sciendo

GEOLOGOS

Geologos 27, 3 (2021): 181–188
DOI: 10.2478/logos-2021-0020

Teaching scientific method to primary school pupils by using the example of adaptation of secondarily aquatic animals to the marine environment

Mateusz Antczak

University of Opole, Institute of Biology, ul. Oleska 22, 45-052 Opole, Poland; e-mail: mateusz.antczak@uni.opole.pl

Abstract

Science classes in public schools are usually strictly linked to several subjects and taught by reference to the reading-listening model. Non-formal educational institutions and events such as 'children universities' and science fairs (and to some degree also some private schools) implement elements of interdisciplinary teaching of science and learning through experiments and the use of scientific methods. Workshops conducted within non-formal educational structures prove that only is this method engaging and understandable to primary school pupils, it also is possibly much more effective than the traditional learning style for coding information and explaining common misconceptions in teaching evolution, palaeontology and biodiversity. The example of a scenario for science classes presented here (the so-called 'aquatic problem', i.e., adaptations of primarily terrestrial animals – amniotes – to the aquatic environment) uses simple props, such as everyday items, to address the problems that teachers in public school face. Thus, it can be implemented independently of school budgets and availability of school equipment.

Key words: Interdisciplinary, experiment-based learning, evolution, non-formal education

1. Introduction

Over many years, numerous educational studies have supplied ample proof that learning through experience is more effective than simply reading (listening) and repeating the studied material (Cutter-MacKenzie & Edwards, 2013; Campos & Sá-Pinto, 2013). Even in higher education, it is proposed that experience-based learning is much more effective. A good example is that of a palaeontological course at the University of Texas, described by Montgomery & Donaldson (2014), which constituted problem-based learning "*centered on fossils and rock samples selected from a research collection*" that was very highly rated by the students. Although in public schools (at all stages from Primary School to High School – ages 7 to 19) the listening-reading model still predominates, many teachers prepare additional activities for their pupils and students in order to improve the teaching process, especially in science classes. Scientific method and learning through experience is the main goal of non-formal educational institutions such as 'children universities' (regular meetings including lectures and workshops conducted by active scientists, usually for children aged 6 to 13) or at workshops during science festivals. These kinds of classes are usually provided by scientists who are specialists in a certain field and can provide not only different apparatuses and tools but, more importantly, a different view on teaching science. Here I present the example of the evolution of a secondarily aquatic lifestyle of primarily terrestrial vertebrates, as well as teaching of scientific method and problem-solving through experiments. Learning through experience, scientific method, and interdisciplinarity of science is important because these bring together the knowledge gained in different science classes so as to address complex questions (Maglaughlin & Sonnenwald, 2005) and integrate modes of thinking (You, 2017). The value of such an approach has been noted in the literature for many decades (Jacob, 1953; You, 2017). According to Jacob (1953), interdisciplinary training should begin as soon as a child (aged 6 or 7) enters school.

The study presented here is a preliminary inquiry into teaching evolutionary processes (specifically, the transition from land to oceans and freshwater settings) through scientific method in schools. Scientific method is here understood as a method of procedure that has characterised natural science since the 17th century, comprising systematic observation, measurement and experiment, and the formulation, testing and modification of hypotheses (Oxford English Dictionary, 2012). The implementation of scientific methods has proved to be engaging and effective in, for instance, the geosciences (topography, field studies, groundwater and weathering laboratories [see Hannula, 2003] and geomorphology [see Markley, 2010]). Evolution is long-term process that is not easily traced and recreated. However, as presented by Cleland (2001) amongst others, although historical science is not inferior to classical experimental science at first glance, this does not mean that historical processes (such as meteorite impacts) cannot be tested by scientific method. Considering this the aim is to set up a conceptual framework for experimental teaching methods using the example of adaptations of primarily terrestrial amniotes to the aquatic environment. Objectives include testing a four-step approach, describing students' misconceptions and teachers' problems in implementing experience-based learning in public schools.

2. Method

2.1. Theme and respondents

The interdisciplinary and experiment-based approach is rarely implemented in public schools, but often applied in non-formal educational courses. In view of this, the workshop presented here was conducted during science festivals, children's university classes and in a private school alongside biology courses. However, the given scenario combines biological issues with the use of physics, chemistry, geology and palaeontology (because adaptations to aquatic lifestyles can be traced not only in modern, but also extinct, species), and it should not be considered as a separate subject. Different educational backgrounds can bring complementary skills when considering any problem (Maglaughlin & Sonnenwald, 2005).

Workshops were given to ten groups of primary school pupils (around 150 participants, aged 7–12) in the years 2018–2020; participants were divided into age groups, i.e., 6–7, 8–9 and 10–12. No specific background was needed, although (especially in older groups), the lecturer might refer to knowledge gained during the first years of science education (such as distinguishing individual groups of vertebrates, the morphology of organisms as adaptations to environment and the knowledge that life on Earth in the past looked different from today's).

2.2. Background of scientific problem

The aim of the workshop is to teach scientific method and use problem-solving learning by using the example of evolutionary boundaries that primarily terrestrial animals encountered when adapting to a marine (or freshwater) environment. The whole set of such challenges is called 'the aquatic problem' (after the Alberta University online course, 'Ancient Marine Reptiles', 2015). All amniotes (i.e., animals with the capacity for embryonic development on land) are primarily terrestrial, which means that their ancestors were terrestrial. Some groups of primarily terrestrial amniotes have subsequently adapted to the aquatic environment, thus they are called secondarily aquatic animals. Different kinds of primarily terrestrial vertebrates adapted to the aquatic environment to varying degrees. For example, hippos walk on their toes on the bottom of the river, but need water to keep their skin moist; outside of water they secrete 'red sweat' which acts like a sunscreen and antibiotic (Saikawa et al., 2004). Crocodiles move smoothly both on land and in water (with such detailed adaptations like the specific design of the peripheral visual system; Nagloo et al., 2016), while sea turtles only leave the water to lay eggs (on the same beach where they hatched; e.g., Cassill, 2021) and whales spend their entire lives in the ocean (e.g., Pyeson, 2019). This means that these taxa occupy different places in the 'semi-aquatic spectrum'. Moreover, the fossil record

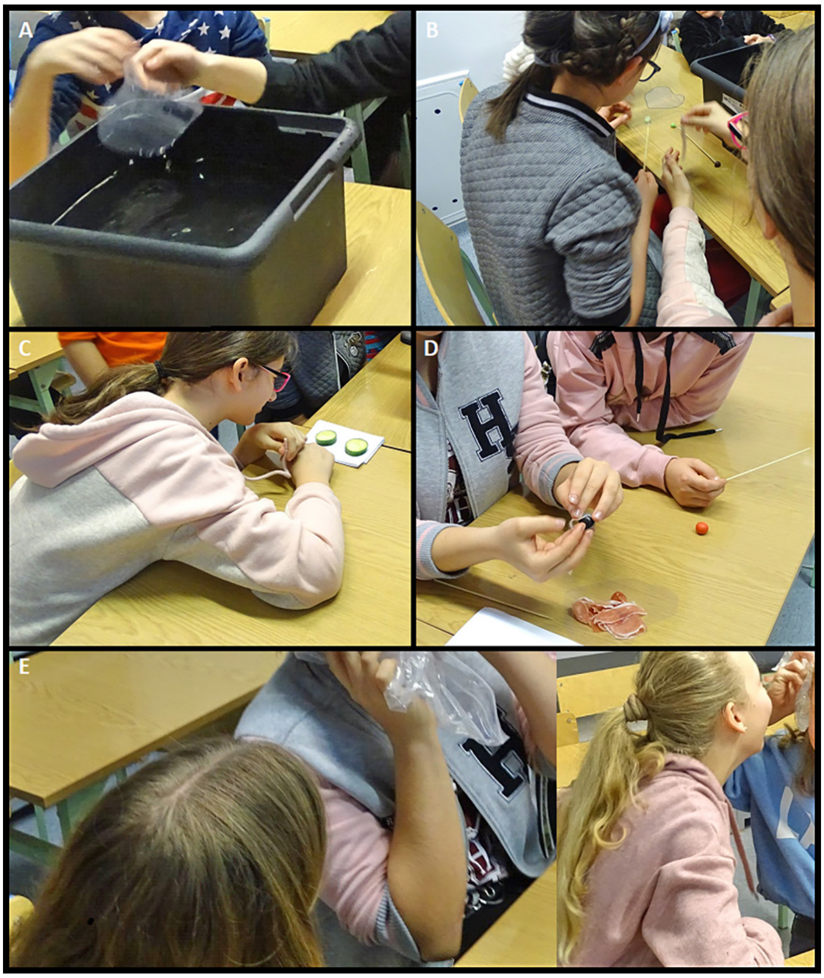

Fig. 1. Students conducting experiments during a workshop at a science festival (Opole, Poland; January 2020). **A –** Testing propulsion in water. Students waved their hands, three times in a row, in a large plastic bowl filled with water; firstly, with widespread fingers; secondly, with straight, joined fingers and, thirdly, with a plastic, hand-sized fin. They tried to compare the effectiveness of such moves, decide which is best and answer the question of what kind of limb yields the highest propulsion in water; **B –** Testing neutral buoyancy. Students observed a thin stick floating on water, like bones of terrestrial animals. By using the given props, they tried to make the stick sink (to achieve neutral buoyancy, as in the body of an aquatic animal). It is quite easy to have the stick sink using plasticine, or gluing stones, but an explanation is needed. Following the experiment, different methods of gaining neutral buoyancy were revealed: 1) pachyostosis (additional layers of bone which cause bone thickening), as seen in, for instance, manatees and plesiosaurs, 2) osteosclerosis (bone gaining a higher density through mineral deposition in inner bone cavities), as seen in, for example, turtles and extinct sloths, 3) swallowing rocks (gastroliths), as seen in, for instance, alligators, birds and ichthyosaurs; **C –** Testing salt acting on the organism. Students took a piece of cucumber with skin and one without, and some amount of salt on both pieces and observed. After some time, when the piece not protected by skin started to dehydrate, students had to answer how salt in water could be harmful to aquatic animals. Subsequently, several examples of dealing with excess salt could be demonstrated (for example, "sneezing" iguanas, "crying turtles"); **D –** Testing preserving body heat. To compare how terrestrial and aquatic environments are linked with losing heat, students produced three plasticine spheres. One (terrestrial environment) stayed on the table and two went into the aquatic setting (cold water); one without any protection and the other wrapped in fat (bacon plaster). After a few minutes students took out the spheres and compared their temperature. Finally, they answered the question of which of the two was warmest and why there was a difference between the spheres taken from the water. Ways to retain heat in water can be explained with the example of a walrus; **E –** Testing the senses: hearing and sight. Students put a long prop (stick, straw or spoon) in water (while part remains above water level) and observed the breakdown of the prop. Students also filled a large plastic bag with water, then put it to their ear and tried to understand what fellow students standing next to them were saying. After these experiments, students concluded that hearing and sight in water differed from hearing and sight on land, and tried to explain why that was. Adaptations of different animals to effective sight and hearing in water were given as examples (dolphins and echolocation, large-eyed ichthyosaurs and seals with a *tapetum lucidum*)**.**

shows that ancestors of modern semi-aquatic and aquatic amniotes also occupied different stages of this spectrum when compared with their descendants (e.g., Gingerich, 2003). This means that different groups of secondarily aquatic (or semi-aquatic) reptiles, mammals and birds adapted to the aquatic environment in different ways.

2.3. Workshop construction

The general problem is subdivided into six smaller issues that pupils need to solve by using designed experiments that employ simple props, so that these can be later repeated at home (or presented in school without the need to buy expensive materials). The 'aquatic problem' is here broken down into propulsion, neutral buoyancy, salt, temperature, hearing and sight issues (modified after the Alberta University online course, 'Ancient Marine Reptiles', 2015). Workshops are composed of lecture-like explanations and discussion parts, and experiments conducted by pupils or students (with instructions given by the lecturer), by using a large bowl of water and simple props, such as sticks, plasticine, plastic 'fins', small rocks, cucumbers, salt, a slice of bacon, etc. (Fig. 1, Table 1). The first experiment is inspired by the Alberta University online course, 'Ancient Marine Reptiles', 2015), while all others have been designed by myself.

The lecture-like elements discuss issues that are difficult to test, such as streamlined body shapes, body cover (problem of drag and water viscosity) and orientation in a fully-3D environment. However, most of these issues are tested by the pupils and students during classes (Table 1).

Table 1. Framework for implemention of scientific method through experience-based learning and activities during exemplary workshops devoted to the 'aquatic problem'.

Framework							
Scientific method	Observation	Scientific problem	Hypothesis / Prediction	Testing hypothesis	Conclusions		
Not observed Workshop adaptation of scientific method	Background	Question	Hypothesis or Prediction	Experiment	Explanation	Problem solved	
Example							
Problem and setting							Misconceptions
Propulsion Stiff-foil 'fin'	Showing anatomy of marine animals (having fins instead of legs)	How primarily terrestrial animals move in water?	They use fins instead of legs to 'push' from water	Test the propulsion in water. Use hand with non-clasped fingers, hand with clasped fingers, and hand with 'fin'	'Fin' gives more power than hand. Hand with clasped fingers gives more power than without it	Presenting different styles of using fins for propulsion	Not observed
Neutral buoyancy Chicken bone or stick imitating the bone + plasticine, small stones, crayons, pipe cleaners, straws, clothes, paper clips, glue, etc.	Terrestrial animals body floats, while aquatic species can control the immersion depth	Why bodies of aquatic species do not float?	They became heavier	Try to change the bone so it will sink	Stick plasticine around – additional layers of bone (pachyostosis). Glued stones – gastroliths	Presenting the examples of animals with pachyostosis, osteosclerosis and swallowing gastroliths	Stones 'held' with limbs rather than swallowed or no explanation

Salt Cucumber with and without skin, salt	Many of the aquatic species lives in salt waters	Can salt be dangerous for aquatic species?	It can be dangerous even for animals living in salt water	Put salt on the cucumber and cucumber's skin	Cucumber without skin looses water more quickly (due to osmosis). Skin protects before salt and dehydration	Presenting examples of animals dealing with salt excess: 'sneezing' iguanas, 'crying' turtles	Animals that live in water are not endangered by dehydration.
Temperature Plasticine, raw bacon slices	Many of the primarily terrestrial species lives in cold waters	How they can stay warm?	They can keep warmth with fur, feathers and blubber	Make three plasticine spheres of the same size. One goes on the table, second to cold water, third to cold water after wrapping in bacon. Take all three after some time and compare its warmth	'Table' and 'bacon' spheres are warmer than the one simply put into water. In water animal's body loose warm faster than on land. Layer of fat allows to keep warm effectively	Presenting animals that live in very cold habitats and their anatomy	Not observed
Hear and sight Sealed bag with water	Sound wave acts differently in air and water	How is hearing under water different than in air?	Dense water makes it difficult for 'terrestrial ear' to hear	Put the bag to your ear. Try to understand what your colleague whispers to you. Listen to your colleague without the bag	It is not easy to hear with water. The reason is that our terrestrial ears are not adapted to effectively hear under water	Presenting difference in the ear anatomy of aquatic and terrestrial species (additional – presenting echolocation	Hearing is the same everywhere as you 'use the same ears'
Sight Spoon, stick, straw or similar	Light acts differently in air and water	How is seeing under water different than in air?	Water diffuses light in a different way than air	Put it to the water so the part is still above the surface. Observe the surface of water	The spoon is 'breaking' at the surface, because light travels with lower speed in dense environment	Presenting adaptations for seeing in deep water (e.g. *tapetum lucidum* in seals, large orbits of ichthyosaurs)	Sight is the same everywhere as you use 'the same eyes'

Based on the scientific method, the lecturer encourages pupils and students to:

1. Ask a scientific question. Examples:
– How do primarily terrestrial animals move in water?
– How can body temperature be maintained in cold water?
2. Formulate hypotheses and predictions. Examples:
– Using webbed-toes and fins (adapted limbs)
– A thick layer of blubber effectively maintains body temperature
3. Test hypotheses and predictions. Examples:
– Comparing the effectiveness of propulsion of the human hand (widespread fingers) and a hand 'transformed' into a fin
– Comparing the temperature of plasticine spheres located 'on land' and in water with and without a layer of fat (bacon slice)
4. Draw conclusions. Example:

– Fins are more effective in the aquatic environment than 'terrestrial limbs'
– Blubber helps to retain body heat.

Results are presented on the basis of experience gained in providing science workshops in non-formal educational settings and interviews with science popularisers, managers of children's universities, early education teachers and parents of workshop participants.

3. Results

Observations of students actively solving issues revolving around the 'aquatic problem' and interviews with managers, teachers and parents have allowed to draw the following conclusions regarding both method effectiveness and misconceptions.

Over the years, several elements of the designed workshops have proved to be more effective learning styles than the traditional pattern. Students ask and answer questions on their own, do experiments to resolve issues, and draw conclusions with the help of a lecturer, if needed; yet, it should be stressed that no simple answers or results are given *a priori* (Martin & Pressley, 1991; Chi et al., 1994).

Although students effectively draw conclusions on their own during the workshop, a few misconceptions occur systematically. Some of these are listed in Table 1; the others are:

– *Marine amniotes do not have terrestrial ancestors* (Paleogene ancestors of modern whales turn out to be amongst the most surprising elements of the lecture/discussion part).
– *Decompression sickness cannot affect marine animals* (explained later using a bottle of sparkling water and photographs of pathologies in fossils as a result of decompression sickness).

With the designed experiments most of the misconceptions are easily explained. Moreover, although the majority of pupils/students did their experiments properly (80 percent in the last group in 2020), they not always knew how to translate this into a scientific explanation of animal anatomy. For example, they stick the stones to the bone in order to make it sink to the bottom, but do not connect this with swallowing, but, for example, with 'holding rocks by limbs'. Additional data were then supplied, in particular a photograph of a ichthyosaur skeleton with gastroliths preserved *in situ*. With this help, most pupils/students improved their answers, stating that animals can swallow stones to achieve neutral buoyancy.

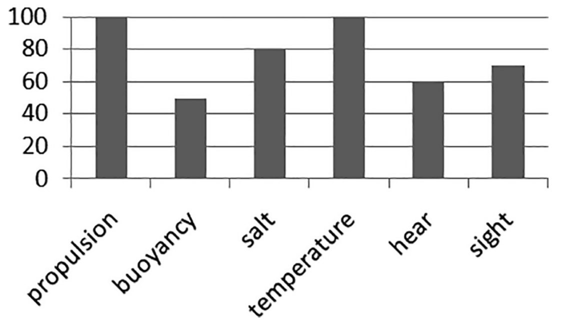

Fig. 2. Percentage of accuracy in explaining results of self-conducted experiments by students (10) at a private school in Poznań, Poland (December 2019).

Parents usually pay attention to how their child(ren) engage(s) in the work and if he/she/they enjoy these activities, but engagement is not equal to effective learning (Frensley et al., 2020). However, teachers and managers (with experience in formal and non-formal teaching) have noted the ability to answer essential questions with high accuracy following workshops (Fig. 2), potentially higher than after traditional lessons. In future studies, proper surveys should be conducted in order to test the level of effectiveness of learning new terms and problems comparing traditional classes and methods described herein.

4. Discussion

In view of the fact that the workshop was conducted within non-formal educational structures and at a private school, the availability of props was not a problem. In addition, the workshop was given by an active scientist with research experience, which is different from the experience of an average school teacher. Garraway-Lashley (2019) listed several problems in teaching science in primary schools that most teachers face; these may affect the quality of science education:

1. A lack of pupils' interest in science classes,
2. A lack of possibilities for the development of teachers, science instructions and knowledge.

You (2017) postulated that professional development can provide teachers with specific input:

3. Stiff curriculum – problems with the implementation of additional activities.

The last point is also connected with the fact that teaching in public schools is test-oriented, which according to Xiaowei et al. (2018) is another problem, because:

4. Test-oriented teaching does not support scientific inquiry; on the contrary, it focuses on the artificial result rather than on students' thinking and productivity.

Fitzgerald & Smith (2016) mentioned another issue:

5. The amount of time devoted to science classes is inconsistent.

Despite this, a shift towards an interdisciplinary presentation of science and emphasis on the scientific method are considered to provide a wide range of benefits that improve public school curriculum and instruction. By teaching deductive reasoning, synthetic and critical thinking and complex understanding and evaluation of multiple perspectives (Nowacek, 2005; You, 2017) multiple aims can be achieved, including cognitive advancement, strengthening memory trace, increased motivation and improvement of affective domains (Newell, 1994; Mulligan & Hornstein, 2003; Nyberg et al., 2003; Lattuca et al., 2004; You, 2017). In general, problem-solving learning leads to higher-order thinking skills (Boix Mansilla & Duraisingh, 2007). It has also been demonstrated that the interdisciplinary approach increases student scores when compared to teaching divided into several subjects (Vars, 1991).

Yet, drawbacks to providing the scientific method to primary school pupils cannot be ignored. The lecturer needs to remember that strict scientific language may confuse and distract younger pupils from productivity. The scientific method has to be presented with an appropriate approach to the students' age and their inquiry can be channelled by using 'their own words' rather than scientific jargon (Xiaowei et al., 2018). For instance, some terms are tricky and occasionally mislead scientists themselves as is seen in the example of the term 'hypothesis'. McPherson (2001) presented multiple examples of how this term is occasionally used incorrectly, not only in schools but even in scientific journals, being confused with 'prediction'.

This kind of workshops can be an efficient addition to the traditional classes. The subjects presented are enclosed in basic development in Polish curricula for biology and geography (classes IV–VIII, age 10–14). Evolution and adaptation are not included in the curricula of science classes (Environment) for classes I–III (age 7–9), although non-formal educational programmes do show that, when taught properly, it can be effectively addressed for the youngest students. Since evolution explains modern biodiversity, this should be mentioned from the start in environment education. It is also important to stress that school curricula are strongly systematised and divided into specific fields, while the workshops presented and most of the experienced-based learning classes during non-formal education highlights relationships between different organisms and organisms and environment, expressing convergent, divergent and adaptative evolution. Based on the Polish curriculum for biology (classes IV–VIII, age 10–14), students for example learn about birds of:

- the diversity of living environments and morphological features of birds,
- observation of bird representatives (photographs, films, diagrams, natural specimens in the field, etc.) and presentation of common features and description of bird adaptations to flight,
- definition of birds as warm-blooded animals,
- presentation of the way of reproduction and development of birds,
- explanation of the importance of birds in nature and for humans.

However, the reasons and processes behind this are not mentioned:

- why do birds possess characteristic features that differentiate them from other groups? (only adaptations for flight are mentioned)
- how did they become so diverse? What did their ancestors look like? (during non-formal education students of different age are often surprised by the fact that birds are the descendants of dinosaurs, while a close relationship between birds and dinosaurs was first proposed in the nineteenth century after the discovery of the primitive bird *Archaeopteryx* in southern Germany.

5. Conclusion

Considering the issues discussed above, similar workshops in future should be tested within public schools, provided by science class teachers and the results should be compared with non-formal education quantitatively in terms of student engagement, accuracy of experimental results and coding of the information presented after some time.

However, the scientific method with an interdisciplinary approach might be taught to primary school student (informal- or non-formal educational structures) groups by learning through experience with an interdisciplinary approach and focused on the scientific method. With designed experiments (within the framework presented), students can come up with scientific questions, formulate hypotheses and draw conclusions based on self-conducted experiments with high accuracy. Experience-based learning also allows to explain misconceptions such as the fact that even fully aquatic animals can suffer from dehydration in salt waters and to overcome some of the problems of implementing the scientific method in schools that are listed by teachers.

Acknowledgements

I am grateful to the participants and organisers of workshops at the Children University of Poznań, the Belward Private School and the Biologists' Night science fair in Opole (Poland) and thank Tomasz Zgoła for discussion on the condition of educational studies in environmental science and for helpful advice.

References

Alberta University, 2015. *Paleontology: Ancient Marine Reptiles, Online course. Lesson 1: Introduction to marine reptile diversity*. Coursera.org, access: 20.06.2021

Boix Mansilla, V. & Duraisingh, E.D., 2007. Targeted assessment of students' interdisciplinary work: An empirically grounded framework proposed. *The Journal of Higher Education* 78, 215–237.

Campos, R. & Sá-Pinto, A., 2013. Early evolution of evolutionary thinking: teaching biological evolution in elementary schools. *Education and Outreach* 6, 25.

Cassill, D.L., 2021. Multiple maternal risk-management adaptations in the loggerhead sea turtle (Caretta caretta) mitigate clutch failure caused by catastrophic storms and predators. Scientific Reports, 11, doi:10.1038/s41598-021-81968-0.

Chi, M.T.H., de Leeuw, N., Chiu, M-H. & Lavancher C., 1994. Eliciting self-explanations improves understanding, *Cognitive Science* 18, 439–477.

Cleland, C.E., 2001. Historical science, experimental science, and the scientific method, *Geology* 29, 987–990.

Cutter-Mackenzie, A. & Edwards, S., 2013. Toward a model for early childhood environmental education: Foregrounding, developing, and connecting knowledge through play-based learning. *The Journal of Environmental Education* 44, 195–213.

Fitzgerald, A. & Smith, K., 2016. Science that matters: exploring science learning and teaching in primary schools. *Australian Journal of Teacher Education* 41, 64–78.

Frensley, B.T., Stern, M.J. & Powell, R.B., 2020. Does student enthusiasm equal learning? The mismatch between observed and self-reported student engagement and environmental literacy outcomes in a residential setting. *The Journal of Environmental Education*, doi: 10.1080/00958964.2020.1727404.

Garraway-Lashley, Y.M., 2019. Teaching Science at the Primary school level: "Problems teachers' are facing". *Asian Journal of Education and e-Learing* 7, 81–94.

Gingerich, P., 2003. Land-to-sea transition in early whales: evolution of Eocene Archaeoceti (Cetacea) in relation to skeletal proportions and locomotion of living semi-aquatic mammals. *Palaeobiology* 29, 429–454.

Hannula, K.A., 2003. Revising geology labs to explicitly use the scientific method. *Journal of Geoscience Education* 51, 194–200.

Jacob, H.J., 1953. *Some applications of the scientific method as applied to the teaching of elementary-school science*. LSU Historical Dissertations and Theses 8055, 189 pp., https://digitalcommons.lsu.edu/gradschool_disstheses/8055.

Lattuca, L.R., Voigt, L.J. & Fath, K.Q., 2004. Does interdisciplinarity promote learning? Theoretical support and researchable questions. *The Review of Higher Education* 28, 23–48.

Maglaughlin, K.L. & Sonnenwald, D.H., 2005. Factors that impact interdisciplinary natural science research collaboration in academia. [In:] Ingwersen, P. & Larsen, B. (Eds), *Proceedings of ISSI* 499–508.

Markley, M.J., 2010. The [Geo]Scientific Method; hypothesis testing and geoscience proposal writing for students. *Journal of Geoscience Education* 58, 198–202.

Martin, V. & Pressley, M., 1991. Elaborative-interrogation effects depend on the nature of the question. *Journal of Educational Psychology* 83, 113–119.

McPherson, G.R., 2001. Source teaching & learning the scientific method author(s). *The American Biology Teacher* 6, 242–245.

Montgomery, H. & Donaldson, K., 2014. Using problem-based learning to deliver a more authentic experience in paleontology. *Journal of Geoscience Education* 62, 714–724.

Mulligan, N.W. & Hornstein, S.L., 2003. Memory for actions: Self-performed tasks and the reenactment effect. *Memory & Cognition* 31, 412–421.

Nagloo, N., Collin, S.P., Hemmi, J.M. & Hart, N.S., 2016. Spatial resolving power and spectral sensitivity of the saltwater crocodile, Crocodylus porosus, and the freshwater crocodile, Crocodylus johnstoni. *Journal of Experimental Biology* 219, 1394–1404.

Newell, W.H., 1994. Designing interdisciplinary courses. *New Directions for Teaching and Learning* 58, 35–51.

Nowacek, R.S., 2005. A discourse-based theory of interdisciplinary connections. *The Journal of General Education* 54, 171–195.

Nyberg, L., Sandblom, J., Jones, S., Neely, A.S., Petersson, K.M., Ingvar, M. & Bäckman, L., 2003. Neural correlates of training-related memory improvement in adulthood and aging. *Proceeding of the National Academy Science* 100, 13728–13733.

Oxford English Dictionary, 2012. 7th Edition. Oxford University Press.

Pyeson, N., 2019. *Spying on whales*. Penguin Books, 336 pp.

Saikawa, Y., Hashimoto, K., Nakata, M., Yoshihara, M., Nagai, K., Ida, M. & Komiya, T., 2004. The red sweat of the hippopotamus. *Nature* 429, 363.

Vars, G.F., 1991. Integrated curriculum in historical perspective. *Educational Leadership* 49, 14–15.

Xiaowei, T., Coffey, J.E., Levin, D. & Hammer, D., 2018. The scientific method and scientific inquiry: tension as in teaching and learning. *Science Education* 94, 29–47.

You, H.S., 2017. Why teach science with an interdisciplinary approach: history, trends and conceptual frameworks. *Journal of Education and Learning* 6, 66–77.

Manuscript submitted: 14 June 2021
Revision accepted: 8 October 2021