IJPBL http:// ijpbl.org

Interdisciplinary Journal of Problem-Based Learning

Volume 11 | Issue 2 Article 3

Published online: 5-17-2017

Problem-Based Learning in K–8 Mathematics and Science Education: A Literature Review

Joi Merritt
Arizona State University, merritjd@jmu.edu

Mi Yeon Lee
Arizona State University, mlee115@mainex1.asu.edu

Peter Rillero
Arizona State University, rillero@asu.edu

Barbara M. Kinach
Arizona State University, barbara.kinach@asu.edu

Recommended Citation

Merritt, J. , Lee, M. , Rillero, P. , & Kinach, B. M. (2017). Problem-Based Learning in K–8 Mathematics and Science Education: A Literature Review. *Interdisciplinary Journal of Problem-Based Learning, 11*(2).
Available at: https://doi.org/10.7771/1541-5015.1674

The Interdisciplinary Journal of
Problem-based Learning

Special Issue on Competency Orientation in Problem-Based Learning

Problem-Based Learning in K–8 Mathematics and Science Education: A Literature Review

Joi Merritt, Mi Yeon Lee, Peter Rillero, and Barbara M. Kinach (Arizona State University)

Abstract

This systematic literature review was conducted to explore the effectiveness of problem-based and project-based learning (PBL) implemented with students in early elementary to grade 8 (ages 3–14) in mathematics and science classrooms. Nine studies met the following inclusion criteria: (a) focus on PBL, (b) experimental study, (c) kindergarten to grade 8 level, and (d) focus on mathematics or science content. For these studies, we examined: the definitions of PBL used, the components of PBL explicitly identified as salient to student learning, and the effectiveness of PBL. This review found that although there is no consistent definition of PBL, PBL is an effective method for improving K–8 students' science academic achievement, including knowledge retention, conceptual development, and attitudes. Implications and limitations are discussed.

Keywords: problem-based learning, project-based learning, elementary school, middle school, mathematics education, science education

Introduction

The history of education is replete with calls to make student learning more active, yet rote learning has long been a staple of education. The explosion of digital information and the ease of its retrieval will perhaps increasingly shift the focus from memorization of information to the utilization of information. Problem-based learning (PBL), is an educational instruction method that fosters learning and the development of 21st century competencies and skills (Bell, 2010) through problem solving and the integration and application of knowledge in real-world settings (Capraro & Slough, 2013). Prior research around the effectiveness of PBL in higher education indicates that PBL is more effective than traditional lecture-based instruction in relationship to long-term retention and skills development (Strobel & Barneveld, 2009). However, not much is known about the effectiveness of PBL for primary to middle grade (secondary) education (ages 5–14). In this paper, we examine the quantitative evidence for the effectiveness of PBL in kindergarten to middle school (K–8) science and mathematics classrooms to determine whether the perception of PBL as a promising learning approach is warranted.

History of PBL

While Dewey (1938) wrote about ideas related to PBL, the first systematic implementation was in the field of medical education in the 1970s at McMaster University (Barrows, 1996; Barrows & Tamblyn, 1980). Medical students learned content and clinical reasoning by identifying symptoms, making diagnoses, and prescribing treatments through interactions with actual or simulated patients and through written case studies (Barrows & Tamblyn, 1980). Other professional fields have adopted the use of PBL based on the advances made in medical education. Advertising, architecture, business administration, engineering, nursing, and physical therapy are among the professions that have researched the affordances of PBL, finding it to be an effective means of learning content and skills in these professional settings (Barrows, 1996; Gould & Sadera, 2015; Quinn & Albano, 2008; Zubaidah, 2005).

Motivation for the Study

PBL methods have also been applied to primary and secondary learning (Kim et al., 2012; Trinter, Moon, & Brighton,

http://dx.doi.org/10.7771/1541-5015.1674

2015), although more research is needed to determine the impact of PBL on student learning in educational settings (Rico & Ertmer, 2015). As researchers, we were particularly interested in the effectiveness of PBL in mathematics and science classrooms, as we are involved in a larger project to investigate the use of PBL as a tool for supporting English language learners in learning academic content in these areas. We conducted this systematic literature review to examine specifically what quantitative research has revealed about the effectiveness of PBL for student learning of mathematics and science concepts from primary to secondary grades (K–8; ages 3–14). Our intent is to apply the findings of this literature review to the larger study on enhancing mathematics and science learning for English language learners through PBL.

As English and Kitsantas (2013) found project-based learning and problem-based learning to closely resemble each other, we included both "problem-based" and "project-based" learning articles in our literature review. Three questions guided our review of the literature:

- How do researchers define PBL?
- What components of PBL were explicitly identified as salient to student learning?
- What is the effectiveness of PBL in relationship to identified dependent variables?

Literature Review Process

To perform a systematic review of the literature, we followed an approach similar to that discussed by Bennett, Lubben, Hogarth, and Campbell (2007). In our approach, we (1) developed search strategy criteria, (2) searched for articles that met our criteria, (3) screened the articles to make sure they met the criteria for inclusion, and (4) extracted reported details of specific aspects of studies. This provided us the opportunity to develop a reproducible and structured review.

This systematic review focused on peer-reviewed journal articles. Our initial search focused on identifying both "problem-based" and "project-based" learning papers related to science and/or mathematics education, with students at the pre-kindergarten to high school levels (ages 3–18). We initially included results for students at the high school level because we were not sure if there were a significant number of quantitative studies at the pre-K to middle school levels. This initial search, which was conducted on the ERIC and PsycInfo databases, yielded the titles and abstracts of 504 articles from these databases. Four researchers screened the articles to identify those that focused on PBL with early elementary to high school students around mathematics and/or science education.

This process involved all four authors who read through the article abstracts to identify the ones that met our initial search criteria: problem- or project-based learning studies related to mathematics and/or science education at pre-K to high school levels that included quantitative analysis. Inter-rater reliability ranged from 0.80 to 0.90, with discrepancies discussed and resolved.

Of the original 504 articles identified, 80 articles remained for further analysis following the review of abstracts. Our second screening of the articles expanded from reading just the abstract to skim reading the articles. This time, in addition to the original criteria, the authors sorted the articles according to five factors:

- Inclusion of quantitative analysis
- Study examines PBL
- Type of PBL (problem-based or project-based learning)
- Level (college, preschool to grade 8, high school)
- Subject (mathematics, science, both, other)

Though abstracts mentioned quantitative analysis, our reading of each of the articles ensured that the article actually presented and discussed quantitative results. The focus on quantitative analysis was due to our interest in the effectiveness of PBL in comparison to traditional modes of instruction. This also applied to examining whether or not PBL was discussed and to determining what type of PBL (problem-based or project-based) the study utilized. We included grade-level and subject-area criteria to narrow the literature review to our areas of interest: K–12 mathematics and science education.

This round of screening resulted in an inter-rater reliability average of 0.80, with discussion of discrepancies resulting in 100% agreement. As aforementioned, we were unsure if there would be a sufficient number of articles on PBL at the early elementary to middle school levels to warrant a review. This process resulted in the identification of 25 articles at these levels and thus, for the purposes of answering our research questions, we were able to eliminate articles at the high school levels and any college level articles that were not eliminated in our initial screening.

The final article screening process involved a thorough reading of each article for four criteria: (a) experimental or quasi-experimental design, (b) definition of PBL, (c) PBL components included, and (d) effectiveness of PBL (variables measured, i.e., academic achievement, attitude). We chose to examine experimental or quasi-experimental studies, so that we would be able to identify those studies that compared PBL to traditional modes of teaching to better understand what makes PBL effective. We were also interested in how researchers defined PBL and what components of PBL were focuses of the study. Finally, we wanted to identify the variables researchers used to examine the effectiveness of PBL.

This round of screening resulted in an inter-rater reliability average of 0.90, with discrepancies discussed and resolved which resulted in 100% agreement. Again, articles that did not meet our criteria were eliminated. This resulted in nine remaining articles.

Table 1 is an overview of the studies that were included in our final analysis. In the discussion of preliminary results, studies have been identified using a paper number. Each listing includes the authors, the grade level(s) at which the study occurred (and age in parentheses if it was included in the study description), and the quantitatively measured dependent variable(s). Some studies used mixed methods, but, as discussed earlier, we focused only on quantitative results. Though our search initially included science and mathematics content areas, the studies that made it through to the final level of analysis only focused on science concepts.

Findings

In this section, we discuss the three themes that emerged from analysis of the articles: (a) definitions of PBL, (b) PBL design components, and (c) effectiveness of PBL.

Defining PBL

Problem-based learning is an instructional method whose definition among researchers lacks consistency. Our analysis of PBL definitions for this literature review identified multiple theoretical sources for researchers' definitions of PBL in K–8 mathematics and science education: clinical-medicine education, functional/curriculum design, constructivism, and conceptual-change theory (see Table 2).

Clinical-medicine education definition. Typically, PBL definitions for K–8 mathematics and science education that are inspired by clinical-medicine education situate PBL in the "learning by doing" principle of Dewey (1938). An illustrative definition of PBL following this tradition characterizes problem-based learning as "a teaching/learning experience that provides students with problems before they receive any instruction" (Drake & Long, 2009, p. 1). Typically problems are ill-structured, requiring students to work actively and collaboratively in small groups to investigate, pose questions, gather information, and carry out the work necessary to resolve the problem. Students engaged in PBL "increase knowledge and develop understanding by identifying learning objectives, engaging in self-directed work, and participating in discussions" (Barrows & Tamblyn, 1980, as cited in Wong & Day, 2009, p. 627). Five of the nine studies reviewed (Akınoğlu & Tandoğan, 2006; Chen & Chen, 2012; Drake & Long, 2009; Potvin, Mercier, Charland, & Riopel, 2011; Wong & Day, 2008) ground their definition of PBL in the medical education literature by Barrows (1986, 1996) and Barrows and Tamblyn (1976, 1980). In contrast to traditional instruction where students apply concepts and principles to real-world applications at the end of a unit, problem-based instruction according to the clinical medicine tradition provides students with opportunities to learn new information while solving real-world problems (Akınoğlu & Tandoğan, 2006; Wong & Day, 2008).

Functional or curriculum design definitions. Some definitions of PBL in the studies reviewed are closely related to classroom practice; we call these functional or curriculum design definitions. Two studies (Araz & Sungur, 2007; Inel & Balim, 2010) employ functional definitions derived either from curriculum handbooks (Curry, 2001; Nowak, 2001; Walton & Matthews, 1989) or problem-based teaching experiments (Yenal, Ira, & Olfas, 2003; Tarhan & Acar, 2007; Tseng, Chang, & Hsu, 2008). The definitions of PBL in these studies focus on the practical application of PBL by detailing steps for implementing PBL in the classroom—specifically, the elementary grades classroom—where, due to the maturity of students, problems may be more structured and teachers may offer more guidance to keep the investigative process going in a positive learning direction. The definition of PBL by Drake and Long (2009, p. 5) is characteristic of the functional curriculum-design conception of PBL:

1. Engagement: The problem is presented to the students and any roles are explained.
2. Inquiry/Investigation: It is determined what information students already know, what information they need to know, and how best to acquire this information.
3. Problem Resolution: Students analyze their options and decide on an action or a decision.
4. Debriefing: Students discuss not only the content they have learned and how it may be useful in new situations but also the processes involved in solving the problem.

Constructivism or project-based learning definitions. Constructivist-inspired PBL, also known as project-based science learning, defines PBL as learning through projects that focus on problems in their real-life settings (Karaçalli & Korur, 2014). Grounded in the work of Krajcik, Czerniak, and Berger (1999), the principal features of project-based learning according to this definition of PBL include "constructing knowledge through trial and error," "learning by doing," and "applying new knowledge to new circumstances" (Colley, 2008; Singer, Marx, Krajcik, & Clay-Chambers, 2000; von Glasersfeld, 1995). In contrast to ill-structured problem solving with minimal teacher guidance in the clinical medicine conception of PBL, project-based science learning typically features progress-report forms that teachers create to guide students' inquiry and knowledge construction processes (Karaçalli & Korur, 2014).

Conceptual change definitions. Finally, conceptual change definitions of PBL are prominent in studies of early science learning and instruction (Leuchter, Saalbach, & Hardy, 2014). Grounded in the work of Duschl, Maeng, & Sezen (2011), this definition responds to research on early

Table 1. Overview of studies included in analysis.

Paper No.	Citation	Participant Grade/(Ages)	Quantitatively Measured Dependent Variable(s)
1	Akınoğlu and Tandoğan (2007)	7th grade	Academic achievement & Attitudes toward science
2	Drake and Long (2009)	4th grade	Content knowledge; Student perceptions of scientists; Time-on-task behavior
3	Wong and Day (2008)	8th grade (12–13 yrs.)	Students' academic performance: Knowledge acquisition; Comprehension; Application of knowledge
4	Araz and Sungur (2007)	8th grade (13–15 yrs.)	Students' academic achievement; Performance skills
5	Inel and Balim (2010)	7th grade	Academic achievement; Concept construction
6	Leuchter, Saalbach, and Hardy (2014)	Kindergarten/1st grade (4–7 yrs.)	Conceptual restructuring; Knowledge application
7	Karaçalli and Korur (2014)	4th grade (9–11 yrs.)	Academic achievement; Attitude; Retention of knowledge
8	Chen and Chen (2012)	7th grade (11–13 yrs.)	Learner performance; Attitude toward science; Inquiry ability
9	Potvin et al. (2011)	8th grade (12–14 yrs.)	Student knowledge

Table 2. Literature sources for PBL definitions.

PBL Definition Literature Source	**Paper Number**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
<u>Dewey</u>									
Dewey, 1938	x	x							
Dewey, 1966		x							x
<u>Clinical-Medicine Education</u>									
Barrows, 1986								x	x
Barrows, 1996		x							
Barrows & Tamblyn, 1976								x	x
Barrows & Tamblyn, 1980	x		x						
<u>Functional/Curriculum Design</u>									
Curry, 2002				x					
Nowak, 2001				x					
Walton & Matthews, 1989				x					
Yenal, Ira, & Olfas, 2003					x				
Tarhan & Acar, 2007					x				
Tseng, Chiang, & Hsu, 2008					x				
Stepien, Gallagher, & Workman, 1993					x				
Stepien & Gallagher, 1993				x					
<u>Constructivism/Project-Based Learning</u>									
Brooks & Brooks, 2001					x				
Gijbels & Loyens, 2009					x				
Krajcik, Czerniak, & Berger, 1999							x		
Colley, 2008							x		
Singer, Marx, Krajcik, & Clay-Chambers, 2000							x		
Von Glasersfeld, 1995							x		
<u>Conceptual Change</u>									
Duschl, Maeng, & Sezen, 2011						x			
Namy & Gentner, 2002						x			
Macbeth, 2000									x
Hewson, 1981									x

science learning and instruction that suggests on the one hand that “open inquiry environments may be unproductive” for young learners “with low self-regulation capacities” while, on the other, traditional science instruction often “fails to achieve long-term concept restructuring with regard to basic science concepts” (Duit & Treagust, 2003; Holliday, 2006) for preschool and primary school children. Thus, the conceptual change definition of PBL defines PBL as an inquiry-oriented science learning environment that emphasizes the importance of cognitive scaffolding through logically sequenced learning tasks for young learners to promote concept development through comparison of structural similarities across tasks (Namy & Gentner, 2002).

Despite differences in the literature from which researchers crafted their definitions of PBL, several components of the PBL definitions were common to all studies. Not surprisingly, studies began the learning process with a problem or structured problem sequence, required students to learn by doing (Dewey, 1938; 1966) prior to any formal instruction, and conceptualized the teacher as a guide rather than a conveyor of information. As an instructional method, the studies situated problem-based learning varied within the contexts of Deweyan philosophy, clinical-medicine education, constructivist learning theory, and conceptual change theory. In the next section we examine what components the authors described as part of the enacted PBL.

Enacted PBL Design Components

PBL design components are defined as elements considered to embody the characteristics or definitions of PBL in the school setting. When investigating the PBL design of each paper, we found that eight components were explicitly addressed in the description of PBL design or implementation in each study: nature of problems, small group, student-centered iterative inquiry process, communication of their findings to whole class, resources, technology, partnership with community, and teachers’ role as facilitators (see Table 3).

Problem. The nature of problems provided in each PBL design is slightly different depending on grade levels. Studies targeting secondary or upper elementary grade levels used scenario- or case-based problems, so that identifying problems from the given context was considered important (Akınoğlu & Tandoğan, 2006; Araz & Sungur, 2007; Chen & Chen, 2012; Drake & Long, 2009; Inel & Balim, 2010; Wong & Day, 2008). For example, in Araz and Sungur (2007), students were asked to deal with cased-based, ill-structured problems by brainstorming and generating ideas related to the problems in order to identify issues involved in the cases. However, studies targeting middle elementary or lower grade levels (Leuchter, Saalbach, & Hardy, 2014; Karaçalli & Korur, 2014) provided more structured and clear access to the problem by allowing students to do experiments with given materials. For example, during the starting phase of PBL instruction

Table 3. Components focused on in PBL design.

Paper No.	Problem	Small Group	Student-Centered Iterative Inquiry Process	Communicate Findings to Whole Class	Resources (e.g., Library, PBL Booklet, Experimental Kit, Laboratory Facilities)	Technology (e.g., Internet, Instructional Website)	Partnership With Community	Teacher as Facilitator
1	X	X	X					
2	X	X	X					
3	X	X	X	X	X	X		
4	X	X	X	X			X	X
5	X	X						X
6	X	X	X		X			X
7	X	X	X	X	X	X		X
8	X	X			X	X		
9	X	X	X		X			

in Karaçalli and Korur (2014), necessary information was shared with students about the role of electricity in their lives and students were asked to undertake projects related to simple electric circuits from the units. This result implies that the PBL approach can be applied to young students, but students' literacy abilities need to be considered when deciding which problem types are given in PBL instruction.

Small group and other components. In terms of the small group component, all studies designed their PBL instruction based on small groups (four to six students), and emphasized collaboration skills to resolve the given problem together. Also, seven studies out of nine (Akınoğlu &Tandoğan, 2006; Araz & Sungur, 2007; Drake & Long, 2009; Karaçalli & Korur, 2014; Leuchter, Saalbach, & Hardy, 2014; Potvin et al., 2011; Wong & Day, 2008) included an iterative inquiry process in their PBL instruction. For example, in paper number one, students were encouraged to adapt new knowledge to the original problem, to revise previous hypotheses and to re-adjust these hypotheses in an iterative inquiry process. In this process, students were asked to analyze their options and to decide what research to do and how to proceed. Also, three studies (Araz & Sungur, 2007; Karaçalli & Korur, 2014; Wong & Day, 2008) put a value on improving students' communication skills by asking them to report their findings to the whole class at the end of their inquiry process. Five studies (Chen & Chen, 2012; Karaçalli & Korur, 2014; Leuchter, Saalbach, & Hardy, 2014; Potvin et al., 2011; Wong & Day, 2008) emphasized providing resources such as school library and laboratory facilities to students during PBL instruction. For example, in Leuchter, Saalbach, and Hardy (2014), each student had an opportunity to work on the task by being encouraged to do experiments with the given materials, using a worksheet as an experimental protocol. In Potvin et al. (2011), students were asked to solve 20 tasks about electricity with the available materials (wire, bulbs, switches, resistors, etc.) after being given information about how to plug the source, to link up wires, and to avoid short-circuits.

Three studies (Chen & Chen, 2012; Karaçalli & Korur, 2014; Wong & Day, 2008) provided students an opportunity to use technology by allowing them to search necessary information though the internet, or to prepare their final presentations on the computer. In particular, Chen and Chen (2012) offered technology-based PBL instruction to students through an instructional website, including news, resources, courseware, simulation, and evaluation. Furthermore, only one paper considered partnership with the community in designing PBL instruction. More specifically, in paper four, students were asked to report both their findings and the inquiry process to guest speakers or invited experts from their community. Finally, four studies (Araz & Sungur, 2007; Inel & Balim, 2010; Karaçalli & Korur, 2014; Leuchter, Saalbach, & Hardy, 2014) explicitly mentioned teachers' roles as facilitators in the PBL instruction by illustrating the following things: distributing worksheets, leading discussions, or helping students determine how to search necessary information. In particular, in paper number six targeting first grade students, teachers provided more facilitation compared to the other studies. Specifically, the teachers were encouraged to provide verbal support and ask questions to advance observation, comparison, and the interpretation of data, as well as the deduction and verification of hypotheses and arguments.

In sum, the PBL interventions designed in all nine studies seem to be divided into two perspectives: "students as active learners" and "teachers as facilitators." In regards to student improvement of skills using these interventions, student-centered learning opportunities appear to be considered in

Table 4. Differences in achievement on themes for each study.

Paper No.	Academic Achievement	Knowledge Retention	Conceptual Development	Attitudes
1	Yes			Yes
2	No	No		Yes
3	Yes*	Yes*		
4	Yes		Yes	
5	Yes		Yes	
6	Yes	Yes		
7	Yes	Yes		No
8	Yes			Yes
9			Yes	

**Difference in achievement with one of two concepts taught* order to improve four skills: namely, problem-solving skills (e.g., identifying problems, iterative inquiry process), cooperative skills (e.g., small group, partnership with community), communication skills (e.g., reporting their finding to the whole class), and technology skills. Among those four skills, problem-solving skills and cooperative skills are prevalent across the nine studies, but communication skills and technology skills are paid less attention.

In the next section, we discuss the quantitatively measured difference in student performance as it pertains to the dependent variables identified by the authors.

Effectiveness of PBL

To determine the effectiveness of PBL, the authors carefully examined each study for the dependent variables and measures used to assess the PBL versus control groups in each study. From this analysis, four main themes emerged: (1) academic achievement, (2) knowledge retention, (3) conceptual development, and (4) attitudes. Table 4 shows whether each study found statistically significant differences between treatment and control group in relationship to the identified theme.

Academic achievement. Academic achievement was identified either as academic achievement or content knowledge in eight of the nine studies (all except paper number nine, which focused on conceptual development, discussed later). For studies looking at this variable, 87.5% of the studies found that students in the PBL group outperformed students in the control group. It should be noted, however, that while Wong and Day (2008) reported achievement differences in only one of the two topics they investigated (reproduction and density), the reviewers have included this study in the academic achievement count of 87.5%. This decision is based on caveats of the authors who account for the lack of achievement differences for the reproduction topic, in contrast to the positive achievement results obtained for the density topic, by noting that while coverage of density occurred only in science class, coverage of reproduction occurred in both health and science classes. Thus, the dual coverage may account for the apparent lack of achievement differences in science class on the topic of reproduction, as the topic had already been learned in health class. Drake and Long (2009) did not find any significant difference in performance; however, the PBL group did perform slightly better than the control group from pre- to posttest. It also should be noted that of all the studies reviewed, the small sample size in the Drake and Long study (14 in treatment and 15 control) might be a reason for not finding any significant difference.

Knowledge retention. Four studies (Drake & Long, 2009; Karaçalli & Korur, 2014; Leuchter, Saalbach, & Hardy, 2014; Wong & Day, 2008) further examined whether there was a difference in knowledge retention between treatment (PBL) and control groups. All of these studies employed a delayed posttest to measure student knowledge. Of these studies, 75% indicated that students in the PBL group had better knowledge retention than the control group. While Drake and Long (2009) did not find significant difference in performance between the groups, results indicate students retained similar information, scoring almost identically on the delayed posttest.

Conceptual Development. Three papers (Araz & Sungur, 2007; Inel & Balim, 2010; Potvin et al., 2011) examined students' conceptual development. Conceptual development in these studies refers to students' understanding of scientific laws and theories and application of these to reason about phenomena. With 100% of these studies finding significant differences between the treatment and control groups on conceptual development, the evidence suggests that PBL can be used to help students in developing reasoning and application skills while developing their understanding of science concepts.

Attitudes. Finally, four studies (Akınoğlu & Tandoğan, 2006; Chen & Chen, 2012; Drake & Long, 2009; Karaçalli & Korur, 2014) examined students' attitudes, including attitudes toward science, PBL, and scientists. Overall, these studies provide a wide-ranging view of students' attitudes. The three studies that examined students' attitudes toward science and scientists indicate that students in PBL have a more positive view of scientists than the control group. Karaçalli and Korur (2014) found no difference in students' attitudes toward PBL. The authors postulate that this could be due to several factors, including the length of implementation (only four weeks) and that this was the first time for the teacher to use PBL in instruction and the first PBL experience for students.

In sum, a majority of the studies examined found that PBL has positive effects on students' academic achievement, knowledge retention, conceptual development, and attitudes. Moreover, the results indicate that PBL is at least as effective as traditional instruction in relationship to student academic achievement and knowledge retention. Though there seems to be a positive effect of PBL on attitudes, it is not clear what students' attitudes are about using PBL in instruction; thus, more research needs to be done in this area. On the other hand, our analysis indicates that PBL has a positive effect on students' conceptual development.

Discussion and Conclusions

PBL has been widely used in medical and postsecondary education to develop learners' abilities to apply their knowledge in real-world settings by working collaboratively on meaningful problems. However, relatively few studies have investigated uses of PBL in science and mathematics education at the primary to secondary levels (ages 5–14), indicating a gap in the literature. To assess the current state of the literature and provide suggestions for further research, we conducted a systematic review of the literature, which ultimately led to the in-depth reviews of nine articles reporting experimental studies of PBL in kindergarten to middle school science education. We explored three aspects of these studies: the definitions of PBL used; the components of PBL that were explicitly identified as salient to student learning; and the effectiveness of PBL in relationship to identified dependent variables. As aforementioned, for this review we were only able to find studies related to elementary science education, a point that will be discussed below.

Findings from this review reveal that PBL has many forms and many possible outcomes. In particular, the definitions of PBL used in these papers were based on four different sources, indicating some inconsistency in how the approach was understood. Also, although the nine studies were investigations of PBL specifically at the kindergarten to middle school grades (K–8), their definitions of PBL were more dependent on sources from medical education than from science or mathematics education. In terms of PBL design components, we found that eight were explicitly addressed in the nine studies. Among them, three components—nature of problems, small group work, and student-centered iterative inquiry—were more salient than the components of communication, technology, and partnership with community. Just as Strobel and van Barneveld (2009) found in their meta-analysis of PBL in higher education, overall these empirical investigations found PBL to be effective for improving students' academic achievement, including knowledge retention, conceptual development, and attitudes, although attitudes were not clearly defined.

Implications

Three implications for the use of PBL to teach elementary students science and mathematics can be drawn from this review. First, it shows there have been fewer quantitative research studies on the use of PBL in mathematics education than in science education. Although we initially sought empirical studies of the use of PBL in both science and mathematics, the nine articles we identified were related only to science education, suggesting the need for the research community to investigate the impact of PBL on teaching mathematics to elementary students. Mathematics seems to be a natural fit for PBL, with one area of focus being problem-solving. Therefore, we recommend that more empirical PBL studies need to be conducted, especially in the area of mathematics at the primary to secondary levels.

Second, a more consistent and clear definition of PBL in science and mathematics education needs to be established. The definitions of PBL in the reviewed studies were not consistent with each other, calling into question the reliability or validity of the research results. To evaluate the soundness of PBL intervention in mathematics and science education for elementary students, rigorous and coherent criteria for its implementation in this setting needs to be established. Thus, we recommend that researchers clearly define PBL when disseminating their research. This would provide opportunities for the field to evaluate the effectiveness of PBL across diverse mathematics and science classroom settings.

Finally, the majority of studies identified in this review involved sixth through eighth grade students (ages 11–14), while only one study focused on Kindergarten/first grade (ages 5–7) settings (Leuchter, Saalbach, & Hardy, 2014), suggesting the need for more investigations in lower elementary grades. While some people might doubt the ability of lower elementary students to engage in PBL, some research has shown their potential to solve ill-structured mathematics problems (Lesh, English, Riggs, & Sevis, 2013; Lesh, English, Sevis, & Riggs, 2013), suggesting the feasibility of applying PBL at these levels. Moreover, the review showed some differences between lower and upper elementary grade settings in the types of problems or PBL components emphasized, indicating the need to develop specific guidelines for applying PBL at different levels. Based on these findings, we recommend more empirical studies of PBL at the lower primary grades. These studies would provide more insight into the effectiveness of PBL for younger students, as well as what components of PBL require more scaffolding at the lower grades.

Limitations

While this review suggests definite directions for future research, it should be noted that the conclusions discussed here are based on a selected group of studies—those employing quantitative experimental designs comparing learning outcomes of traditional and PBL groups. Thus, qualitative studies investigating the effects of PBL in mathematics and science education and studies examining effects among different versions of the PBL approach were not included. Also, although some approaches such as inquiry-based learning, problem-centered learning, problem solving, and discovery-guided learning involve components of PBL, if the term "problem-based learning" or "project-based learning" was not explicitly used in an article, it was excluded to avoid subjectivity in judging what should be considered PBL. Had the terms "problem-centered learning" and "problem solving" been considered forms of PBL and the focus included studies other quasi-experimental/experimental quantitative studies, the collection of reviewed studies would have included more analysis of PBL in mathematics education. Thus, inclusion of a broader range studies may have led to different recommendations.

References

Akınoğlu, O., & Tandoğan. R. O. (2007). The effects of problem-based active learning in science education on students academic achievement, attitude and concept learning. *Eurasia Journal of Mathematics, Science & Technology Education, 3*(1), 71–81.

Araz, G., & Sungur, S. (2007). Effectiveness of problem-based learning on academic performance in genetics. *Biochemistry and Molecular Biology Education*, *35*(6), 448–451.

Barrows, H. S. (1986). A taxonomy of problem-based learning methods. *Medical Education*, *20*(6), 481–486.

Barrows, H. S. (1996). Problem-based learning in medicine and beyond: A brief overview. In L. Wilkerson & W. H. Gijselaers (Eds.), *Classrooms and staff rooms: The sociology of teachers and teaching* (pp. 36–47). Milton Keynes, UK: Open University.

Barrows, H. S., & Tamblyn, R. M. (1976). An evaluation of problem-based learning in

small groups utilizing a simulated patient. *Journal of Medical Education, 51*(1), 52–

54.Barrows, H., & Tamblyn, R. M. (1980). *Problem-based learning: An approach to medical education.* New York: Springer.Bell, J. (2010). *Doing your research project.* New York: McGraw-Hill.

Bennett, J., Campbell, B., Hogarth, S., & Lubben, F. (2007). *A systematic review of the effects on high school students of context-based and science-technology (STS) approaches to the teaching of science.* York, UK: Department of Educational Studies, The University of York.

Boyce, M. C., & Singh, K. (2008). Student learning and evaluation in analytical chemistry using a problem-oriented approach and portfolio assessment. *Journal of Chemical Education*, *85*(12), 1633.

Brooks, J. G., & Brooks, M. G. (2001). *In search for understanding the case for constructivist classrooms.* Upper Saddle River, NJ: Prentice Hall.

Capraro, R. M., & Slough, S. (2013). Why PBL? Why STEM? Why now? An introduction to STEM project-based learning: An integrated science, technology, engineering, and mathematics (STEM) approach. In R. M. Capraro, M. M. Capraro, and J. Morgan (Eds.), *Project-based learning: An integrated science, technology, engineering, and mathematics (STEM) approach* (2nd ed., pp. 1–6). Rotterdam, Netherlands: Sense.

Chen, C. H., & Chen, C. Y. (2012). Instructional approaches on science performance, attitude and inquiry ability in a computer-supported collaborative learning environment. *Turkish Online Journal of Educational Technology-TOJET*, *11*(1), 113–122.

Colley, K. E. (2008). Project-based science instruction: A primer. *The Science Teacher*, *75*(8), 23–28.

Curry, J. J. (2002). *Problem-based learning pathway student handbook*. Columbus: The Ohio State University, College of Medicine and Public Health.

Dewey, J. (1938). *Experience and education*. New York: Macmillan.

Dewey, J. (1966). *Democracy and education*. New York: Free Press.

Didem, I. E., & Balım, A. G. (2010, December). The effects of using problem-based learning in science and technology teaching upon students' academic achievement and levels of structuring concepts. *Asia-Pacific Forum on Science Learning & Teaching, 11*(2).

Drake, K. N., & Long, D. (2009). Rebecca's in the dark: A comparative study of problem-based learning and direct instruction/experiential learning in two 4th-grade classrooms. *Journal of Elementary Science Education*, *21*(1), 1–16.

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education, 25*(6), 671–688.

Duschl, R., Maeng, S., & Sezen, A. (2011). Learning progressions and teaching sequences: A review and analysis. *Studies in Science Education*, *47*(2), 123–182.

English, M. C., & Kitsantas, A. (2013). Supporting student self-regulated learning in problem- and project-based Learning. *Interdisciplinary Journal of Problem-Based Learning, 7*(2), 128–150.

Gallagher, S. A., & Stepien, W. J. (1995). Implementing problem-based learning in science classrooms. *School Science and Mathematics*, *95*(3), 136–147.

Gallagher, S. A., & Stepien, W. J. (1996). Content acquisition in problem-based learning: Depth versus breadth in American studies. *Journal for the Education of the Gifted*, *19*(3), 257–275.

Gijbels, D., & Loyens, S. M. M. (2009). Constructivist learning (environments) and how to avoid another tower of Babel: Reply to Renkl. *Instructional Science*, *37*(5), 499–502.

Gould, K., & Sadera, W. (2015). Evaluation of health profession student attitudes toward an online nutrition education problem-based learning module. *International Journal of Online Learning, 14*(2), 181–198.

Hewson, P. W. (1981). A conceptual change approach to learning science. *European Journal of Science Education*, *3*(4), 383–396.

Holliday, W. G. (2006). A balanced approach to science inquiry teaching. In L. B. Flick & N. G. Lederman (Eds.), *Scientific inquiry and nature of science* (pp. 201–217). Dordrecht: Springer.

Howard, J. (2002). Technology-enhanced project-based learning in teacher education: Addressing the goals of transfer. *Journal of Technology and Teacher Education, 10*(3), 343–364.

Hsu, L. (2004). Developing concept maps from problem-based learning scenario discussions. *Issues and Innovations in Nursing Education*, *48*(5), 510–518.

Karaçalli, S., & Korur, F. (2014). The effects of project-based learning on students' academic achievement, attitude, and retention of knowledge: The subject of "electricity in our lives." *School Science and Mathematics*, *114*(5), 224–235.

Kim, H. K., VanTassel-Baska, J., Bracken, B. A., Feng, A., Stambaugh, T., & Bland, L. (2012). Project Clarion: Three years of science instruction in title I schools among k-third grade students. *Research in Science Education, 42*(5), 813–829.

Krajcik, J., Blumenfeld, P. C., Marx, W. R., Bass, M. K., & Fredricks, J. (1998). Inquiry in project-based science classrooms: Initial attempts by middle school students. *Journal of the Learning Sciences*, *7*(3–4), 313–350.

Krajcik, J. S., Czerniak, C. M., & Berger, C. (1999). *Teaching children science: A project-based approach*. Boston: McGraw-Hill.

Kwon, O. N., Park, J. H., & Park, J. S. (2006). Cultivating divergent thinking in mathematics through an open-ended approach. *Asia Pacific Education Review*, *7*(1), 51–61.

Leuchter, M., Saalbach, H., & Hardy, I. (2014). Designing science learning in the first years of schooling: An intervention study with sequenced learning material on the topic of "floating and sinking." *International Journal of Science Education*, *36*(10), 1751–1771.

Macbeth, D. (2000). On an actual apparatus for conceptual change. *Science Education*, *84*(2), 228–264.

Namy, L., & Gentner, D. (2002). Making a silk purse out of two sow's ears: Young children's use of comparison in category learning. *Journal of Experimental Psychology: General*, *131*(1), 5–15.

Nowak, J. A. (2001). *The implications and outcomes of using problem-based learning*
to teach middle school science (Doctoral dissertation). Indiana University, Bloomington, IN.

Potvin, P., Mercier, J., Charland, P., & Riopel, M. (2012). Does classroom explication of initial conceptions favour conceptual change or is it counter-productive? *Research in Science Education*, *42*(3), 401–414.

Quinn, K. A., & Albano, L. D. (2008). Problem-based learning in structural engineering education. *Journal of Professional Issues in Engineering Education and Practice*, *134*(4), 329–334.

Rico, R., & Ertmer, P. A. (2015). Examining the role of the instructor in problem-centered instruction. *TechTrends*, *59*(4), 96–103.

Savin-Baden, M., & Wilkie, K. (2006). Possibilities and challenges. In M. Savin-Baden (Ed.), *Problem-based learning online* (pp. 105–126). Buckingham, UK: Open University Press.

Singer, J., Marx, R., Krajcik, J., & Clay-Chambers, J. (2000). Constructing extended inquiry projects: Curriculum materials for science education reform. *Educational Psychologist*, *35*(3), 165–178.

Stepien, W. J., & Gallagher, S. A. (1993). Problem-based learning: As authentic as it gets. *Educational Leadership*, *50*(7), 25–28.

Strobel, J., & van Barneveld, A. (2009). When is PBL more effective? A meta-synthesis of meta-analyses comparing PBL to conventional classrooms. *Interdisciplinary Journal of Problem-Based Learning, 3*(1), 44–58.

Taber, K. S. (2000). Chemistry lessons for universities?: A review of constructivist ideas. *University Chemistry Education*, *4*(2), 63–72.

Tarhan, L., & Acar, B. (2007). Problem-based learning in an eleventh grade chemistry class: "Factors affecting cell potential." *Research in Science & Technological Education*, *25*(3), 351–369.

Trinter, C. P., Moon, T. R., & Brighton, C. M. (2015). Characteristics of students' mathematical promise when engaging with problem-based learning units in primary classrooms. *Journal of Advanced Academics*, *26*(1), 24–58.

Tseng, K. H., Chiang, F. K., & Hsu, W. H. (2008). Interactive processes and learning attitudes in a web-based problem based learning (PBL) platform. *Computers in Human Behaviour, 24*(3), 940–955.

von Glasersfeld, E. (1995). *Radical constructivism: A way of knowing and learning*. London: Palmer Press.

Walton, H. J., & Mathews, M. B. (1989). Essentials of problem-based learning, *Medical Education, 23*(6), 542–558.

Wong, K. K. H., & Day, J. R. (2009). A comparative study of problem-based and lecture-based learning in junior secondary school science. *Research in Science Education*, *39*(5), 625–642.

Yenal, H., İra, N., & Oflas, B. (2003). Etkin öğrenme modeli olarak: Soruna dayalı öğrenme ve yüksek öğretimde uygulanması. *Sosyal Bilimler Dergisi*, *1*(2), 117–126.

Zubaidah, S. (2005). Problem-based learning: Literature review. *Singapore Nursing Journal*, *32*(4), 50–55.

Joi Merritt is an assistant professor in the Mary Lou Fulton Teachers College at Arizona State University. Her research currently focuses on designing science curriculum materials and assessments to investigate K–12 student learning over time as well as research and development on approaches for preparing preservice teachers to provide equitable science instruction.

Mi Yeon Lee is an assistant professor of mathematics education in the Mary Lou Fulton Teachers College at Arizona State University. She is interested in preservice teachers' mathematical teaching knowledge and noticing abilities, K–16 students' algebraic reasoning, project-based learning, and the use of technology in mathematics education.

Barbara Kinach is an associate professor of mathematics education in the Mary Lou Fulton Teachers College at Arizona State University. Her research investigates the tasks of mathematics teacher preparation and their impact on prospective teachers' mathematical understanding, epistemological beliefs, and teaching practices. Progressive visualization and semiotic chaining tasks are the focus of her current work.

Peter Rillero is an associate professor of science education at Arizona State University, who began his career in Kenya (1982) teaching science with the U.S. Peace Corps. Rillero's scholarship interests include deep-conceptual learning, problem-based learning, inquiry, teacher education, program evaluation, modeling, and the history of science education.