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Review

Science Teaching and Learning for Productive Disciplinary Engagement (PDE) through Model-Based Learning (MBL): Insights from Relevant Literature

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Abstract: The practice turn in the science education community emphasizes students' engagement in the activities that scientists and engineers actually do when they see, explain, and critique a phenomenon, or solve a problem. This turn highlights the importance of science learning environments for students. Consequently, the purpose of this study was the examination of relevant literature with the aim of proposing theoretically and empirically derived teaching strategies for students' productive disciplinary engagement (PDE) through model-based learning (MBL) in science classrooms. To this end, collected literature focusing on PDE and MBL was analyzed to better understand 1) how teachers can foster students' PDE in science classrooms, 2) how PDE can be connected to MBL, and 3) what supports are required for students' PDE through MBL. As a result of our analysis, a close relationship between PDE and MBL was identified. Importantly, this research reveals the promise of MBL for supporting students' PDE through the problematizing, authority, accountability, and resources. Further, our literature examination provided a better understanding of what supports are required for students' engagement in PDE through MBL and why this matters in the context of the practice turn in science education.

Keywords: earth science, model-based learning (MBL), productive disciplinary engagement (PDE), science learning

Introduction

Recently in science education, there is an increased emphasis on a turn toward practice (Ford and Forman, 2006; Ford, 2015; Foreman, 2018; Passmore et al., 2014; Stroupe, 2014; Windschitl and Calabrese Barton, 2016). This turn toward practice, or practice turn, emphasizes a move toward engaging students in the professional activities that scientists and engineers engage in as they refine and critique explanations about events that happen in the world or solve problems of consequence. One way researchers have conceptualized students' engagement in more authentic representations of the activities of scientists and engineers or the practice turn resides in Engle and Conant's (2002) notion of productive disciplinary engagement (PDE). PDE emphasizes the convergence of students' everyday sensemaking with disciplinary discourses as they make intellectual progress in their sensemaking pursuits (e.g., explaining events or phenomena, solving problems). Importantly, Engle and Conant (2002) recognized that coming into contact with disciplinary discourses in ways that were consequential to making intellectual progress in sensemaking pursuits involved encouraging students to pose questions and make proposals (i.e., problematizing), giving students authority to make decisions, holding students accountable to others and disciplinary norms (i.e., accountability), and supporting students with sufficient resources to make progress in their disciplinary pursuits.

Korean Science Education Standards (KSES), recently released to provide a vision for science education for our next generation, set the 'making and applying models' as the second ability that is required for

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students' scientific inquiry (Song et al., 2019). Over the last few decades, model-based learning (MBL) is an approach that researchers in science education have proposed for engaging students meaningfully in more authentic representations of scientific activity and PDE (Clement, 2000; Grosslight et al., 1991; White and Frederiksen, 1998). Here, MBL is defined as "an approach for teaching and learning in science whereby learning takes place via student construction of models as representations of physical phenomena" (Louca and Zacharia, 2012, p. 471). Further, in relation to the charateristics of the contents in earth science education, researchers have highlighted how MBL can play an important role in supporting students engagement in learning earth science (Campbell and Oh, 2015; Kim et al., 2010; Oh and Oh, 2011; Oh et al., 2007; Park et al., 2019; Zangori et al., 2017). Researchers highlighted how engaging in MBL afforded learners' opportunities to not only engage more deeply with disciplinary content, but also provides them a better sense of the epistemic characteristics of how scientific knowledge is explanatory, testable, revisable, conjectural, and generative (Windschitl et al., 2008).

Yet, while there is research that points to the needs for the implementation of MBL in earth science education, only a limited amount of research intentionally has explicitly explored the role of MBL in earth science education (Campbell and Oh, 2015; Cho and Nam, 2017; Oh and Oh, 2011; Guy-Gaytán et al., 2019). Further, only a few studies have explored effective teachers pedagogical strategies teachers can use to support students' engagement in knowledge building through MBL. Given this, the purpose of this study was to examine the literature related to PDE and MBL to propose a theoretically and empirically grounded pedagogical strategies that can support PDE through MBL.

Method

Because this current study sought to propose theoretically and empirically sound pedagogical strategies for students' PDE through MBL, a comprehensive understanding about the meaning and characteristics of productive disciplinary engagement (PDE) and model-based learning (MBL) are necessary. Therefore, relevant theoretical and empirical research literature about PDE and MBL was reviewed to synthesize what is known in each area. To this end, an exhaustive search of peer-reviewed journal articles using the databases Google Scholar, ERIC via EBSCOhost, and PsycINFO was conducted using the combinations of the keywords *productive disciplinary engagement (PDE)* and *model-based learning (MBL)*. The database search was confined to articles published between 2000 and 2020. The initial search was conducted in August 2020 and yielded 125 articles. After an abstract review and the removal of duplicated articles or those determined to be outside the scope of this research, 78 articles remained. Additionally, to be sure that all relevant articles were included in the articles pool used for this research, a close comparison was made between the corpus of articles and articles published since 2010 in high impact science education journals and the highest impact educational review journal. In the end, this led to 82 articles included at the conclusion of the abstract review. Finally, the database of articles was narrowed during the review process if articles did not meet the following inclusion/exclusion criteria: the article (a) provided theoretical backgrounds or framework for PDE or MBL, (b) described characteristics of student learning through PDE or with models, and (c) offered implications for PDE or MBL for K-12 students and teachers. After the review process a total of 73 articles (i.e., 22 PDE and 51 MBL articles) were included and used in the analysis.

During the review of each article included, as applicable, information was collected about each of the following related to (1) how teachers can foster students' PDE in science classrooms, (2) how PDE can be connected to MBL, and (3) what supports are required for facilitating students' PDE through MBL. In the end, an in-depth understanding was synthesized to consider how students learning with PDE through MBL can be better supported.

Results

What Supports are Required for Students' PDE through MBL

Based on the PDE and MBL literature reviewed (i.e., 22 & 51 articles, respectively), among the many important aspects in supporting students' PDE and MBL researchers discussed, the main findings center on the close relationships between PDE and MBL and how particular supports for MBL can foster students' engagement in the four fundamental principles of PDE, such as how learning opportunities with modeling practice can help strengthen students' authority and resources (Svoboda and Passmore, 2010), or how models play an important role in supporting students' problematizing (Dasgupta, 2019). Further, within the close relationships identified between PDE and MBL, the supports students need are discussed.

MBL holds considerable promise in supporting students' PDE through the reciprocating interactions between the four elements of PDE (i.e., problematizing, authority, accountability, and resources) and the epistemic practices that students experience during their engagement in developing, refining, and using models as they engage in MBL. Among the important characteristics of MBL, researchers have highlighted how engaging in developing and using models affords students' deep opportunities to engage not only with disciplinary content, but also the epistemic characteristics of how scientific knowledge is testable, revisable, explanatory, conjectural, and generative (Kenyon et al., 2008; Windschitl et al., 2008). Further, as is evident in the following, science education researchers (e.g., Dasgupta, 2019; Svoboda and Passmore, 2010) have explicitly highlighted the ways in which MBL can be used to support students' PDE:

> When students have the chance to do things like construct, reconstruct, critique, or revise models, they become authors [authority]. That is, they are able to take at least partial ownership over the choices that they make [problematizing] rather than simply following a series of steps that have been predetermined for them. Giving students ownership can change the way they relate to the task. When students feel that they are being asked to contribute intellectually to an authentic problem, they are more likely to remain motivated and engaged. (Svoboda and Passmore, 2010, p. 275)

> It is likely that the seed model [resources] helped anchor students' initial ideas and then enabled them to use it as a stage for brainstorming multiple ideas ... The visual representations potentially primed the students and served as anchors while students made design decisions [problematizing], thus scaffolding their disciplinary engagement (Dasgupta, 2019, p. 411).

These characteristics of MBL as an approach for supporting PDE are grounded in the notion that models are critical epistemic tools which can support students' sensemaking in explaining natural phenomena (Campbell et al., 2016; Campbell and Oh, 2015; Oh and Oh, 2011; Passmore et al., 2014; Schwarz et al., 2009; Svoboda and Passmore, 2013) through focusing on 'models for' and 'figuring out' rather than only focusing on 'models of' or 'learning about' (Gouvea and Passmore, 2017; Russ and Berland, 2019). Beyond these more general connections between MBL and PDE, more is shared next related to how the four principles of PDE (i.e., problematizing, authority, accountability, resources) are manifest in the context of MBL in meaningful ways that were highlighted in the literature that was reviewed.

Problematizing: To support students' PDE through MBL, teachers carefully consider ways they can support students' problematizing content, authority, and accountability through developing and using models, as well as how relevant resources can be provided in this context. In this way, MBL prioritizes students problematizing from the outset as emphasis is placed on providing a safe space for students to make public their initial ideas about a phenomena with peers and the teacher. In this, problematizing involves individual and collective actions that encourage disciplinary uncertainties (Engle, 2011) and sees learners' initial ideas about how the uncertainties might be resolved as the start of problematizing.

Meyer (2014) noted, in her study about how science classroom activities served to support students' PDE, that the instructional strategy of supporting students to engage in collaborative group work with autonomy to share their ideas instead of providing guided instruction, offered students opportunities to consider their own understandings and ideas that could help explain target phenomenon, while also affording them opportunities to correct their own mistakes with the disciplinary resources. Meyer's findings connected to PDE, also aligned with what other researchers found related to how the purposive restraint of teachers in withholding prescriptive guidance provided students more opportunities to engage in PDE (Amade-Escot and Bennour, 2017; Chen, 2020). Models and the practices that students experience during developing and using models play an important role in both revealing and improving students' initial ideas and developing explanations. More specifically, initial models students create at the beginning of an MBL learning experience can be used to identify uncertain processes or structures that students draw on related to the target phenomenon. In addition, as students propose models, collaborative group work (e.g., open-ended discourse or brainstorming) is fostered such that students' ideas and those of their peers are made visible in ways that allow for proposed group models to be supported or refuted (Ambitious Science Teaching, 2015a, 2015b; Dasgupta, 2019; Grimes et al., 2019; Windschitl et al., 2008) as they identify potential errors in their proposals (Forman and Ford, 2014). Finally, students can act as epistemic agents while they improve the initial models through iterative revisions and use and are positioned, through modeling practices, to actively participate in the production and negotiation of knowledge (Gouvea and Passmore, 2017; Schwarz et al., 2009; Windschitl et al., 2008).

Authority: The degree of participation and contribution to the practices where students produce and advance their knowledge plays an important role in enhancing the level of students' intellectual authority. In order to support students' authority, Engle (2011) proposed developing and strengthening students' intellectual authority through 1) authoring "what they really think", 2) being recognized as "authors of those ideas", 3) being "contributors to the ideas of others", and 4) being "*socially* recognized as an authority" about the topic(s) (p. 170). Engle and Conant (2002) highlighted centering the conversation on students' ideas to support their authentic questioning and distribution of authority. Subsequently, researchers found that scaffolding and encouraging students to share, express their ideas, and to ask substantive questions, and build off peers' ideas indeed promoted PDE (Chen, 2020; Grimes et al., 2019; Koretsky et al., 2019; Meyer, 2014). Connected to strategies Engle (2011) proposed for developing and strengthening PDE, developing and using models as an epistemic practice involves sharing students' initial ideas, proposing, testing, and revising models to explain how and why target phenomena occur (Campbell and Fazio, 2018; Neilson and Campbell, 2017; Schwarz and White, 2005; Zangori et al., 2017; Zangori and Forbes, 2016). Further, modeling practices support students' authorship, contributorship, and authority by encouraging their intellectual agency through engagement in discursive practices, such as argumentation (Campbell et al., 2012; Nunez-Oviedo and Clement, 2019; Passmore and Svoboda, 2012). Still further, researchers have also demonstrated how MBL can involve encouraging students to decide how to collect and analyze data to test models (Windschitl et al., 2008), how MBL can help shift teachers view of models from 'the canon of science to be learned' to 'the sensemaking practice for working at knowing' (Guy-Gaytán et al., 2019), and how science instruction can move beyond pushing students to one correct answer with closed-ended questions (Mortimer and de Araújo, 2014; Russ and Berland, 2019) or waiting for students to justify their ideas (Scott et al., 2006; Windschitl et al., 2008).

Accountability: Engle (2011) noted how students should not only be responsible for how their ideas make sense to themselves, but also take responsibility for how their ideas make sense to others and are consistent with expected local and global disciplinary norms. In this, students recognize that epistemic agency involves not only learning disciplinary knowledge, rules, and methods, but also to "think of themselves as epistemic agents ... [in relation to] how to take responsibility for what they believe, and why it is important to be able to do so" (Elgin, 2013, pp. 148-149). This is connected to Ford's (2008) notion of *a grasp of practice* whereby students must "know that scientific knowledge is held accountable through its explicit connections to nature's behavior, know how to play the roles of constructor and critiquer appropriately, and know that the interaction of these on the communal level produces reliable scientific knowledge…" (p. 416). When considering MBL, epistemic practices such as knowledge production (e.g., elaborating hypothesis and planning investigation), communication (e.g., arguing and describing), and evaluation (e.g., opposing and criticizing) (Campbell et al., 2012; Gouvea and Passmore, 2017; Mortimer and de Araújo, 2014; Neilson and Campbell, 2017; Passmore and Svoboda, 2012; Schwarz et al., 2009; Windschitl et al., 2008) all involve accountability both internal and to others. In addition to Engle's (2011) suggestion of inside-out accountability development, which can be understood as starting from accountability to how ideas make sense to one's-self, to peers, authorities, and the public, Suárez (2020) pointed out, in the context of developing and using models, the importance of encouraging students to reflect on their own ways of communicating and semiotic repertoires, particularly related to ways in which scientists think and share their ideas (Ford, 2008).

Resources: Engle and Conant (2002) highlighted how students should be supported with sufficient resources, as the fourth principle of PDE. In relation to this, Freedman (2020) noted how allotting more time and supporting students with robust resources permitted them to take more knowledgeable authoring stances and engage in more productive discussions in ways that ultimately promoted their PDE. However, Engle (2011) also pointed out the importance of balance between the resources provided to students for support and space left for student problematizing since both insufficient resources or too many resources might thwart their PDE. In relation to providing too many resources, both Kawasaki and Sandoval (2019) and Svoboda and Passmore (2010) noted how providing students with too much or irrelevant information could get in the way of their intellectual progress. This uncertainty around providing resources to students were documented by Venturini and Amade-Escot (2014) as they noted the diverse and multiple formats possible for providing resources and considerations that must be undertaken related to whether to provide "documents with discrepancies, time, and students' experience of debates and document management" and how these uncertainties "arise due to various processes used by the teacher: regular identification of the knowledge at stake, delimitation of the elements submitted to discussion, delimitation of the relevant features of the milieu, frequent institutionalizations, and formulation of the conclusion when the students do not succeed in doing it" (pp. 180-181). In examples like what Venturini and Amade-Escot shared, researchers have emphasized the importance of the teacher's role in managing and providing curriculum materials and resources in the ways that foster students' productive use of them for intellectual progress through disciplinary engagement (Amade-Escot and Bennour, 2017; Freedman, 2020; Meyer, 2014; Scott et al., 2006; Svoboda and Passmore, 2010). Related to this last question about the teachers' role in serving as a resource or supporting students to engage with resources provided or that they identify, researchers have also documented how student-centered engagement with resources can be supported through how teachers actively engage with students in ways that refrain from providing evaluative feedback, and instead encourage students to answer their own questions by providing them with access to an appropriate amount and type of resources to support their intellectual progress (Chen, 2020; Scott et al., 2006; Svoboda and Passmore, 2010). Finally, Venturini and Amade-Escot (2014) also highlighted the importance of considering not only which resources teachers can provide to students, but when to provide them so that they are timely and their usefulness is more apparent, instead of providing all relevant resources at the beginning of the learning experience. In the end, because of the nature of MBL related to how students propose initial models and subsequently draw on resources, both that they identify and those that are identified by their teacher, resources play an important role, just like they do in PDE, in supporting students development of more sophisticated explanations overtime.

Conclusion

The findings from the literature reviewed offered important implications for instructional strategies for K-12 students' PDE through MBL in relation to how MBL can foster students' PDE in science classrooms and what supports are required. The characteristics of MBL (i.e., positioning students to recognize the need for resources while also providing space for them to use the resources in making intellectual progress), alongside how central problematizing, authority, and accountability are in MBL reveal its promise for supporting PDE. Further, our discussion about what supports are necessary for students' PDE through MBL provides insights into the ways teachers can use models in support of students' science learning. Specifically, to support students' problematizing, teachers can encourage students to identify uncertainties related to phenomena they are explaining or problems they are working to solve. This can be accomplished as students are afforded autonomy to share their initial ideas as part of group work. For authority, teachers can support students' authorship and contributorship by encouraging agentic decision-making (e.g., sharing, proposing, testing, and revising models). For accountability, teachers can help students recognized that every decision they make has an impact that needs to meet the expectations related to knowledge construction and problem solving of the classroom community specifically and society more generally. Lastly, teachers who use MBL for students' PDE need to constantly examine what, how, and when the resources should be provided, while also seeking to learn from their teaching experiences and others. This, teachers' reflective practice related to engaging students in MBL, is important because teachers play an important role in developing a supportive learning environments for students (Bybee & Chopyak, 2017; Davis et al., 2016; Knight-Bardsley & McNeill, 2016). Although most of the literature reviewed occurred internationally, the implications suggested are based on relatively recent theoretical and empirical research on PDE and MBL. Further, the examples of how these instructional strategies can guide both new and experienced science teachers' professional learning in science education in Korea, especially since MBL has recently emerged as one of the important forms of scientific inquiry. However, a need still exists for further research on the type of teacher professional learning that might be most helpful in a teacher PD framework and accompanying anchoring MBL curriculum. Given this, the fundamental goal of future research then is to apply what is known about students, teachers and teacher professional learning to support teacher learning that will lead to better experiences for students' PDE and MBL in science classrooms.

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