, using analogies with a strong social content. *Chemistry Education Research and Practice*, *5*(1), 33–50. https://doi.org/10.1039/B3RP90029K

Sasson, I., & Dori, Y. J. (2015). A three-attribute transfer skills framework-part II: Applying and assessing the model in science education. *Chemistry Education Research and Practice*, *16*(1), 154–167. https://doi.org/10.1039/c4rp00120f

Schönborn, K. J., & Bögeholz, S. (2009). Knowledge transfer in biology and translation across external representations: Experts' views and challenges for learning. *International Journal of Science and Mathematics Education*, *7*(5), 931–955. https://doi.org/10.1007/s10763-009-9153-3

Schwartz, D., Bransford, J., & Sears, D. (2005). Efficiency and innovation in transfer. In J. Mestre (Ed.), *Transfer of learning from a modern multidisciplinary perspective* (pp. 1-51). Information Age Publishing.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching*, *46*(6), 632–654. https://doi.org/10.1002/tea.20311

Seel, N. M. (2017). Model-based learning: A synthesis of theory and research. *Educational Technology Research and Development*, *65*(4), 931-966. https://doi.org/10.1007/s11423-016-9507-9

Settlage, J. (2007). Demythologizing science teacher education: Conquering the false ideal of open inquiry. *Journal of Science Teacher Education*, *18*(4), 461–467. https://doi.org/10.1007/s10972-007-9060-9

Slabin, U. (2017). Scientific eponym in educational universe. *Journal of Baltic Science Education*, *16*(2), 144-147. https://doi.org/10.33225/jbse/17.16.144

Sun, D., & Looi, C.-K. (2013). Designing a web-based science learning environment for model-based collaborative inquiry. *Journal of Science Education and Technology*, *22*(1), 73–89. https://doi.org/10.1007/s10956-012-9377-9

Sunyono, S., & Sudjarwo, S. (2018). Mental models of atomic structure concepts of 11th grade chemistry students. *Asia-Pacific Forum on Science Learning and Teaching*, *19*(1), 1–21.

Supasorn, S., & Promarak, V. (2015). Implementation of 5E inquiry incorporated with analogy learning approach to enhance conceptual understanding of chemical reaction rate for grade 11 students. *Chemistry Education Research and Practice*, *16*(1), 121–132. https://doi.org/10.1039/c0xx00000x

Taber, K. S. (2001). When the analogy breaks down: Modelling the atom on the solar system. *Physics Education*, *36*(3), 222–226. https://doi.org/10.1088/0031-9120/36/3/308

Taber, K. S. (2005). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education*, *89*(1), 94–116. https://doi.org/10.1002/sce.20038

Taber, K. S. (2013). Upper secondary students' understanding of the basic physical interactions in analogous atomic and solar systems. *Research in Science Education*, *43*(4), 1377–1406. https://doi.org/10.1007/s11165-012-9312-3

Taber, K. S. (2014). Ethical considerations of chemistry education research involving 'human subjects.' *Chemistry Education Research and Practice*, *15*(2), https://doi.org/109–113. 10.1039/C4RP90003K

Taber, K. S. (2018). The use of Cronbach's alpha when developing and reporting research instruments in Science Education. *Research in Science Education*, *48*(6), 1273–1296. https://doi.org/10.1007/s11165-016-9602-2

Trey, L., & Khan, S. (2008). How science students can learn about unobservable phenomena using computer-based analogies. *Computers and Education*, *51*(2), 519–529. https://doi.org/10.1016/j.compedu.2007.05.019

Tsai, C. C. (1999). Overcoming junior high school students misconceptions about microscopic views of phase change: A study of an analogy activity. *Journal of Science Education and Technology*, *8*(1), 83–91. https://doi.org/10.1023/A:1009485722628

https://doi.org/10.33225/jbse/22.21.325

Tsaparlis, G., & Papaphotis, G. (2009). High-school students' conceptual difficulties and attempts at conceptual change: The case of basic quantum chemical concepts. *International Journal of Science Education*, *31*(7), 895–930. https://doi.org/10.1080/09500690801891908

Vosniadou, S. (1988). Analogical reasoning as a mechanism in knowledge acquisition: A developmental perspective. Center for the Study of Reading Technical Report; no. 438. https://www.ideals.illinois.edu/bitstream/handle/2142/18000/ctrstreadtechrepv01988i00438_opt.pdf?sequence=1

Wang, C.-Y., & Barrow, L. H. (2013). Exploring conceptual frameworks of models of atomic structures and periodic variations, chemical bonding, and molecular shape and polarity: A comparison of undergraduate general chemistry students with high and low levels of content knowledge. *Chemistry Education Research and Practice*, *14*(1), 130–146. https://doi.org/10.1039/C2RP20116J

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, *92*(5), 941–967. https://doi.org/10.1002/sce.20259

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