Learning Nanoscience Concepts Through a Nanoscale Experience

Polly K. Lai, University of New South Wales, polly.k.lai@gmail.com
Michael J. Jacobson, The University of Sydney, michael.jacobson@sydney.edu.au
Micah Goldwater, The University of Sydney, micah.goldwater@sydney.edu.au

Abstract: Invisible nanoscale phenomena are difficult to learn, as people have no experience of observing nanoparticles and their behaviors in everyday life. To help address this issue, two different treatment conditions were developed: (a) working with two different Agent-Based Models (ABMs) and (b) watching two dynamic visualizations. An empirical study was conducted to compare students in these two groups in terms of reasoning strategies on assessments of declarative and explanatory knowledge as well as solving transfer problems. The findings suggest that the ABM students' reasoning strategies on the explanatory knowledge tasks and problem-solving activities seemed to have been influenced by the previous computationally embodied learning experience. Nevertheless, the dynamic visualization students seemed to rely on memory retrieval of information from the videos.

Keywords: Agent-Based Model, Dynamic visualization, Nanoscience education, Embodiment of thought

Introduction

Earlier research has argued that students contextualize their science experience into three different mental contexts consisting of imagination, previous experience, and the science investigation itself (Shepardson, Choi, Niyogi, & Charusombat, 2011). In line with this view, it is a big challenge for students to conceptualize and understand the behavior of individual nanoparticles emerges into the properties of matter. This is because their intuition about behaviors of objects is built upon the experience in their daily lives at the human scale instead of the nanoscale (Jones et al., 2013; Magana, Brophy, & Bryan, 2012; Peng, Isaac, & Wilkins, 2012). Thus, the question is how to provide students a nanoscale experience in terms of nanoscience phenomena investigations to enhanced learning of nanoscale concepts? To help facilitate the learning of nanoscience concepts, current research has explored various visualization approaches such 2D static images (Landau, Groscurth, Wright, & Condit, 2009), animated visualizations (Blonder & Dinur, 2011), and 3D virtual environments (Peng et al., 2012). However, research to date on the use of multimedia visualizations in nanoscience classrooms has mainly reported on students' interests and motivation rather than enhanced deep learning of nanoscience phenomena. Further, there are concerns that merely having students passively watch a visualization would not provide an interactive and cognitively engaging experience to gain a deep understanding of challenging concepts (Chi & Wylie, 2014).

In our previous work, we conducted an initial investigation of comparing students' learning outcomes of nanoscience concepts after learning with Agent-Based Models (ABMs) and dynamic visualizations respectively (Lai, Jacobson, & Markauskaite, 2016). We found that both treatment groups had a higher declarative knowledge gain; however, the students in the ABM group outperformed the students in the dynamic visualization group on the assessments of explanatory knowledge and transfer problem. To expand our previous work, this study explores the premise that whether learning with ABM provided an opportunity for students to experience an embodiment of thought, which leads to a higher learning gain on the assessments of explanatory knowledge and problem solving. This premise is based on Goldstone and Wilensky's (2008) argument, which they proposed that the use of "ABMs to teach complex systems topics fits under the wide umbrella of embodied cognition" (p.506). Therefore, according to the wide umbrella of embodied cognition, cognitive processes are influenced and shaped by the body, including the visual perceptual system, body morphology, motor system as well as the body's interactions with the surrounding world and manipulations of objects in the environment (Barsalou, 2008; Clark, 1998; Gibbs, 2006). This study explores that using ABMs to learn nanoscale phenomena can provide an embodied experience through active hypothesis testing, manipulating individual objects (agents) to increasing an ability, for first-person perspective taking, and eliciting gestures to reason nanoscience concepts afterwards.

Based on the embodied cognition theory, we propose a Framework of Embodiment of Thought to compare and explore the impact of using ABMs and dynamic visualizations to learn nanoscience knowledge: (a) Perspective Taking (Clark, 1998; Soylu, 2016), (b) Causal Inference Making (Gibbs, 2006), (c) Motor-supported Thinking (Mahon & Caramazza, 2008; Schwartz & Holton, 2000). First, research has suggested that ABM learning environments present unique perspective taking challenges to learners (Sengupta & Wilensky, 2009). In ABM learning environments, for instance, students are able to observe an individual agent's actions such as how this agent behaves and interacts with its surroundings (a first-person perspective) and accumulates in an aggregate-level representation (a third-person perspective). In contrast, dynamic visualization learning environments provide a story line animation to represent the scientific concepts only from a third-person perspective. Second, embodied cognition theorists have argued that manipulating objects and exploratory procedures are useful in identifying objects and making goals meaningful (Gibbs, 2006). In other words, when people see a tool, they know what they are going to do with the tool for causal consequences (Gibson, 1986; Schwartz & Holton, 2000; Soylu, 2016). In line with this view, an ABM learning environment allows the learner to run hypothesis testing by setting parameters and exploring procedures and consequences. Thus, the learner knows she is the cause of the individual agent's behavior, and she also understands the causality directly from her perceptual and embodied experience. However, the information and behavior of dynamic visualizations do not change. The learner has no opportunity to test hypotheses and only passively receives information from the videos. Finally, Schwartz and Holton (2000) argued that mental simulations only mediate coupling of action and imagery in the context of manipulation. Given an ABM environment is allowed learners to manipulate and experience an individual agent behavior and interactions with its surroundings from the first-person perspective, and she also predicts and makes inferences about causality of the agent and the system. After learning with ABMs, she may be influenced by the ABMs and use spontaneous gestures and imagery to form their mental simulations from her past learning experience with the ABMs. Nevertheless, the dynamic visualizations provide a visual representation, learners may form their mental representations through their multimodal perceptions (de Koning & Tabbers, 2011). In short, we argue that the strength of learning with ABMs is how the control of simulations give opportunity for perceptually rich mental models of the nanoscale phenomena, and taking advantage of cognitive capacities in visuospatial thinking, motor simulation, and causal reasoning.

In order to understand why the students in the ABM group outperformed than the students in the dynamic visualization group on the assessments of explanatory knowledge and transfer problems (Lai et al., 2016, April), a study was conducted to compare students' reasoning strategies on declarative as well as explanatory knowledge and transfer problems after learning from the ABMs and dynamic visualizations respectively.

In line with this, the research questions are:

1. Do students change their reasoning strategies in terms of embodiment of thought from the pre-test to post-test on declarative and explanatory knowledge?
2. Are students' reasoning strategies grounded in embodiment of thought on the post transfer problems?

This study explored whether students' reasoning strategies were engaged in the embodiment of thought prior to and after the learning activities. Students' pre-test and post-test think-aloud protocols were analysed in detail by the three indicators of reasoning strategies in terms of an embodiment of thought framework we propose in this paper. According to the Embodiment of Thought Framework, this study hypothesised that the use of ABMs helps students' conceptualization development grounded in embodiment thought processes and influence their reasoning strategies afterward, particularly, on the explanatory knowledge and problem solving.

Methods

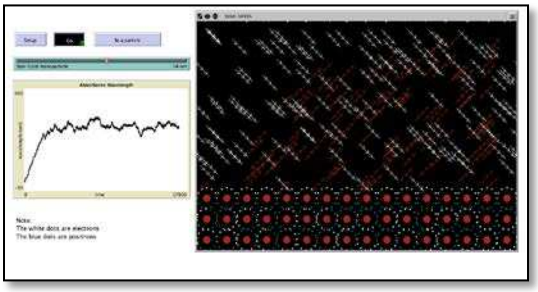
Research design and procedure

This study had a mixed method design that consisted of a quasi-experimental intervention, and think-aloud tasks, over one three-hour period (see Table 1). The experimental condition investigated the efficacy of the ABM approach using two Agent-Based Models, which were developed by the first author using NetLogo (Wilensky, 1999). The models provided interactive and manipulative simulations for learning two target nanoscience topics: Nano Gold (see Figure 1 (left)) and Nano Magnetics. In contrast, the comparison condition involved two dynamic visualizations, which were also developed by the first author, for the same topics and activities (see Figure 1 (right)). Finally, think-aloud tasks were used in this study to assess participants' cognitive processes prior to and after the interventions.

Participants were undergraduate students at Australian universities, who were enrolled in nanoscience programs. Of the twenty-seven participants (average 20.1 years old), seven were females, and 20 were males. Participants received instruction for the think-aloud task and practiced the think-aloud process before the pre-test think-aloud tasks. After completing the pre-test think-aloud tasks, participants were introduced to either the ABM or the dynamic visualization learning environments depending on their group assignment. In the experimental group (14 students), the introduction briefly explained how to use Nano Gold and Nano Magnetics models to run the simulations related to the learning activities. In the comparison group, 13 students were told that they were able to start, stop and rewind the videos as much as they wanted to during the learning activities. Participants then were given two hours to complete learning activities online with the ABMs or the videos individually. Finally, both groups were administrated the post-test think-aloud tasks, which included all the items on the pre-test think-aloud questions and two extra transfer problems.

Table 1: Study design

Activities	Content	Experimental Condition	Comparison Condition
Pre-test think-aloud tasks			
1	Size-Dependent Property in Nano Gold	Gold nanoparticles model	Gold nanoparticles video
2	Size-Dependent Property in Nano Magnetics	Nano magnetics model	Nano magnetics video
3	Comparison and Contrast	Compare and contrast two models	Compare and contrast two videos
Post-test think-aloud tasks			



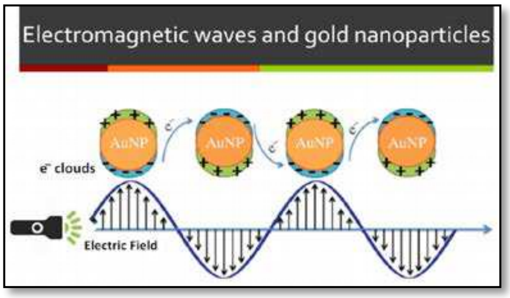


Figure 1. Nano Gold model (left) and Nano Gold video (right) were used in the study.

Table 2: Pre-test and post-test think-aloud questions

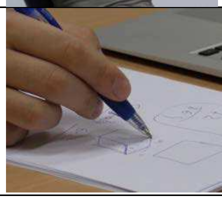
Assessment Type	Questions
Declarative nanoscience knowledge tasks	Q1: What is the concept of surface area to volume ratio?
	Q2: Do the individual atoms or molecules of a substance have the same properties as the bulk substance or not?
Explanatory nanoscience knowledge tasks	Q3: Why does an increase in surface area change the way materials interact with each other on a molecular or atomic level?
	Q4: Why are properties not the same in all three directions (one-, two- and three-dimensional) in a given material?
Transfer problems (Post-test only)	P1: Imagine you are on a clear sunny day. The sky above us looks bright blue. A few hours later, in the evening, the sunset puts on a brilliant show of reds, pinks and oranges. Why is the sky blue? Why twilight and sunset are in red or orange color? Please write a short essay to answer this question.
	P2: Hard drives and data recording tapes are applications of nanotechnology that depend on magnetic materials. When a magnet is cut into small enough pieces, its magnetic moment becomes increasingly sensitive to the random motion of particles. At a certain point, known as the superparamagnetic limit. Recently, you got a mission from your supervisor to develop a device with maximum storage. Please describe how you will achieve this mission.

Data sources and analysis

Multiple sources of data were gathered prior to, and at the conclusion of the study, including: (a) video/audio recordings of pre- and post-test think-aloud protocols; and (b) video data of participants' bodily movements during pre- and post-test think-aloud tasks.

The transcripts of participants' think-aloud protocols were integrated with the video recordings of their bodily movements during the think-aloud tasks, and analyzed in detail by using a coding scheme for reasoning strategies (see Table 3), which was built on the Framework of Embodiment of Thought proposed in this paper. It provided a mechanism to explore whether using ABMs and dynamic visualizations to learn about nanoscience concept might influence participants' reasoning strategies afterwards, precisely in relation to the target concepts. Two coders each coded 60% of the subset with a 20% overlap for the coding reliability. The inter-rater reliability was good with the Kappa (κ) = .86, with a significance of $p < .0005$. After coding, the percentage of participants, who showed each indicator during the think-aloud tasks, was calculated.

Table 3: Coding scheme for reasoning strategies

Indicators		Description	Example
Perspective Taking	A first- to third-person perspective	A verbal explanation involves: (a) an agent-level view: illustrating how an individual nanoparticle behave and interact with its neighbours, and (b) an aggregate-level view: illustrating how individual nanoparticles emerge to system properties.	*You know like the gold that if the particular is smaller, then more space between each other, and the light with different wavelength hits it, resulting in different colours.*
	A third-person perspective	A verbal explanation involves: an aggregate-level view: illustrating a system-level phenomenon.	*Gold nanoparticles at 12 nanometres appear to be red in humane eye.*
Causal Inference Making	Generating causal inferences	A verbal explanation involves idea generating related to causality.	*The sky is blue because of the size of particles in the atmosphere. The particles in the atmosphere are reflecting and refracting the blue light wavelengths that come from the sun.*
	Information retrieval	A verbal explanation mentions prior experience and knowledge.	*Well, from the video tow. I think the answer is not.*
Motor-supported Thinking	Use of gestures	A verbal explanation supported by gesturing.	 *When the light hits the nanoparticle…*
	Use of handwriting/ drawing	A verbal explanation supported by handwriting/drawing on a blank paper.	 *This is surface area.*

Results

Declarative and explanatory knowledge tasks

In the ABM group (see Figure 2 (left)), there was an interesting difference between pre-test and post-test think-aloud tasks on Perspective Taking. First, prior to the intervention with ABMs, none of students showed a first- to third-person perspective (an agent- to aggregate-level view). However, after the intervention with ABMs, 71% of students' verbal responses demonstrated that they presented their scientific understandings from an agent-based perspective (a first-person perspective) to an aggregate-level perspective (a third-person perspective). Second, 64% of students took a third-person perspective (an aggregate-level view) to explain the concept of structure matter at the nanoscale on the pre-test. In contrast, only 18% of students took a third-person perspective on the post-test. In addition, there was a slight increase in the number of students (64% to 68%) who generated causal inferences from the pre- to post-test think-aloud protocols; on the other hand, the percentage of students on recalling information from previous knowledge to respond to the tasks decreased (100% to 68%). Although none of students took notes to structure their ideas prior to and after the interventions, an increased number of students used gestures to support their thinking (11% to 43%).

Figure 2 (right) shows that most students' verbal responses reflected a third-person perspective (an aggregate-level view) on both the pre-test and post-test think-aloud tasks (88% and 100%), and none of students used a first- to third-person perspective (an agent- to aggregate-level view) on either task. Prior to the intervention, although 19% of students drew causal inferences to construct their ideas, after the intervention, all of students changed to recall previous information for idea generations. Although 8% of students used gestures associated with their ideas, prior to the intervention, there were no gestures at all, after the intervention. In addition, there was a slightly increased number of students taking notes to form their mental representations from the pre- to post-test declarative tasks (12% to 15%).

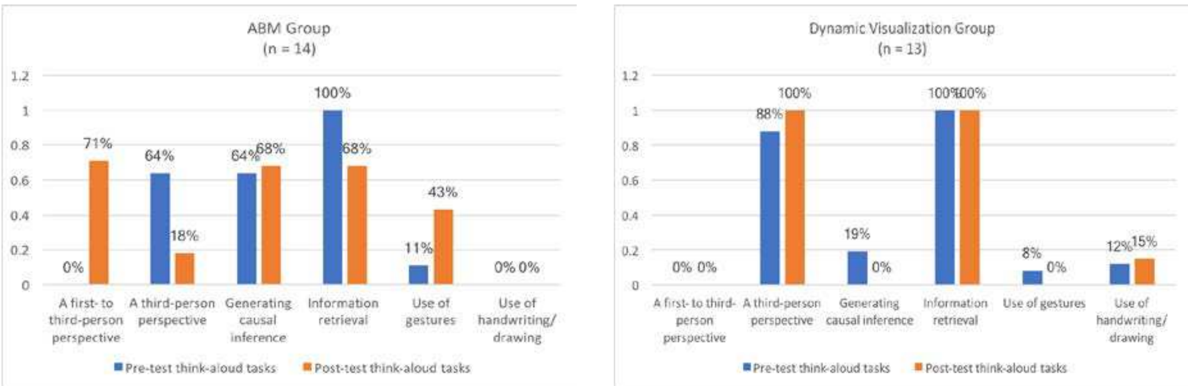


Figure 2. The percentage of students in the ABM group (left) and students in the Dynamic Visualization group (right) showing the reasoning strategies on pre-test and post-test think-aloud tasks on declarative knowledge.

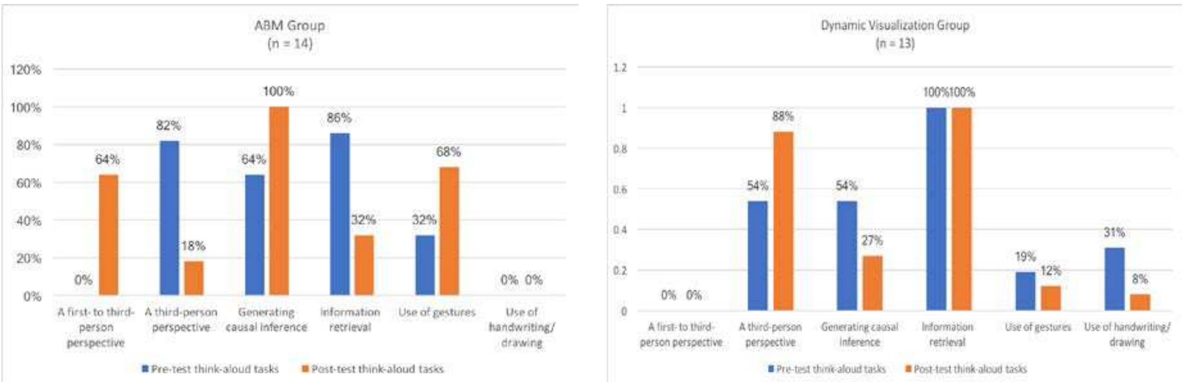


Figure 3. The percentage of students in the ABM group (left) and students in the Dynamic Visualization group (right) showing the reasoning strategies on pre-test and post-test think-aloud tasks on explanatory knowledge.

For the explanatory knowledge tasks, Figure 3 (left) shows that in the ABM group, prior to the intervention, the verbal responses of most students (82%) showed a third-person perspective (an aggregate-level view) for idea constructions. However, after the intervention, 64% of students provided their explanations in the way, which switched between a first-person perspective (agent-based view) and a third-person perspective (the aggregate-level view) to link the agent-level interactions with emergent outcomes in the ABMs. In addition, 86% of students constructed their ideas on the pre-test explanatory tasks by recalling their previous knowledge. In contrast, on the post-test explanatory tasks, all the students (100%) drew causal inferences for idea constructions. Moreover, there was an increased percentage of students spontaneously using gestures to simulate the nanoscientific phenomena from the pre- to post-test explanatory tasks (32% to 68%). None of the students wrote/drew on the blank paper provided on either task.

In the dynamic visualization group (see Figure 3 (right)), there was an increased number of students providing their explanations from a third-person perspective (an aggregate-level view) from the pre- to post-test explanatory tasks (54% to 88%). None of the students' verbal responses showed a first- to third-person perspective (an across agent- to aggregate-level view) during their explanations on either task. Additionally, all of the students utilized the similar reasoning strategies to respond to the pre- and post-test explanatory tasks by recalling previous knowledge. It is also noteworthy that fewer students drew causal inferences after the intervention with the videos than prior to the intervention (27% versus 54%). After the intervention with videos, there was a slightly decreased number of students using gestures (19% to 12%), as well as writing/drawing on the blank paper provided for idea constructions (31% to 8%).

Transfer problems

Transfer problems in both groups were conducted after the interventions only. Figure 4 shows notable differences between groups in terms of showing the reasoning strategies during the transfer problems. A Fisher Exact test indicated that the ABM groups had a significantly higher percentage of students demonstrated the solution constructions across an agent-based view to an emergent system view (a first- to third-person perspectives) compared with the dynamic visualization group, $x^2(1, n = 27) = 23.14$, exact $p = .000$, phi = -1.0. In contrast, the percentage of students in the dynamic visualization group was significantly higher than the ABM group in regards to the use of a third-person perspective (an aggregate-level view) on solutions, $x^2(2, n = 27) = 27$, exact $p = .000$, phi = 1.0. Further, all of the students in the ABM group developed solutions based on generating causal inferences, $x^2(2, n = 27) = 14.54$, exact $p = .001$, phi = .73 All the students in the dynamic visualization group searched the solutions from their prior knowledge, $x^2(2, n = 27) = 12.53$, exact $p = .002$, phi = .68. Finally, it is also noteworthy that there was a significant difference between groups regarding using gestures as a support for their problem, $x^2(2, n = 27) = 21.66$, exact $p = .000$, phi = .9 In other words, the ABM group had 85% of students spontaneously using gestures for supporting problem-solving, while the dynamic visualization group only had 8% of students did so. Although 35% of students in the dynamic visualization group wrote on the blank paper provided to support their solutions, none of students in the ABM group used note-taking on the post-transfer problems, $x^2(1, n = 27) = 14.54$, exact $p = .000$, phi = .73.

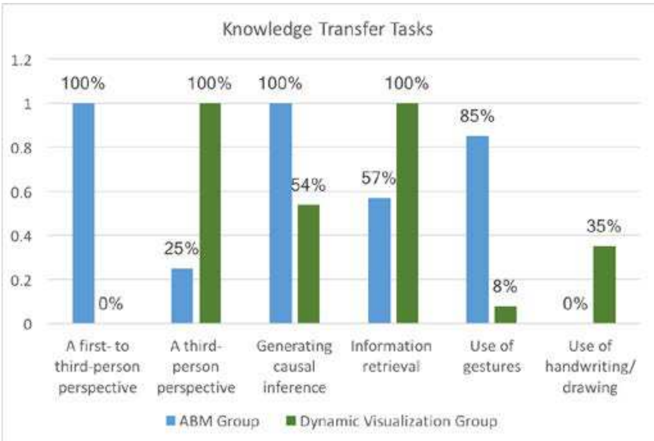


Figure 4. The percentage of students in the ABM group (in blue) and students in the Dynamic Visualization group (in green) showing the reasoning strategies on post-test think-aloud tasks on transfer problems.

Discussion and conclusion

The results of this study show that the students in the ABM group during the post-test think-aloud tasks were found to use significantly more of the proposed reasoning strategies in terms of embodiment of thought—(a) Perspective Taking: a first- to third-person perspective, (b) Causal Inference Making: generating causal inferences, and (c) Motor-supported Thinking: use of gestures—than the dynamic visualization group did. For example, the students in the ABM group changed their perspectives from a third-person perspective to a first- to third-person perspective to describe the nanoscale concepts. They did not seem to change their ideas on the post-test tasks by searching their previous knowledge, but rather they started generating causal inferences to conceptualize the nanoscale knowledge in the post-test. This suggests that regarding declarative knowledge, students' reasoning strategies were slightly influenced by learning with the ABMs. Moreover, the most students changed their reasoning strategies from the pre-test to post-test on explanatory knowledge tasks and transfer problems. For example, during the pre-test, students searched their previous knowledge from a third-person perspective to structure their ideas. However, during the post-test, the ABM students generated causal inferences from a first- to third-person perspective and they were found to spontaneously use gestures as part of their reasoning strategies.

According to recent research in an embodiment framework of cognition, it has been proposed that interacting with tools may change ways an individual thinks and perceives (Gibbs, 2006; Soylu, 2016). In other words, when one manipulates tools, which is usually related to particular goals, this interaction may change an individual's perceptions and conceptualizations of the environment. The results of this study are consistent with this embodiment view of tools as mediating changes in ways of thinking and perceiving phenomena. For example, the tools used by the ABM group allowed the students to manipulate an individual nanoparticle by setting up the parameters to observe the individual nanoparticle's behaviors and interactions (a first-person perspective), and then to explore the consequences of their setting (a third-person perspective). This may have set up opportunities for the students to notice that these parameters settings had a causal impact on the behavior of the nanoparticle (the agent), even though the students did not have direct bodily contact with the nanoparticle. In this way, the ABMs functioned as a learning tool that provided a "virtual" nanoscale learning experience whereby the learner has experiences via by their bodily movements with the model, and in turn to see in the behavior of the agents in the model causal consequences of their selections.

This paper proposes that the students in the ABM group had computationally mediated embodied experiences that helped them construct new schema about the nanoscale experience in terms of the target concepts. This in turn allowed them to "run" mental simulations based on these new schema as part of their reasoning strategies when working on the post-test explanatory knowledge tasks and problems. Earlier research has demonstrated a mental simulation recruits the same neural networks involved in action and perception (Gallese & Lakoff, 2005; Jeannerod, 2007), and thus functions as a form of re-enactment of past sensorimotor experience (Borghi & Cimatti, 2010). From this cognitive perspective, it seems that the use of gestures by the ABM group indicated the running of mental simulations during post-test explanatory knowledge and problem solving, and it was the use of the ABMs that provided the "past sensorimotor experience" for students to construct the cognitive representations (i.e., schema) necessary to support these mental simulations.

In contrast, the students watching the videos were only permitted a limited set of interactions with the visualization—albeit with "focus" on selected content information. According to Lai et al. (2016, April), this type of learning activity has been found to foster the acquisition of declarative knowledge but not to be effective for achieving the higher order learning outcomes of explanatory knowledge and knowledge transfer. Most students in the dynamic visualization group had no change from the pre-test to post-test think-aloud tasks in their reasoning strategies in that they took a third-person perspective and recalled previous information to structure their ideas during their assessments. Further, students in the dynamic visualization group demonstrated their reasoning strategies were influenced by the videos in terms of reproductive memory of declarative information and ability to recall images from the videos to draw figures when answer the post-test questions.

In general discussion, this study has found students' reasoning strategies during the post-test explanatory knowledge tasks and problem solving activities have been influenced by their previous experience of using of ABMs, which suggests that embodied cognition have been a critical aspect of this type of learning experience. This is because students' mental imagery activates in the ABM group were integral to simulating and activating gestures were highly compatible with an embodiment framework of cognition (Gibbs, 2006; Hostetter & Alibali, 2008). The mental simulations were based on the previous experience of students' perceptual and motor processes associated with the interactions of the ABM learning environment.

However, current work on embodied cognition and learning design merely focus on physical activity. The design of this body of research was: (a) using physical motion/gestures as a control mechanism for three-dimensional (3D) game-based learning (e.g., virtual environment; Lindgren & Johnson-Glenberg, 2013); or (b) using fingers tracing on paper/iPad as a control mechanism (e.g., Hu, Ginns, & Bobis, 2015); Although the use of physical activity might support enhanced learning, not all learning activities that involve physical activity can be regarded as embodied learning experience.

Moreover, to determine whether physical activities are actual factors in supporting enhanced learning, most research related to action, movement, and gesture studies tends to manipulate physical activities. However, the manipulation of physical activities might complicate research findings. For example, during learning activities, leaners' attention might be disturbed by factors such as remembering gesturing, or not gesturing, rather than learning contents. Another example is that using fingers to trace on paper/iPad might help learners focus on the information they are tracing, and then this concentration leads to learning gains, instead of finger tracing per se. Furthermore, earlier research has claimed that gestures are a natural way of expressing thoughts and spatial information (Hegarty et al., 2005). In line with this view, this study had no manipulation of physical activities. The gestures and handwriting/drawing in this study were students' strategy choices in a way to express their thoughts spontaneously after learning with the ABMs and dynamic visualizations respectively. In this sense, students moved their hands to simulate the nanoscale phenomena from previous learning experience with the ABMs, and thus, embodied their thought in actions.

In conclusion, the findings of this study are significant in three ways. First, this study has proposed a Framework of Embodiment of Thought with three indicators of reasoning strategy from which to differentiate embodied versus non-embodied learning experiences associated with learning technologies. Second, the findings of this study demonstrated that students in the ABM group spontaneously used gestures to reason the target nanoscale phenomena, which suggests the ABM approach may help students construct new schema and to generate mental simulations as part of their reasoning strategies when problem solving. As this was a small-scale study, there is limitation to the generalizability of the findings beyond the sample of university students who participated in the study. Overall, it is hoped this study might stimulate further interest in these research areas concerning the nature of innovative learning experiences for understanding difficult scientific knowledge and their underlying theoretical mechanisms.

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