

Research evidence on the benefits of IBL

Regina Bruder · Anne Prescott

Accepted: 16 September 2013 / Published online: 4 October 2013
© FIZ Karlsruhe 2013

Abstract This paper describes the current state of knowledge of empirical studies in the broader sense dealing with inquiry-based learning (IBL) of mathematics and science subjects in schools and universities. The advantages, disadvantages, and effects on relevant outcomes that students can achieve in IBL classrooms are discussed from the aspect of further developing teaching quality. First, the conceptual aspects of IBL are considered briefly to show the background of the studies and the results are categorized. Secondly, references are given with explanations or possible reasons for the results that are not always consistent and, at times, even contradictory. Finally, conclusions from current studies including this overview are drawn with respect to open scientific questions.

“Tell me and I forget, show me and I remember,
involve me and I understand”
(Chinese Proverb)

1 Teaching quality and research history of IBL

Whenever one looks at teaching quality, the chosen instruction design plays an important role. In general there are two basic concepts: teacher-centred (where the new knowledge is learned using mathematical definitions, rules,

contexts and methods given by the teacher) or student-centred (where new knowledge is discovered by the students with more or less help or direct instruction by the teacher).

Inquiry-based learning in its different variations is considered an opposing approach to the teacher as the centre of instruction—often manifested as ‘rule and example’: R+E—where the teacher explains the work and then students practise. The desired learning effect of R+E is described as ‘memorizing’ and ‘transfer’ and the results are assessed in tests with a pre-test/post-test design. Other types of teacher-centred instruction include direct instruction for the learning of specific skills and subject matter, and demonstrations of particular skills and processes. The most common aspect of the teacher-centred approach is that the teacher determines what will be learned and the students tend to be passive recipients of that knowledge rather than being actively engaged with their learning.

In reality, the situation is less black-and-white so it is more practical to see these terms as being at either end of a continuum. Successful teachers’ strategies in the classroom are situated somewhere along the continuum between the two ends, depending on the teaching and learning goals, the special strengths of the teacher, and the special needs and level of competence of the students. This is an important conclusion for inquiry-based learning (IBL) too, since IBL as a student-centred concept focuses on one end of instruction design.

Investigations on the effect of IBL have been around for a long time and may even be seen as a tradition that is more than 100 years old (Artigue and Blomhøj 2013; Kahn and O’Rourke 2005), even though the terminology has changed. Hermann (1981) reported on the presumably first IBL experiments by Winch (1913) who determined that memorizing is better for receptive learning and a more

R. Bruder (✉)
Technische Universität, Darmstadt, Germany
e-mail: r.bruder@math-learning.com;
bruder@mathematik.tu-darmstadt.de

A. Prescott
University of Technology, Sydney, Australia
e-mail: anne.prescott@uts.edu.au

favourable transfer is reached by inductive learning. This result stands as a stereotype for most of the studies that followed, mainly carried out in the 1960s. More recently, different measurement categories have been used for memorizing and transfer. According to Hermann (1981), the results in general are:

- The method of inquiry is superior to the rule and example (R+E) approach (significant results are 12:5 in favour of the inquiry method).
- The inquiry method is superior in stimulation transfer of learning (a ratio of 10:1 for significant results).
- Memorizing benefits from the R+E method (significant results with a ratio of 4:2), although many studies did not find any significant differences.

The question about which kind of learning method has the greatest (individual) learning effect has always been at the centre of empirical research on classroom teaching. The goals, questions and results of such research (e.g. Anderson 2002; Barron and Darling-Hammond 2008; Ergül et al. 2011; Thomas 2000) are central to more recent IBL-related research. However, there is still no common understanding of IBL (Maaß and Doorman 2013). In the project PRIMAS, the acronym IBL is treated as a key to solving more global problems, particularly in science and mathematics education. Inquiry is often conflated or used interchangeably with other terms that describe similar learning and teaching approaches such as hands-on, problem-based, project-based, student-centred, inductive and dialogic approaches (Anderson 2002; Maaß 2011). For the present review only studies that explicitly use the term ‘inquiry-based learning’ are selected, even though Artigue and Blomhøj discuss the close relation between problem solving and IBL—especially in the field of mathematics.

2 Research results on aspects of IBL

It is difficult to compare studies on a subject as complex as IBL because of the different forms of IBL, the different research methods used, the different methods of assessment and the lack of definition about IBL. Further, most are experiments and not field studies. Though IBL has been broadly investigated, it is therefore difficult to generalize the results on a global level, even when these results are in agreement.

Hattie (2009) analysed 205 studies/meta-analyses on inquiry-based teaching, with most in science education rather than mathematics education. He found that the effects were greatest at elementary level but decreased as students progressed through their school years. Furthermore, the effects were twice as large on processes as on content. Hattie concluded that inquiry-based instruction

might be more appropriate when students have the cognitive capacity to think critically but have not previously been encouraged to think that way. “Overall, inquiry-based instruction was shown to produce transferable critical thinking skills as well as significant domain benefits, improved achievement, and improved attitude towards the subject” (Hattie 2009, pp. 209–210).

Kremer and Schlüter (2006) described inquiry-based science teaching as one way to introduce students to science. Students formulated their own questions, created hypotheses and designed investigations that tested these hypotheses, and answered the proposed questions (Germann et al. 1996). The basis of the inquiry method is phenomena or problems that have to be worked on by the students, in various forms, independently (Colburn 2000; Tafoya et al. 1980). When Kremer and Schlüter (2006) analysed IBL they discriminated between:

Structured Inquiry: The teacher gives the students a problem or question to be solved as well as the appropriate method and materials to solve it.

Guided Inquiry: The teacher provides the students with the problems or questions and the necessary materials. The students have to find the appropriate problem-solving strategies and methods.

Open Inquiry: The students have to find problems or questions they would like to solve and answer. They also decide the methods and materials they would like to use.

The breadth of the research into IBL, as evidenced by Hattie (2009), meant that we had to be selective in the studies we included here. We looked for studies that would give a global view of IBL: small scale (at the class level), large scale (at the year level or school level), short-term (in months or less), long-term (over years), across subjects, and including students with many different backgrounds. We analysed the mathematics and science research on IBL using the above three strategies of IBL in the first instance. When we considered each study, we looked first at the amount of guidance given by the teacher, then the methodology of each study, the scale and time interval as well as the students who participated, the goals, the kind of intervention connected with the tasks for learning, the effects on motivation, the acceptance by the teachers and students, and the effects on the learning outcomes. Each study sought to answer different research questions so their results often cannot be compared, but each study adds to our global understanding of student learning and the student learning outcomes in an IBL classroom.

Open tasks or open-ended mathematics problem tasks (e.g. Chan 2006) and learning mathematics while problem solving (see for example the *ZDM* issue on problem solving 2007: ‘Problem Solving Around the World: Summing Up the State of the Art’) have been the focus of a number of studies. We focused our analysis on studies that

Table 1 Studies associated with *Structured Inquiry*

Study	Design	Participant details	Discipline ^a Level ^b	Data collection methods
Egan and Greeno (1981)	2 days, 2 different material-based learning designs	78 university students	M Sec	Pretest/post-test, analysis of mistakes and learning time
Beinbrech (2003)	Comparison group, some weeks, 2 different instruction-settings	50 students (grade 3)	Sc E	Pretest/post-test, analysis of the applicability of the learned knowledge

^a M mathematics, Sc science

^b E elementary school, S secondary school

integrated more generally a combination of the three most important characteristics of IBL (Chan 2006):

- (i) opportunities for students to generate several options and solutions
- (ii) opportunities for students to discuss together
- (iii) opportunities for students to make decisions and justify their decisions.

2.1 Studies on *Structured Inquiry*

There are few studies on the *Structured Inquiry* approach in comparison with a classic instructional design, e.g. R+E (Table 1). One reason could be that there is little difference between the two instructional designs. However, we have already seen that the efficiency of these methods corresponds to the specific learning goals of the students and to their individual preconditions in this field of learning and assessment. If learning outcomes are measured only in the field of basic knowledge, then the effect on other important variables for sustained learning are neglected.

2.1.1 Small cohort short-term studies

Egan and Greeno (1981) considered whether different kinds of learning activities lead to different forms of knowledge. They used computer-based experiments in the topic of probabilistic theory using structured inquiry-based teaching strategies in conjunction with R+E. Their results indicated that students who did not have the necessary knowledge and skills could learn more effectively when they were instructed with methods requiring interpretation and usage of rules (R+E). The study also showed that the best support for learning new terms depended on the special learning preconditions of the student.

In the past, IBL was often associated with self-regulated science learning in the elementary school in order to determine the degree of self-regulation necessary to advance problem solving, or to target achievement with multiple criteria. Beinbrech (2003) found that no significant group differences occurred in a result-oriented

evaluation where the level of problem solving was recorded. The participants in the experimental group often demonstrated new and more creative ideas for solutions. The experimental and comparison groups both showed a higher degree of factual knowledge, but without a group difference. There were also no significant differences in self-efficacy.

2.2 Studies on *Guided Inquiry*

The majority of the IBL research discussed here used *Guided Inquiry* in the classroom but there is a great deal of difference between studies in terms of the cohort, the length of the study, whether there was a comparison group, and the assessment of the learning effects. Table 2 shows large cohorts for longitudinal studies, large cohorts for short-term studies, and smaller cohorts with particular groups of students.

2.2.1 Large cohort longitudinal studies

Many teachers are reluctant to venture into teaching using an IBL perspective since they believe that students need to know the content before they can look at applications (i.e. the traditional classroom). Boaler (1998) showed that the IBL students' content knowledge was as good as, or better than, the students' content knowledge from the traditional classroom, especially on standardized tests, and attitudes were more positive. Amaral et al. (2002) found more positive attitudes to learning across all subjects.

The longitudinal study by Amaral et al. (2002) used IBL in science classes where the students were all English Language Learners (ELL). They found that there were many benefits for the students, including developing positive attitudes toward learning and engaging in authentic conversation with their peers. These attributes developed during the life of the project with long-term participants showing more benefits than those who had been in the programme for less time. Importantly, they also showed greater proficiency not just in science, but also in English language, reading and mathematics.

Table 2 Studies associated with *Guided Inquiry*

Study	Design	Participant details	Discipline ^a Level ^b	Data collection methods
Amaral, Garrison and Klentschy (2002)	Longitudinal 4 years	615 4th grade students 635 5th grade students English language Learners (ELLs)	M/Sc E	Stanford Achievement Test in science and mathematics
Boaler (1998)	Longitudinal 3 years Open-ended projects vs Traditional (teacher directed)	200 7th–9th grade (open-ended) 110 9th–12th grade (traditional)	M Sec	Pretest/post-test National exam results Student observation
Newmann, Marks and Gamoran (1995)	1 year Range of student achievement	2,128 students (elementary, middle and high school) 23 schools 3 classes in each school	M E + Sec	Student observation Teacher questionnaire Assessment tasks Student work samples
Meyer, Turner and Spencer (1997)	One project	14 students 1 class	M E	Surveys of Challenge and Adaptive learning Student observation Interviews
Lind et al. (2004)	Learning session about 3 h, novices versus experts in physics	34 gifted students	Sc Sec	Student observation, thinking aloud
Gallagher, Stepien and Rosenthal (1992)	P/S in an IBL class Comparison class	78 students 7th grade Gifted students	Sc Sec	Pretest/post-test (open-ended poorly-defined problems)
Scruggs and Mastropieri (1993)	2 science units	26 junior high students Learning disabilities Students	Sc Sec	Pretest/post-test Interviews
McCarty et al. (1991)	Small collaborative peer groups	4 social studies classes Indigenous students (Navajo) Non-indigenous teachers	All subjects	Observation

^a M mathematics, Sc science^b E elementary school, S secondary school

Boaler compared two schools, one using a textbook approach and the other using project-based activities (IBL) at all times. The students in the IBL classes described their experience of mathematics as being “noisy” (23 %), with “a good atmosphere” (17 %) and “interesting” (15 %), but their counterparts in the traditional classroom used terms like “difficult” (40 %), something related to their teacher (36 %) and “boring” (28 %). IBL students commented on their enjoyment of mathematics, whereas the students from the traditional classrooms were more concerned about a lack of understanding and their dislike of textbooks. Students who had been taught in the traditional way “did not think it was appropriate to try to think about what to do; they thought they had to remember a rule or method they had used in a situation that was similar” (Boaler 1998, p. 47). On the other hand, IBL students could use mathematics in novel situations as they had developed the belief that mathematics required active, flexible thought.

2.2.2 Large cohort short-term studies

Newmann et al. (1996) found a positive impact on learning when students participated in lessons that required them to construct and organize knowledge, consider alternatives, engage in detailed research, inquiry, writing and analysis, and communicate effectively with audiences. Indeed, use of these practices resulted in stronger performance regardless of race, gender, or prior achievement.

Students’ achievement in all grade levels increased:

“We found that authentic pedagogy helps all students substantially. However, it provides an extra boost for students already performing at higher levels. In other words, if a low-achieving student moved from a class low in authentic pedagogy to a class high in authentic pedagogy, that student’s performance would be enhanced significantly. But a high-performing student

making the same move would improve even more.” (Newmann et al. 1995, p. 8)

When Meyer et al. (1997) assessed students for challenge-seeking or challenge-avoidance, they found that challenge-seekers approached an IBL classroom more positively, allowing for collaboration, while the challenge-avoiders expressed self-doubt and did not find the experience enjoyable, even when the task was successfully completed. Challenge-seekers reported a tolerance for failure and higher-than-average self-efficacy in mathematics, while challenge-avoiders reported higher negative affect after failure and lower self-efficacy in mathematics.

Lind et al. (2004) worked with 34 gifted students to compare two different methods of learning—independent problem solving, and working on problems with commented solutions. The students were asked to solve a problem while ‘thinking aloud’ and were given opportunities to elaborate on their answers. They found that previous knowledge played a crucial part in the problem solving in terms of the ability to solve problems and in the way they were able to explain their solution. Chi (2000) indicates that self-explaining is effective for learning because it is easily used and beneficial to students of all abilities.

It “engages students in active learning and ensures that learners attend to the material in a meaningful way while effectively monitoring their evolving understanding. ... Several key cognitive mechanisms are involved in this process including, generating inferences to fill in missing information, integrating information within the study materials, integrating new information with prior knowledge, and monitoring and repairing faulty knowledge.” (Roy and Chi 2005, p. 273)

The study by Lind et al. (2004) extended Chi’s results, finding that self-explanations are independent of previous knowledge and that a deep elaboration of examples was not sufficient to provide necessary background knowledge—that is, an encyclopaedia cannot substitute for well-integrated knowledge.

Gallagher et al. (1992) also studied the abilities of gifted students to solve problems, in this case poorly-structured problems. They defined these problems as realistic problems that did not give sufficient information, changed as more information was added to the situation, had many perspectives for interpreting the situation, and no absolutely right answer. The students who were provided with guided experience in solving problems in an IBL class showed significant improvement in problem-solving schemes whereas the comparison class did not. The IBL students’ motivation and dedication also increased. In a

later study, Stepien et al. (1993) found that gifted students had an enhanced ability to support their reasoning with clear arguments.

Scruggs and Mastropieri (1993) compared IBL with a textbook approach for students with learning needs. They concluded that IBL yielded significantly higher achievement for high school students with special needs because they learned more and remembered more than those who were taught by more direct instructional methods. The students who studied using both methods favoured hands-on science IBL activities over textbook activities—96 % reported that they enjoyed the inquiry approach more, and over 80 % considered the activities more facilitative of learning and more motivating.

In the North American context, Rains et al. (2000) discussed the native cultures’ epistemologies and beliefs that have developed over thousands of years of continuous living on the land. This connection to the land means that native peoples have different ways of approaching knowledge, learning, understanding and remembering (Rains et al. 2000).

McCarty et al. (1991) found significant gains in IBL student participation levels and greater student interest in connecting content to the social, economic and cultural realities of their society when they engaged in IBL rather than whole-class lecture and discussion. Prior to this study the non-Navajo teachers had struggled to engage the students, but found that in the IBL classes the students actively participated in class and applied what they learned in new contexts.

While Perso (2003) is not a study of IBL, it makes an important contribution to our understanding of IBL with indigenous students. Perso pointed out that indigenous students in Australia also have different learning styles that relate to their cultural background. Perso discussed the Yolngu people’s style of learning and IBL and pointed out the similarities between their learning styles and IBL. The indigenous students learn:

- by observation and imitation rather than verbal instruction;
- through trial and error rather than verbal instruction and demonstration;
- on the whole task rather than a sequence of skills;
- by approaching problem solving with persistence and repetition;
- by using hands-on materials to assist learning.

Perso also points out that Aboriginal behavior is governed by discussion and group decisions so participation is important. Indigenous students are reluctant to take risks publicly, preferring to try out new things privately or in groups and seek help from peers rather than the teacher. It is therefore not surprising that Perso advocates an IBL

Table 3 Studies associated with *Open Inquiry*

Study	Design	Participant details	Discipline ^a Level ^b	Data collection methods
Marx et al. (2004)	3 year Longitudinal study Comparison group	8,000 students 6th, 7th and 8th grade Low achievers Physics students	Sc E/Sec	Achievement tests
Kahle, Meece and Scantlebury (2000)	Longitudinal study Comparison group	African American students 8 middle schools	Sc	Achievement tests Questionnaires
Penuel, Means and Simkins (2000)	1 year	3 3rd grade classes	E	Performance task Standardized tests
Kremer and Schlüter (2006)	One unit	38 students 8th grade	Sc Sec	Student observation (video)
Asmussen (2009)	Intervention study Miniphänomena (without instruction)	75 students 3rd and 4th grade	Sc E	Pretest/post-test Student observation, interview
Palmer (2002)	Group-work, seminars are peer assessed	42 Master-students, 1 university semester	Psych.	Student observation with interviews and questionnaires

^a M mathematics, Sc science

^b E elementary school, S secondary school

approach as being the most effective learning strategy for indigenous Australians.

In his analysis of IBL research, Thomas (2000) indicated that higher-achieving students were able to make greater gains academically than low-achieving students when IBL was used. There were many school districts in the United States where similar results were achieved using Expeditionary Learning and Co-nect.¹

Thomas (2000) suggests that the reported effects of IBL-based programmes on students' basic skills achievement may be the result of a generalized effect associated with the whole school reform effort or, perhaps, the motivational effect of inquiry-based instruction may lead to increased student attendance, attention and engagement during the (non-project) periods students spend learning basic skills. In earlier work, Newmann et al. (1995) suggested that such results may have been due to the increased content knowledge of the high achievers. For example, there was a positive effect on 4th and 5th grade students' acquisition of critical thinking skills. Using a problem related to an apparent housing shortage in six countries, there was a significant increase (compared with the fifteen traditionally taught students) on a test of critical thinking skills by the IBL students (The Cornell Critical Thinking Test). The

students in the IBL group also reported increased confidence and learning.

The research discussed here indicates that Guided Inquiry is successful in improving student attitudes and motivation. Importantly, Guided Inquiry was important for all students (including gifted students, ELL students and Indigenous students), across subjects and grade levels. The results concerning improved content knowledge are mixed—while some studies found that content knowledge, as measured by standardized tests, improved, others did not.

2.3 Studies on *Open Inquiry*

The third method of inquiry is the most student-centred of all with the students often deciding the problem or question and then deciding on the method or strategy to solve it (Table 3). By deciding their own approach to the problem, students generate new ideas or solutions that are beyond what anyone could have thought before. They create a different level of understanding of the problem. In this way, open inquiry teaches problem-solving skills providing learners with the freedom to solve problems in a variety of different ways.

2.3.1 Large cohort longitudinal study

Marx et al. (2004) conducted a longitudinal study and found that IBL classes allowed the students to fulfil the curriculum requirement and understand the process of IBL without sacrificing state curriculum standards. The

¹ Expeditionary Learning and Co-nect provide school leaders and teachers with professional development, curriculum planning resources, and new school structures to boost student engagement, character, and achievement through 'authentic learning'—linking school mathematics with real-life mathematics.

students, who were historically low achievers in science, succeeded in IBL science classes when they were asked to create projects to explore simple machines and the concept of force. Kahle et al. (2000) found similar results for African-American students, especially boys. They also found that IBL narrowed the achievement gap between male and female students, with the students showing greater interest in mathematics. The research also compared eight teachers who had participated in IBL teacher professional development with ten teachers who had not. Since Boaler (1998) found similar results in the United Kingdom, these large-scale longitudinal studies are important in our understanding of IBL and its benefits.

2.3.2 Small cohort short-term studies

A comparison of studies that are small cohorts and short-term is difficult. Each one is specific in its purpose, students and results. Such complexity indicates the variety of approaches in IBL and in the research associated with it.

A multimedia project was used as the basis of the study by Penuel et al. (2000). The students investigated the problems of the homeless in their local area culminating in an exhibition of their presentations at the local history museum. They earned higher scores than the comparison group on content mastery, sensitivity to audience and coherent design, and performed equally well on standardized test scores of basic skills.

Asmussen (2009) prepared 53 stations with experiments for primary students, installed for self-guided learning during the breaks between the lessons—he called this interactive exposition MINIPHÄNOMENTA. The research goal was to analyse possible changes of the abilities of the students by participating. Asmussen found explicit and sustainable effects for the methodical abilities of the students, in particular their science-thinking and logical and experimental abilities.

Inquiry-based learning was the basis of a Developmental Psychology unit where peer-assessed student-led seminars were part of the assessment. Palmer used IBL for the students “to take charge of their own learning and [give] them more freedom to research ... topics of personal interest in a way which suits their own learning style (Palmer 2002, p. 82). The students increased their knowledge of a broad range of topics, learning advanced research and presentation skills, and improved their ability to undertake independent and cooperative learning. Student evaluations showed that, although they did not like the approach initially, they felt they had learned more than they would have through a more conventional approach (Palmer 2002).

However, when Kremer and Schlüter (2006) reported on aspects of the development of science-knowledge with IBL students, their results were not as positive. They found that

students intuitively used the framework set up by Fradd et al. (2002): questioning, planning, implementing, analysing, concluding, reporting and applying, but could not generate different hypotheses because they lacked basic knowledge for creating new hypotheses. The students rarely gave interpretations and explanations of the results of the experiments.

The results for Open Inquiry are mixed. The large-scale studies found content knowledge enhanced by IBL, but the smaller studies are mixed in terms of their results. Each one looked at a different aspect of student learning so it is difficult to compare them or find an overall result.

2.4 Summary of research results

In summary, most IBL projects showed some positive gains for the students—sometimes the gains were in mathematics or science content, but more often the gains concerned the processes. The *Guided Inquiry* projects showed the greatest gains in both content and process but it is difficult to generalize the results because of the different methodologies, participants and length of studies. However, it is evidence that there is a growing body of research showing that students learn more deeply from strongly guided learning than from discovery learning (e.g. Moreno 2004).

3 Task difficulty

If one assumes that IBL has positive learning effects, further research questions arise in terms of the level of difficulty of the questions posed when learners are to discover the results themselves. There are a number of aspects to discussing the difficulty of tasks given to students in IBL. Problems or questions can vary in the level of difficulty for the students, and the amount of help given by the teacher can also vary.

Klauer and Leutner (2007) described a study of 156 university students solving tasks where the level of difficulty was known from other studies. The goal was to discover rules or patterns in the solutions of the tasks. The students worked on tasks with different levels of difficulty, and the results were clear: the students were more successful when the teacher guided the students toward discovering the rule whereas the students had much less success with tasks that had little teacher guidance.

Neber (2001) found IBL was most promising when the process of discovery was gently steered by the teacher with the necessary knowledge communicated only when necessary. Furthermore, the problems should not be too complicated but reduced to an appropriate level. Varying the level of the tasks forms the basis for generalizing understanding and for practising transfer.

Nußbaum and Leutner (1986) support these results, stating that the old didactical rule of thumb ‘moving from simple to difficult’ is still relevant. Reversing the rule, however, was not supported so only giving students difficult tasks, or working from difficult to easier tasks, was problematic. When tasks were very difficult, the learning effect was almost zero—often having devastating effects on the motivation to learn.

As with any teaching, the choice of task and the actions of the teacher have an important effect on the student learning. Teachers must choose the task for the students carefully, ensuring that the tasks are challenging but not demotivating because they are too difficult. The Guided Inquiry strategy where the teacher has a supportive role in the students’ learning is the most effective in several aspects of student learning, with tasks that extend the students’ problem solving.

4 Critiques of IBL

Many studies produce different findings on IBL since there is a level of uncertainty associated with a complex teaching/learning relationship (Leikin and Rota 2006; Phelan 2005). Cronbach (1981) contrasted a variety of experiments and research on IBL and indicated that there are aspects in the research that have been neglected. For example, he criticized the methodology when different times for experimental and control groups were used. Cronbach discussed the conditions for the finding of the result that teaching efficacy depends more on what is learned than how it is learned or how teaching is conducted. He postulated that, in order to get useful results, there needs to be a fivefold interaction between the type of learning-content, the type of teacher, the teaching and learning time, the type of student, and the outcome.

More recent studies agree with Hartinger (2001) who claimed that forms of inquiry-based learning regarding knowledge acquisition and transfer of knowledge are more successful than solely autonomous, inquiry-based learning.

Students’ prior understanding also crucially influences IBL. Many studies show that children with little prior understanding of a topic have better results in learning when it is not inquiry-based (e.g. Egan and Greeno 1981; Hermann 1981; Kirschner et al. 2006). There are some skills that are required in order for students to engage in IBL—identifying and solving problems, for example—but these skills can be taught and then practised.

Kirschner et al. (2006) argue that studies from the last 50 years show that IBL is less effective than most educators believe. IBL has good results compared with R+E if the students have a high level of prior knowledge. They suggest that for successful problem solving we work with

our long-term memory, which is responsible for a flexible application of our knowledge and our strategies. However, for the transfer of relevant task-information into the long-term memory it is necessary to have enough working memory. IBL needs a lot of working memory to find solutions for the actual problem and then there is not enough working memory available for the transfer of important information into the long-term memory (e.g. Sweller et al. 1982).

Brown and Campione (1994) noticed that IBL could be inefficient if there was little feedback when the students engaged in it. Chan (2006, p. 3) described a successful IBL-situation as follows: “The teacher had to practise management by walking about, and would sit with individual groups at different times to listen to their discussion and elicit their thoughts through questioning their assumptions, bearing in mind that without some form of support and encouragement, the problem-solving process could deteriorate into a frustrating experience for them. The teacher used ‘what if...’ questions to prompt them to think further and deeper. The teacher encouraged the students to do likewise, to question students who provided inputs, so as to challenge them to rationalize their viewpoints.” Obviously such a teacher’s behaviour is measurable only in terms of its effects.

Moreno (2004) concluded that (strongly) guided learning helps the students to learn more deeply than discovery learning (i.e. Open Inquiry).

Kirschner et al. (2006) describe the important study of Klahr and Nigam (2004) who not only tested whether science learners learned more via a discovery versus direct instruction approach but also tested, once learning had occurred, whether the quality of learning differed. Specifically, they tested whether those who had learned through discovery (Open Inquiry) were better able to transfer their learning to new contexts. The findings were unambiguous. Direct instruction involving considerable guidance (teacher-centred) resulted in vastly more learning than discovery (Kirschner et al. 2006).

These results are important for educators so that IBL is given an appropriate place in the every-day teaching and learning of mathematics. Sometimes the expectations of IBL are too high when teachers prefer IBL as their favourite instructional design. A suitable combination of different instructional designs could be the solution. The cited studies indicate that there are other important benefits besides the aim of generating content knowledge. Often programmes and testing are implemented with the specific aim of improving the results through an emphasis on content knowledge, especially in mathematics and reading. However, IBL projects do not target the basic skills tapped by standardized achievement tests, at least not directly. There are explanations from the cognitive load-theory,

from feedback, from different learning styles etc., to explain why IBL does not always give positive results in testing. Typically, projects target content area topics or technological operations. Skills of reading, writing and computation are often involved in constructing project products, but these skills are rarely introduced in the context of projects.

Our conclusion from the state of the research concerning different instructional designs is that we probably do not need any more studies comparing IBL with other strategies. Rather, we should look carefully at the appropriate implementation of IBL in schools. Researchers should consider the professional development needed to implement IBL because many teachers are reticent about changing from the teacher-centred approach that they know to a student-centred approach that removes some of their control over what happens in the classroom. The measurement of the outcomes of IBL is also an avenue for further consideration so that teachers can see its benefits.

5 Implementation of IBL with implications for teachers

The implementation of IBL teaching strategies has implications for the content knowledge of the teachers. Kahle et al. (2000), among others, found a positive relationship between teacher professional development and the use of IBL in the classroom. In some cases, professional development occurs just once before teachers start using IBL in the classroom; while in other cases, professional development continues long after the initial introduction to IBL. Many studies and school districts include teacher professional development as part of the change to IBL. In a traditional classroom, the teacher is able to plan for every minute of the lesson, whereas in an IBL classroom there is a level of uncertainty associated with a complex teaching/learning relationship (Leikin and Rota 2006; Phelan 2005). In the IBL classroom, teachers respond to students in a different way—student thinking is explored through skilful probing and making sense of students' ideas (Nelson & Moscovici 1998). Teaching for understanding includes fluency in teaching with manipulatives, guiding small-group work, and capitalizing on students' multiple solution strategies, in order to draw out the deep structure of the discipline so that learners learn to reason and connect ideas (Puntambekar et al. 2007).

The science teachers of English Language Learners (ELLs), in a study conducted by Amaral et al. (2002), were given at least 100 h of professional development “designed to deepen their own content understanding, address pedagogical issues and to prepare them to teach the units at their grade level” (p. 221). The training was continuous and cumulative for the 4 years of the study. The teachers were

initially introduced to the content in the same way they would introduce it to their students so they could see how the units were connected and how to lead the students to “the big ideas of science” (p. 222). In this way the teachers became acquainted with the pedagogical strategies, and the content and concepts. After the professional development, teachers were given in-class support.

On the other hand, Leikin and Rota (2006) found that the teacher's proficiency developed in the course of their teaching experience without any professional development intervention. The teachers had been a part of the preparation of the IBL lessons that were conducted 10 months and 6 months apart. They found that teachers became more proficient in their lesson organization, and the discussion structure with the students reflected teacher flexibility in that it was more responsive than active (Leikin and Rota 2006).

There are also implications for teachers' pedagogical content knowledge. Diezmann et al. (2001) found that teachers who were aware of the mathematical literacy necessary to undertake investigations were able to plan and implement mathematically rich tasks that developed children's investigatory abilities. While these investigations placed demands on mathematical literacy for the 7- and 8-year-old students in the study, they also provided a powerful context for the development of their mathematical literacy. They also showed that the failure to understand certain aspects of language inhibited the student's capacity to identify the key issues in a problem. The role of the teacher is therefore to optimize conditions for learning and to introduce children to the culture of mathematics by teaching them how to think like experts to reinforce the importance of representation and problem solving as crucial processes of mathematical literacy.

6 Summary and open research questions

There is some empirical evidence from different studies about the quality of mathematics teaching or the quality and effects of mathematics education with IBL.

The effects of IBL include benefits for motivation, for better understanding of mathematics, and for the development of beliefs about mathematics as well as for the relevance of mathematics for life and society.

There is some empirical evidence from different studies about the effect of IBL compared with other more traditional teaching strategies. Here, it is important to separate the following aspects of IBL: a changed teacher role from the teacher-centred approach to a student-centred approach, and a change in the type of work in the classroom with open tasks that ask for creativity versus strategy;

Structured Inquiry, *Guided Inquiry* and *Open Inquiry* are variations of IBL and allowing comparisons between

studies. Guided Inquiry was shown to be the most effective method of implementing IBL in the classroom with closed tasks that support learning of rules. A combination of both aspects—open and closed tasks—is possible. For this article we distinguished studies about IBL with a view on the possible stamping, sighting and functions from IBL.

There is another dimension to IBL—what teaching and learning is about. How do we know when any teaching is effective? Many of the pressures on teachers today arise from the different expectations of student learning. If we want students who are able to understand mathematics, enjoy mathematics and have an ability to work through problems to a conclusion then IBL with guidance could be thought successful—but how do we measure that? However, if our aim is for students to be able to achieve high marks in standardized knowledge-based tests then IBL is sometimes less successful—but what are we measuring in standardized tests? These are important questions for all teachers and many researchers have attempted to answer them over the years.

The next step to improve the teaching quality in mathematics lessons could be supporting teachers to improve their ability to support students in the IBL classroom using the three strategies from structured to guided to (sometimes) open inquiry. Furthermore, teachers need professional development so they feel comfortable implementing IBL.

These ideas leave us with further research questions, many of which have been known for a long time:

1. Some studies showed that IBL needs a high level of content-knowledge and strategies for problem solving as a precondition for success.
 - Which problem-solving strategies are required for flexibility in IBL? Which strategies are relevant for IBL and how can the students learn these strategies effectively?
2. Often there are problems for the students in posing mathematical questions or making a hypothesis.
 - How can students effectively gain the ability to pose (mathematical) questions?
 - What special knowledge is needed for successful modelling with mathematics and how can students improve this knowledge?
3. One of the problems of using IBL in school is how to integrate problem-solving abilities in the assessments. For the acceptance of IBL by students, parents and teachers, the benefits of IBL and assessment tasks have to be complementary. If the students learn through discovery, then it is important for them to communicate their findings.
 - How do students improve their ability to talk about their mathematics and the used problem solving strategies and to present their results step by step using correct mathematical language?
4. A precondition for successful IBL is previous experience of group work and of independent work. The three aspects of IBL depend on the ability of students to work with each other and depend on different cognitive styles which influence the success of the learning situation.
 - How can students gain abilities in self-regulation and knowledge about their individual strength and learning styles for successful working in groups and in independent work?

For all this to work, students need all of these things in conjunction. Working on only one of these aspects will not exploit the full potential of IBL. Furthermore, the students need suitable help and support in their learning process. However, more information is needed concerning the best strategies for giving support and feedback in different learning situations and which are linked to the individual needs and preconditions of the students.

Other open questions and recommendations for future investigations are large-scale studies for the sustainability of different learning outcomes depending on the instructional design and the support for teachers and students. Since teachers need material-based support for using IBL and professional development with individual levels of support before instituting IBL and then during IBL in classes, further research on the success of IBL with respect to the surrounding conditions (support of the teachers) is needed.

References

- Amaral, O., Garrison, L., & Klentschy, M. (2002). Helping English learners increase achievement through inquiry-based science instruction. *Bilingual Research Journal*, 26(2), 213–239.
- Anderson, R. D. (2002). Reforming science teaching: What research says about inquiry. *Journal of Science Teacher Education*, 13(1), 1–12.
- Artigue, M., & Blomhøj, M. (2013). Examples of inquiry-based activities with reference to different theoretical frameworks in mathematics education research. *ZDM—The International Journal on Mathematics Education*, 45(6) (this issue). doi:10.1007/s11858-013-0506-6.
- Asmussen, S. (2009). Der Einfluss der MINIPHÄNOMENTA auf die methodisch-formalen naturwissenschaftlichen Fähigkeiten von Schülerinnen und Schülern der Primarstufe. Skizze einer Interventionsstudie im Kontext eines naturwissenschaftlichen Bildungsprojekts. *Widerstreit Sachunterricht*, 13. <http://www.widerstreit-sachunterricht.de/ebeneI/superworte/naturwiss/mini2.pdf> (Accessed 27 July 2012).
- Barron, B., & Darling-Hammond, L. (2008). Teaching for meaningful learning: A review of research on inquiry-based and cooperative

- learning. <http://www.edutopia.org/pbl-research-annotated> (Accessed Sep 2013).
- Beinbrech, C. (2003). Problemlösen im Sachunterricht der Grundschule. Eine empirische Studie zur Gestaltung von Lehr-Lernumgebungen im Hinblick auf die Förderung des Problemlöseverhaltens im Sachunterricht. http://miami.uni-muenster.de/servlets/DerivateServlet/Derivate-1307/Diss_Beinbrech.pdf (Accessed 12 Sep 2013).
- Boaler, J. (1998). Open and closed mathematics: Student experiences and understandings. *Journal for Research in Mathematics Education*, 29(1), 41–62.
- Brown, A., & Campione, J. (1994). Guided discovery in a community of learners. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 229–270). Cambridge, MA: MIT Press.
- Chan, C. M. E. (2006). Engaging students in open-ended mathematics problem tasks—a sharing on teachers' production and classroom experience (Primary). Paper presented at ICMI-EARCOME3. <http://math.ecnu.edu.cn/earcome3/TSG2.htm> (Accessed 12 Sep 2013).
- Chi, M. T. H. (2000). Self-explaining expository texts: The dual processes of generating inferences and repairing mental models. In R. Glaser (Ed.), *Advances in instructional psychology* (pp. 161–238). Mahwah, NJ: Erlbaum.
- Colburn, A. (2000). An inquiry primer. *Science Scope*, 3, 42–44.
- Cronbach, L. J. (1981). Die Logik von Experimenten über Entdeckung. In H. Neber (Ed.), *Entdeckendes Lernen* (pp. 153–165). Weinheim: Beltz.
- Diezmann, C. M., Watters, J. J., & English, L. D. (2001). Implementing mathematical investigations with young children. In J. Bobis, B. Perry & M. Mitchelmore (Eds.), *Numeracy and beyond. Proceedings 24th Annual Conference of the Mathematics Education Research Group of Australasia* (pp. 170–177). Sydney: MERGA.
- Egan, D. E., & Greeno, J. E. (1981). Der Erwerb kognitiver Strukturen durch Entdeckendes- und Regellernen. In H. Neber (Ed.), *Entdeckendes Lernen* (pp. 190–207). Weinheim: Beltz.
- Ergül, R., Simsekli, Y., Calis, S., Özdilek, Z., Göcmencelebi, S., & Sanli, M. (2011). The effects of inquiry-based science teaching on elementary school students' science process skills and science attitudes. *Bulgarian Journal of Science and Education Policy (BJSEP)*, 5(1), 48–68.
- Fradd, S. H., Lee, O., Suutman, F. X., & Saxton, M. K. (2002). Promoting science literacy with English learners through instructional materials development: A case study. *Bilingual Research Journal*, 25(4), 479–501.
- Gallagher, S., Stepien, W., & Rosenthal, H. (1992). The effects of problem-based learning on problem solving. *Gifted Child Quarterly*, 36(4), 195–200.
- Germann, P. J., Haskins, S., & Auls, S. (1996). Analysis of nine high school biology laboratory manuals: Promoting science inquiry. *Journal of Research in Science Teaching*, 33(5), 337–357.
- Hartinger, A. (2001). Entdeckendes Lernen. In W. Einsiedler, M. Götz, H. Hacker, J. Kahlert, R. W. Keck, & U. Sandfuchs (Eds.), *Handbuch Grundschulpädagogik und Grundschuldidaktik* (pp. 330–335). Bad Heilbrunn: Julius Klinkhardt.
- Hattie, J. A. C. (2009). *Visible learning. A synthesis of over 800 meta-analyses relating to achievement*. London and New York: Routledge.
- Hermann, G. (1981). Lernen durch Entdeckung: Eine kritische Erörterung von Forschungsarbeiten. In H. Neber (Ed.), *Entdeckendes Lernen* (pp. 166–189). Weinheim: Beltz.
- Kahle, J. B., Meece, J., & Scantlebury, K. (2000). Urban African-American middle school science students: Does standards-based teaching make a difference? *Journal of Research in Science Teaching*, 37(9), 1019–1041.
- Kahn, P., & O'Rourke, K. (2005). Understanding enquiry-based learning. In T. Barret, I. Mac Labhrainn, & H. Fallon (Eds.), *Handbook of enquiry & problem based learning*. Galway: CELT.
- Kirschner, A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, 41(2), 75–86.
- Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction: Effects of direct instruction and discovery learning. *Psychological Science*, 15(10), 661–667.
- Klauer, K., & Leutner, D. (2007). *Lehren und Lernen. Einführung in die Instruktionspsychologie*. Weinheim: Beltz.
- Kremer, A., & Schlüter, K. (2006). Analyse von Gruppensituationen beim forschend-entdeckenden Lernen. *Ergebnisse einer ersten Studie. Erkenntnisweg Biologiedidaktik*, 5, 145–156.
- Leikin, R., & Rota, S. (2006). Learning through teaching: A case study on the development of a mathematics teacher's proficiency in managing an inquiry-based classroom. *Mathematics Education Research Journal*, 18(3), 44–68.
- Lind, G., Friege, G., Kleinschmidt, L., & Sandmann, A. (2004). Beispiellernen und Problemlösen. *Zeitschrift für Didaktik der Naturwissenschaften*, 10, 29–49.
- Maaß, K. (2011). *Report about the survey on inquiry-based learning and teaching in the European partner countries*. EU-Project Information: PRIMAS. <http://www.primas-project.eu> (Accessed 12 Sep 2013).
- Maaß, K., & Doorman, M. (2013). A model for a widespread implementation of inquiry-based learning. *ZDM—The International Journal on Mathematics Education*, 45(6) (this issue). doi:10.1007/s11858-013-0505-7.
- Marx, R. W., Blumenfeld, P. C., Krajcik, J. S., Fishman, B., Soloway, E., Geier, R., et al. (2004). Inquiry-based science in the middle grades: Assessment of learning in urban systemic reform. *Journal of Research in Science Teaching*, 41, 1063–1080.
- McCarty, T. L., Hadley Lynch, R., Wallace, S., & Benally, A. (1991). Classroom inquiry and Navajo learning styles: A call for reassessment. *Anthropology and Education Quarterly*, 22(1), 42–59.
- Meyer, D. K., Turner, J. C., & Spencer, C. A. (1997). Challenge in a mathematics classroom: Students' motivation and strategies in project-based learning. *Elementary School Journal*, 97, 501–521.
- Moreno, R. (2004). Decreasing cognitive load in novice students: Effects of explanatory versus corrective feedback in discovery-based multimedia. *Instructional Science*, 32, 99–113.
- Neber, H. (2001). Entdeckendes Lernen. In D. Rost (Ed.), *Handwörterbuch Pädagogische Psychologie* (pp. 115–121). Weinheim: Beltz.
- Nelson, T. H., & Moscovici, H. (1998). Shifting from activitymania to inquiry. *Science and Children*, 35(4), 14–17.
- Newmann, F. M., Marks, H. M., & Gamoran, A. (1995). Authentic pedagogy: Standards that boost student performance. *Issues in Restructuring Schools*, 8, 1–4.
- Newmann, F. M., Marks, H. M., & Gamoran, A. (1996). Authentic pedagogy and student performance. *American Journal of Education*, 104(4), 280–312.
- Nußbaum, A., & Leutner, D. (1986). Entdeckendes Lernen von Aufgabenlösungsregeln unter verschiedenen Anforderungsbedingungen. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie*, 18, 153–164.
- Palmer, S. (2002). Enquiry-based learning can maximise a student's potential. *Psychologie Learning and Teaching*, 2(2), 82–86.
- Penuel, W. R., Means, B., & Simkins, M. B. (2000). The multimedia challenge. *Educational Leadership*, 58, 34–38.
- Perso, T. (2003). *Improving Aboriginal numeracy*. Perth: MASTEC.

- Phelan, A. M. (2005). A fall from (someone else's) certainty: Recovering practical wisdom in teacher education. *Canadian Journal of Education/Revue Canadienne de l'éducation*, 28(3), 339–358.
- Puntambekar, S., Stylianou, A., & Goldstein, J. (2007). Comparing classroom enactments of an inquiry curriculum: Lessons learned from two teachers. *Journal of the Learning Sciences*, 16(1), 81–130.
- Rains, F. V., Archibald, J. A., & Deyhle, D. (2000). Introduction: Through our eyes and in our own words. *International Journal of Qualitative Studies in Education*, 13(4), 337–342.
- Roy, M., & Chi, M. T. H. (2005). Self-explanation in a multi-media context. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning* (pp. 271–286). Cambridge, MA: Cambridge University Press.
- Scruggs, T. E., & Mastropieri, M. A. (1993). Reading versus doing: The relative effects of textbook based and inquiry-oriented approaches to science learning in special education classrooms. *Journal of Special Education*, 27(1), 1–15.
- Stepien, W. J., Gallagher, S. A., & Workman, D. (1993). Problem-based learning for traditional and interdisciplinary classrooms. *Journal for the Education of the Gifted*, 16(4), 338–345.
- Sweller, J., Mawer, R., & Howe, W. (1982). The consequences of history-cued and means-ends strategies in problems solving. *American Journal of Psychology*, 95, 455–484.
- Tafoya, E., Sunal, D., & Knecht, P. (1980). Assessing inquiry potential: A tool for curriculum decision makers. *School Science and Mathematics*, 80, 43–48.
- Thomas, J. W. (2000). A review of research on project-based learning. http://www.bie.org/index.php/site/RE/pbl_research/29 (Accessed 12 Sep 2013).
- Winch, W. A. (1913). *Inductive versus deductive methods of teaching*. Baltimore: Warwick and York.