



ASSISTME

Report on current state of the art in formative and summative assessment in IBE in STM - Part I

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– Part I –

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Summary

The EU project 'Assess Inquiry in Science, Technology and Mathematics Education' (ASSIST-ME) investigates formative and summative assessment methods to support and improve inquiry-based approaches in European science, technology and mathematics (STM) education.

In the first step of the project, a literature review was conducted in order to gather information about the current state of the art in formative and summative assessment in inquiry-based education (IBE) in STM. Searches were conducted in data bases, in the most important journals in the field of STM education, and in the reference lists of relevant publications. This report describes the search strategies used in detail and presents the results of the empirical studies described in the found publications in this field.

Especially in science education, numerous publications were found by the search strategies whereas in technology and mathematics education the numbers of publications are much lower. On the one hand, the chosen keywords and search strategies might be a reason. On the other hand, the research foci of the disciplines might be another reason.

The results of the literature review indicate that only a small number of empirical studies have simultaneously investigated both the use of formative and summative assessment in the learning of inquiry in STM and the influence of this form of assessment on the learning of inquiry in STM. Moreover, most of the studies did not assess inquiry directly, but rather knowledge, understanding or attitudes. Nevertheless, there are examples of methodological approaches which illustrate the successful application of several assessment instruments and explain their advantages or disadvantages.

1. Introduction

The overall rationale for ASSIST-ME is that assessment should enhance learning in STM education. It is well acknowledged that assessment is one of the most important drivers in education and is a defining aspect of any educational system. However, it can be observed that instruction – and especially innovative approaches to instruction – and assessment very often are not aligned. Evaluations of inquiry-based teaching and learning are often based on traditional summative assessments of content knowledge that need not necessarily show achievement gains. Stieff (2011), for instance, found that using an inquiry curriculum in combination with a visualization tool yielded only small to moderate gains in a summative achievement test but significantly increased students' representational competence. In recent years, however, the need to align curriculum, instruction and assessment has become more and more obvious.

One major objective of ASSIST-ME is to develop a set of assessment methods suitable for enhancing IBE with regard to STM related competences. Based on these methods, strategies for the formative and summative assessment of competences in STM will then be identified that are adaptable to various European educational systems (Dolin, 2012). The research into the formative and summative assessment of competences relevant to IBE in STM will be based on an understanding of the concept of competences (both domain-specific and transversal), of IBE and of formative versus summative assessment.

In order to achieve this understanding, work package 2 (WP 2) in the ASSIST-ME project carried out a review of the existing research literature on the formative and summative assessment of IBE in STM. The aim of this review is to summarize what we know about the formative and summative assessment of competences in STM – with a special focus on IBE – and to identify methods that can improve student outcomes. Part II of the review (conducted by Pearson Education International) deals specifically with computer-based assessment and the use of information and communication technology (ICT) tools.

One major challenge for the literature review was that the field of interest is not clearly defined. With respect to science education, there is still disagreement among researchers and educators about what features define the instructional approach of IBE (Furtak, Shavelson, Shemwell, & Figueroa, 2012; Hmelo-Silver, Duncan, & Chinn, 2007). A rich vocabulary is used to describe inquiry-based approaches to teaching and learning, such as inquiry-based teaching and learning, authentic inquiry, model-based inquiry, modelling and argumentation, project-based science, hands-on science, and constructivist science (Furtak, Seidel, Iverson, & Briggs, 2012). These approaches might include characteristics of IBE to a varying degree but they are not necessarily synonyms of IBE. The situation gets even more complicated because, e.g. in the US, the field of science education has moved away from using the term inquiry and now calls it "scientific and engineering practices" (National Research Council, 2012). Moreover, the definitions of IBE or inquiry-based approaches to teaching and learning differ between the three domains of science, technology, and mathematics (see D 2.5).

A similar situation is described by Black and Wiliam (1998) in their meta-analysis of formative assessment in the classroom. They state that a literature search carried out by entering keywords in the ERIC data base was inefficient for their purposes because of “a lack of terms used in a uniform way” (Black & Wiliam, 1998, p. 8). As in the case of IBE, formative assessment may be described with a variety of names, such as classroom evaluation, curriculum-based assessment, feedback or formative evaluation (Black & Wiliam, 1998). With respect to the literature review of WP 2, this had consequences for the search strategies. They will be described in chapter 4. Procedure of the literature review.

In this report, some background information about inquiry-based approaches (see 2.1 IBE in STM) and formative and summative assessment in STM education (see 2.2 Assessment in education) will first be given. With respect to IBE, this report puts a special focus on the aspects and definitions of inquiry competences found in the literature and used by previous EU projects. These definitions form the basis for the data base searches and the analysis of results. A detailed description of the definition of IBE in the three domains is given in deliverable D 2.5 ‘A definition of inquiry-based STM education and tools for measuring the degree of IBE’.

In the paragraphs about the formative and summative assessment in STM, first, the concepts are briefly defined. Afterwards, their role in and their influence on STM teaching and learning and the factors that might support or impede their employment are discussed. The main part of the report, however, deals with the results of the search for empirical studies which have investigated the effects of IBE and assessment methods employed to assess and measure these effects. After describing the methodology of the literature search in section 4, the aspects of inquiry which are assessed in STM education are discussed, along with the formative and summative assessment methods which are used (see section 5). The results of a literature search which focussed on the computer-based assessment of IBE in STM that was performed by the ASSIST-ME partner Pearson are presented in part II of this document.

2. Theoretical background

2.1 IBE in STM

According to Anderson (2002) – whose definition forms the basis of the ASSIST-ME application – inquiry-based STM education includes students' involvement in questioning, reasoning, searching for relevant documents, observing, conjecturing, data gathering and interpreting, investigative practical work and collaborative discussions, and working with problems from and applicable to real-life contexts. Whereas these characteristics generally apply to all three subject areas – science, technology and mathematics – the ASSIST-ME application explicitly acknowledges that various meanings and forms of inquiry are possible in different disciplines and need to be addressed in the project. These different approaches to inquiry, however, need to be aligned with a general definition of the construct that will be produced by the project and form deliverable D 2.5 'A definition of inquiry-based STM education and tools for measuring the degree of IBE'.

Looking at the literature, it seems that IBE has mainly been investigated in the field of science education. Performing a basic search in the Web of Science for the period 1996 to 2012 using the keywords 'science/scientific' crossed with 'teaching', 'learning', 'education' and 'instruction' and crossed with 'inquiry' resulted in 2034 entries. Replacing 'science/scientific' by 'mathematics' reduced the number of results to 218, by 'technology' to 567 with most of the entries in technology dealing with the use of technology in inquiry-based (science) education and not with inquiry in technology education (search performed in November 2012).

This might partly be due to the fact that in mathematics and technology the term 'inquiry' is not common and thus inquiry-based approaches go under different names. In the case of mathematics, for instance, teaching approaches and learning theories that include characteristics of mathematical inquiry are – as named in the ASSIST-ME application – inquiry mathematics (Cobb, Wood, Yackel, & McNeal, 1992), open approach lessons (Nohda, 2000), and problem-centred learning (Schoenfeld, 1985). The Fibonacci-project (Artigue & Baptist, 2012) extends this list towards the Dutch approach of realistic mathematics education (Freudenthal, 1973) and the French theory of didactical situations (Brousseau & Balacheff, 1997). Moreover, they include the Swiss concept of dialogic learning (Gallin, 2012). In dialogic learning, instead of immediately trying to solve the problem, students should instead focus on exploring the question and related aspects in depth, thus relating it to their own world. A decisive factor for dialogic learning is that feedback is provided to the students during the exploration process (Gallin, 2012). Another approach of inquiry in mathematics education is the concept of 'problem-based learning' that is also mentioned in the well-known Rocard report (European Commission, 2007, p. 9): "In mathematics teaching, the education community often refers to 'Problem-Based Learning (PBL)' rather than to IBE. In fact, mathematics education may easily use a problem-based approach while, in many cases, the use of experiments is more difficult. PBL describes a learning environment where problems drive the learning." Problem- or project-based learning is also used in technology education. The closest connection to inquiry, however, is provided by approaches to teaching and

learning using the concept of design that bears close resemblance to IBSE. The main difference is seen in the fact that “‘doing’ holds a central position in all aspects relating to both technology and technological literacy” (Ingerman & Collier-Reed, 2011, p. 138). Action is seen as an important component of technological literacy especially in view of “the need to be able to ‘select, properly apply, then monitor and evaluate appropriate technologies’ ([Hayden, 1989] p. 231 – emphasis added) in a given situation. In this way, technological literacy in a situation is constituted through actions” (Ingerman & Collier-Reed, 2011, p. 138; see also Vries & Mottier, 2006).

A lot of former and on-going EU projects in the field of IBE (e.g. Mind the Gap, S-TEAM, ESTABLISH and Fibonacci) have based their understanding of IBSE on a definition from Linn, Davis and Bell (2004, p. 4):

“[inquiry is] the intentional process of diagnosing problems, critiquing experiments, and distinguishing alternatives, planning investigations, researching conjectures, searching for information, constructing models, debating with peers and forming coherent arguments”.

In IBSE, students should be able to identify relevant evidence and use critical thinking and logical reasoning to reflect on its interpretation. They should develop the skills necessary for inquiry and the understanding of science concepts through their own activity and reasoning. This involves exploration and hands-on experiments (Fibonacci project, not reported). IBSE should foster critical and creative minds, it should encourage students to engage in, explore, explain, extend, and evaluate real-life situations in collaboration and cooperation with their peers (PRIMAS project, 2010). It is thus based on a specific understanding of learning as deliberately involving linguistic processes such as argumentation (Dolin, 2012) and requires students to take charge of their own learning in order to achieve genuine understanding (Harlen, 2009). The ESTABLISH project dissected the definition of Linn, Davis and Bell (2004) and articulated nine aspects or elements of inquiry (ESTABLISH project, 2011):

1. Diagnosing problems
2. Critiquing experiments
3. Distinguishing alternatives
4. Planning investigations
5. Researching conjectures
6. Searching for information
7. Constructing models
8. Debating with peers
9. Forming coherent arguments

These aspects can be regarded as inquiry competences. Because of their prominent role in European IBE projects, it was decided to use them as the foundation of the ASSIST-ME definition of IBE. Comparing them with other definitions of inquiry-based science education (e.g. American Association for the Advancement of Science, 2009; Hmelo-Silver, Duncan, & Chinn, 2007; Kessler & Galvan, 2007; National Research Council, 1996, National Research Council, 2012) and with definitions of inquiry-based approaches in mathematics (Artigue & Baptist, 2012; Artigue, Dillon, Harlen, & Léna, 2012; Hunter & Anthony, 2011; Kwon, Park, & Park, 2006) and technology education (American Association for the Advancement of Science, 2009; National Research

Council, 2012) however, the need to elaborate on and extend the list of aspects became clear.

A characteristic feature of technology education, for instance, is that knowledge, experience and resources are applied purposefully to create products and processes that meet human needs (Davis, Ginns, & McRobbie, 2002). Thus, inquiry-based approaches in technology education often focus on the design process as a process of problem solving consisting of

1. defining the problem and identifying the need,
2. collecting information,
3. introducing alternative solutions,
4. choosing the optimal solution,
5. designing and constructing a prototype, and
6. evaluating and correcting the process (Doppelt, 2005).

Differences and similarities between inquiry-based science and mathematics education have been investigated and discussed within the Fibonacci project. In the Fibonacci Background Resource Booklets 'Learning through Inquiry' (Artigue, Dillon, Harlen, & Léna, 2012) and 'Inquiry in Mathematics Education' (Artigue & Baptist, 2012), the authors present the similarities and specificities of mathematical inquiry compared to scientific inquiry:

"Like scientific inquiry, mathematical inquiry starts from a question or a problem, and answers are sought through observation and exploration; mental, material or virtual experiments are conducted; connections are made to questions offering interesting similarities with the one in hand and already answered; known mathematical techniques are brought into play and adapted when necessary. This inquiry process is led by, or leads to, hypothetical answers – often called conjectures – that are subject to validation." (Artigue & Baptist, 2012, p. 4)

The main differences between mathematical and scientific inquiry are based on the type of questions or problems they address and the processes they rely on for answering or solving them. These are aspects that characterize mathematical inquiry: the distinction between mathematical and extra-mathematical systems, a need to construct mental representations, a search for structure, patterns, and relationships and the principal aim of generalization (Hunter & Anthony, 2011; Mathematical Sciences Education Board, 1990).

Table 1 gives an overview of the similarities and differences between aspects of IBE within the three domains (The origin of the table is explained in D 2.5). The term 'aspects' was chosen in order to avoid overlaps to constructs such as 'abilities', 'competences', 'skills', 'standards' etc. Often they are not used distinct. The listed aspects might be skills, competence or abilities. The different aspects can principally be regarded as steps in the inquiry process that have a chronological order. However, an important characteristic of inquiry processes is that they are seldom linear. Students continually (or at least frequently, at different stages) have to check their progress or results with the plan they made in the beginning and make corrections or adaptations if necessary so that steps can be repeated or left out.

Table 1: Aspects of IBE in STM

Science	Technology	Mathematics
diagnosing problems and identifying questions	diagnosing problems and identifying needs	diagnosing problems
searching for information	searching for information	searching for information
	considering alternative solutions	considering multiple solutions
	creating mental representations	creating mental representations
formulating hypotheses	formulating hypotheses in view of the function of a device	formulating hypotheses
planning investigations	planning design	planning investigations
constructing and using models	constructing and using models	constructing and using models
researching conjectures		researching conjectures
	constructing prototypes/a prototype	
		finding structures/patterns
collecting and interpreting data		
evaluating results	evaluating results	
searching for alternatives	modifying designs	
		searching for generalizations
		dealing with uncertainty
constructing and critiquing arguments or explanations/argumentation/reasoning/using evidence	constructing and critiquing arguments or explanations/argumentation/reasoning/using evidence	constructing and critiquing arguments or explanations/argumentation/reasoning/using evidence
debating with peers/communicating	debating with peers/communicating	debating with peers/communicating
<i>Notes.</i>		
	Aspect of IBE in STM	
	Aspect of IBE in TM, SM or ST	
	Domain-specific aspects	

Although aspects have the same name, they might have slightly different meanings in the different domains and even within one domain (e.g. reasoning in science). Different frameworks might exist which have to be taken into account when comparing assessment methods and results between different studies. A detailed description of the different frameworks is beyond the scope of this report. A summary of theoretical papers dealing with different frameworks that were found during the review, however, is given in section 7.1 Frameworks of inquiry competences and/or assessment together with theoretical papers focusing on assessment methods.

In addition to these domain-specific skills, there are also transversal competences that are ascribed to inquiry. For example, the Benchmarks for Science Literacy (American Association for the Advancement of Science, 1998) pay special attention to the so-called 'habit of mind' which describes problem-solving skills that are relevant in all subjects. These skills are computation and estimation, manipulation and observation, communication and quantitative thinking, critical response skills (evaluating evidence and claims) and creativity in designing experiments and solving mathematical or scientific problems; the competence of the students is reflected in the quality of questions they pursue and the rigor of their methodology (American Association for the Advancement of Science, 1998). Moreover, a habit of mind also includes values and attitudes like honesty, curiosity, open-mindedness and scepticism. The key competences for lifelong learning described in the Recommendation of the European Parliament (European Parliament, 2006) supplement this list by the ability of learning to learn and a sense of initiative and entrepreneurship (creativity, innovation and risk-taking, as well as the ability to plan and manage projects in order to achieve objectives).

Attitudes investigated in the context of inquiry-based approaches to teaching and learning include, e.g., enjoyment, value, interest, and self-efficacy expectations. In mathematics, Schukajlow et al. (2012) found that student-centred, modelling-based teaching approaches most beneficially affected students' attitudes towards mathematics. Similar results were obtained for science (e. g. Gibson & Chase, 2002). Nolen (2003) investigated the relationship between learning environment, motivation and achievement in high school science. She found that task orientation and the value of deep-processing strategies are mediated by a learning environment that supports deep understanding and independent thinking. Moreover, a focus on science learning combined with a shared belief in the teacher's desire for student understanding and independent thinking accounted for all the predictable variation in satisfaction with learning. In technology education, there is still a lack of research on learning and instruction (Miranda, 2004). A recent review came to the conclusion that technology education research is still dominated by descriptive studies that rely on self-reports and perceptions (Johnson & Daugherty, 2008). However, an appreciation of the interrelationships between technology and individuals, society and the environment (International Technology Education Association, 1996) as well as of the concepts of sustainability, innovation, risk, and failure (Rossouw, Hacker, & Vries, 2011) is regarded as an important goal of technology education.

2.2 Assessment in education

Assessment is one of the most important driving forces in education and a defining aspect of any educational system. Assessment signals priorities for curricula and instruction since teachers and curriculum developers tend to focus on what is tested rather than on underlying learning goals which encourage a one-time performance orientation (Binkley et al., 2012; Gardner, Harlen, Hayward, Stobart, & Montgomery, 2010). However, assessment can be regarded from different perspectives. The European report "Europe needs more scientists" (European Commission, 2004, p. 137) distinguishes between three perspectives: (1) traditionally, as the function of evaluating stu-

dent achievement for grading and tracking, (2) as an instrument for diagnosis to give students and teachers continual feedback about learning outcomes and difficulties, and (3) as a means to enable broader knowledge about the conditions behind and influences on students' understanding and competence (e.g. in international large-scale assessments). In the last decades, accountability has become an increasingly important issue in assessment that strongly influences teaching practice – especially when high stakes are connected to it. Educational research in the United States and the United Kingdom has provided empirical evidence that high stakes, standard-based assessment systems have negative effects (for reviews see Cizek, 2001; Nichols, Glass, & Berliner, 2006; Pellegrino, Chudowsky, & Glaser, 2001). Given the anticipated consequences of their students' test results, it has been shown that teachers adapt their classroom activities to the test, often devoting a considerable proportion of instructional time to test preparation. This could be seen in a positive light if the student competencies as assessed by the test were actually fostered but comparisons between the assessment systems of different US states showed that such positive effects rarely exist (Nichols et al., 2006). A similar result is reported by Anderson (2012) who argues that under accountability policies, many research-based reform efforts in science have become side-tracked and disrupted. Teacher practice has become more fact-based, science is taught less, teachers are less satisfied, and many students' needs are not met.

2.2.1 Characteristics of assessment systems

There is general agreement in the literature about the characteristics that define 'good' assessment systems. An important feature of assessment systems that support learning is coherence – classroom and external assessments have to share the same or compatible underlying models of student learning. Moreover, the design of international, national, state, and classroom-level assessments must be clarified and aligned (Bernholt, Neumann, & Nentwig, 2012; Mislevy, Steinberg, Almond, Haertel, & Penuel, 2001; Pellegrino et al., 2001; Quellmalz & Pellegrino, 2009; Waddington, Nentwig, & Schanze, 2007). The alignment of learning goals, instructional activities, and assessment is also stressed by Krajcik, McNeill, and Reiser (2008). Another important issue is instructional sensitivity. Ruiz-Primo et al. (2012) proposed an approach for developing and evaluating instructionally sensitive assessments in science called DEISA (Developing and Evaluating Instructionally Sensitive Assessments). The development approach considered three dimensions of instructional sensitivity; that is, assessment items should represent the curriculum content, reflect the quality of instruction, and have formative value for teaching. A similar point is made by Pellegrino et al. (2001). Items should be selected or combined in such a way that they provide additional information useful for diagnosis, feedback, and the design of next steps in instruction. Shepard (2003) focused on the student level and defined effective assessment as an assessment that makes students' thinking visible and explicit, engages students in the self-monitoring of their learning, makes the features of good work understandable and accessible to students, and provides feedback specifically targeted toward improvement (Shepard, 2003 and references therein).

2.2.2 Summative and formative assessment

Assessment always involves the collection, interpretation and use of data for some purpose. The purpose and often also the manner of data collection may differ. These different purposes are often summarized under the terms of summative and formative assessment.

Summative assessment has the purpose of summarizing and reporting learning at a particular time and, for this reason, it is also called 'assessment of learning'. It involves processes of summing up by reviewing learning over a period of time or checking up by testing learning at a particular time. Summative assessment has an undeniably strong impact on teaching methods and content (Harlen, 2007), especially if high stakes are connected to it. This is also emphasized in the European report mentioned above: "Although the results [of large international assessments like PISA and TIMSS] may be used to identify strengths and weaknesses in each country, there is a danger that these studies may trivialize the purpose of schooling by its implicit definition of how educational 'quality' might be understood, defined and measured. It is likely that national school authorities put undue emphasis on these comparative studies, and that curricula, teaching and assessment will be 'PISA-driven' in the years to come" (European Commission, 2004, p. ix). The dominance of external summative assessment leads to situations where testing remains distinct from learning in the minds of most students and teachers. Thus, when teachers are required to implement their own assessments they tend to imitate external assessments and think only in terms of frequent summative assessment (American Association for the Advancement of Science, 1998; Black & William, 1998).

Formative assessment, in contrast, is "the process used by teachers and students to recognize and respond to student learning in order to enhance that learning, during the learning" (Bell & Cowie, 2001, p. 536). It thus has the purpose of assisting learning and, for this reason, it is also called 'assessment for learning'. The term formative with respect to evaluation and assessment was first used by Scriven (1967) and Bloom (1969) in the late 1960s. According to Black and William (1998) and William (2006), assessments are formative if, and only if, something is contingent on their outcome and the information is actually used to alter what would have happened in the absence of that information – it thus shapes subsequent instruction. In their 1998 review of formative assessment, Black and William (1998) were able to show that formative assessment methods and techniques produce significant learning gains that are among the largest ever identified for educational interventions (Looney, 2011). As a consequence, formative assessment attracted a considerable amount of research interest because of its potential to improve student learning and to achieve a better alignment between learning goals and assessment (for reviews see Bennett, 2011; Dunn & Mulvenon, 2009; Kingston & Nash, 2011). Nevertheless, in one of the most recent reviews of formative assessment, (Bennett, 2011) states that "the term formative assessment does not yet represent a well-defined set of artefacts or practices" (p. 19). He observes a 'split' between those who regard formative assessment as referring to an instrument and those who understand it as a process; in his view, each view point is an oversimplification. Moreover, he regards the distinction between assessment 'for' and 'of' learning

as problematic since it absolves summative assessment from any responsibility to support learning.

2.2.3 Characteristics of formative assessment

Although a variety of methods, techniques, and instruments exists for formative assessment purposes, the methods show some common characteristics. Formative assessment has to be an integral part of teaching and learning (Bell & Cowie, 2001; Birnbaum et al., 2006). It has to be continuous, it has to actively engage students by peer- and self-assessment, and it has to provide feedback and guidance to learners on how to improve their learning by scaffolding information and focusing on the learning process (Looney, 2011; Wilson & Sloane, 2000).

Feedback has to be specific, has to be given in a timely manner, and has to be linked to specific criteria (Sadler, 1989). Not only is its quantity important but also its quality with respect to its technical structure (e.g. accuracy, appropriateness, and comprehensiveness), its accessibility to the learner and its catalytic and coaching value (Bangert-Drowns, Kulik, Kulik, & Morgan, 1991; Sadler, 1998). Reviews of feedback aspects and their effects on education have been conducted, e.g., by Hattie and Timperley (2007), Kluger and DeNiSi (1996), and Shute (2008). The desired learning outcomes are clearly specified in advance which makes the learning process more transparent for students by establishing and communicating clear learning goals (Looney, 2011). The methods to be employed are deliberately planned but still allow teachers to adjust their teaching and vary their instruction method to meet individual student needs (OECD, 2005).

Formative assessment can be distinguished by its time frame (short – within/between lessons; medium – within/between teaching units; long – over semesters/years) and its amount of formality. The amount of formality ranges on a continuum from informal to formal depending on the amount of planning involved, the nature and quality of the data sought, and the nature of the feedback given to students by the teacher. Shavelson et al. (2008) describe three anchor points on the continuum: (1) 'on-the-fly', (2) planned-for-interaction, and (3) formal and embedded in the curriculum. The amount of planning is also defined by the distinction of Bell and Cowie (2001) between planned and interactive formative assessment. Whereas the former tends to be carried out with the whole class and involves the teacher in eliciting and interpreting assessment information and then taking action, the latter involves the teacher in noticing, recognizing and responding, and tends to be carried out with some individual students or small groups.

2.2.4 Assessment methods and techniques

In the preparation phase of the review, one goal was to find out which methods and techniques are used in formative and summative assessment in STM. It is a characteristic of formative assessment that it uses multiple instruments and techniques ranging from traditional paper and pencil tests to student observations. In general, this is also true for summative assessment, although, especially in large-scale assessments (e.g. PISA), a tendency to use multiple-choice, constructed-response or short open-ended questions can be observed. In contrast to, e.g., extended essays, student notebooks or

performance assessments, these questions can be comparatively easily and reliably scored. Alternative assessment methods in STM include, e.g., quizzes (e. g. Hickey, Taasobshirazi, & Cross, 2012), portfolios (e. g. Gitomer & Duschl, 1995), learn logs or student notebooks (e.g. Barron & Darling-Hammond, 2008), artefacts (e. g. Kyza, 2009), concept or mind maps (e. g. Ruiz-Primo & Shavelson, 1997), performance assessments (e.g. Barron & Darling-Hammond, 2008), and different methods of assessment discourse such as effective questioning (Learning how to Learn Project, 2002), assessment conversations (e. g. Ruiz-Primo & Furtak, 2006), or accountable talk (e. g. Michaels, O'Connor, & Resnick, 2008). Often, these methods are accompanied or complemented by techniques of student observation like video, audio, or field notes (see 5.2.1 Science; e. g. Vellom & Anderson, 1999). Moreover, interviews are employed to gain deeper insights into student thinking (see 5.2.1 Science, e. g. Berland, 2011). In computer-assisted learning and assessment environments, information from log-files can provide additional information. If the assessment method is more open (in contrast, e.g., to multiple-choice items), general or specific rubrics often exist to make a valid and reliable analysis and scoring of student responses possible (e.g. Barron & Darling-Hammond, 2008). Rubrics are also employed in student peer- and self-assessment (Toth, Suthers, & Lesgold, 2002). A summary of assessment instruments found during the literature review is given in Appendix 8.2 and 8.3.

2.2.5 Formative assessment – barriers and support

Recent OECD publications stress the importance of formative assessment and its integration with summative assessment (Looney, 2011; OECD, 2005). They also realize, however, that assessment in many countries still seems to be dominated by summative assessment (see D 2.3 'National reports of partner countries reviewing research on formative and summative assessment in their countries'). Looney (2011) attributes this, among other things, to a perceived tension between formative and highly-visible summative assessments. Moreover, many logistical barriers to making formative assessment a regular part of teaching practice exist.

In order to foster the use of formative assessment, it is essential to first enable teachers to change their deeply held pedagogical beliefs of assessment as a tool for teacher use and accountability rather than as a method to involve students in a constructivist assessment environment. The understanding and acceptance of innovations by the teachers is crucial to the ultimate success of change (Wilson & Sloane, 2000). This can be supported by:

- **Integrating assessment and instruction**
Assessment still often remains distinct from learning in the minds of most students and teachers (American Association for the Advancement of Science, 1998). Assessment is discussed in terms of particular strategies, techniques, and procedures, distinct from other teaching and learning activities (Coffey, Hammer, Levin, & Grant, 2011).
- **Embedding formative assessment in the curriculum**
The effectiveness of an assessment depends, to a large part, on how well it aligns with the curriculum to reinforce common learning goals (Pellegrino et al., 2001; Shavelson et al., 2008). In order for assessment to become fully and

meaningfully integrated into the teaching and learning process, it must be curriculum dependent i.e. linked to a specific curriculum (Wilson & Sloane, 2000).

- **Fostering the collaboration between curriculum and assessment experts as well as teachers**

Building stronger bridges between research, policy and practice is essential for success but is also challenging (Shavelson et al., 2008).

Teachers should review the assessment questions that they use and discuss them with peers (Ayala et al., 2008; Black & Wiliam, 1998).

- **Enhancing accountability**

Teachers must feel confident that new assessment methods will be accepted for accountability purposes by school administrators and the public at large (American Association for the Advancement of Science, 1998).

- **Supporting teachers by teacher professional development (TPD)**

(Pedder, 2006; Wiliam, 2006). Wiliam considers “the task of improving formative assessment [to be] substantially, if not mainly, about TPD”. The provision of tools for formative assessment – although a necessary condition – will only improve formative assessment practices if teachers can integrate them into their regular classroom activities. To reach this goal, teachers need help to change the perception of their own role (American Association for the Advancement of Science, 1998). Moreover, TPD could foster the integration of assessment into instruction by combining work on assessment with work on instruction and materials.

In her report about the integration of formative and summative assessment, Looney (2011) identifies barriers to an implementation of formative assessment as well as policies that might support it. Although ASSIST-ME is primarily interested in approaches or policies for fostering the implementation of formative assessment, the perceived barriers can provide valuable information that has to be kept in mind when developing assessment methods.

Barriers to an implementation of formative assessment are seen in large classes, extensive curriculum requirements, the difficulty of meeting diverse and challenging student needs, fears that formative assessment is too resource-intensive and time consuming to be practical, a lack of coherence between assessments and evaluations at the policy, school and classroom level, the perception of formative assessment methods as ‘soft’, non-quantifiable assessments by policy makers/administrators, and a perceived tension between formative assessment and highly visible summative assessment (see above). Within the ‘Learning How to Learn’ project, Pedder (2006) found that classroom assessment practices are influenced and defined by conflicting and quite separate principles, namely assessment for learning principles (making learning explicit and promoting learning autonomy) and assessment of learning principles (performance orientation). Teachers’ assessment practices were often out of step with their teaching values.

Difficulties in informal assessment of mathematics are the focus of a study by Watson (2006). In this theoretical paper, the informal assessment practices of two experienced lower secondary mathematics teachers are used as cases for generating questions about future developments in formative assessment practice. In their instruction, both teachers maintain a consistent formative assessment focus on the development of their students as inquirers which one of them supplements with explicit self-assessment

activities. Nevertheless, there are differences in their teaching styles and in the ways in which they assess and describe their students (e.g. levels of formality, amount of content focus or opportunities for self-audit). One conclusion of the author is that a mixture of observation, interaction and judgment that is informed by belief, image and purpose is typical of teachers' informal assessment habits. From the analysis, several questions emerge with respect to the future of formative assessment practice: (a) Can ways be found to use performance data from large-scale studies to construct relevant information for individual teachers? (b) Can non-linear pathways of mathematical development be described?, and (c) How can such descriptions be used by teachers and students without reducing mathematical inquiry to a rubric without purpose?

In contrast, formative assessment practices could be supported by fostering teachers' and school leaders' assessment literacy (i.e. an awareness of the different factors that may influence the validity and reliability of results, the capacity to make sense of data, to identify appropriate actions and to track processes (Alkharusi, 2011 and references therein; American Federation of Teachers, National Council on Measurement in Education, & National Education Association, 1990; Brookhart, 2011; Looney, 2011; OECD, 2005). This could be accomplished by investing in teacher training and support, e.g. by providing guidelines and tools to facilitate formative assessment practice, by encouraging innovation and creating opportunities for teachers to innovate, and by developing clear definitions of learning goals and a theoretical framework of how that learning is expected to unfold as the student progresses through the instructional activity. Policy makers and administrators have to be convinced that formative assessment methods are not 'soft' but rather that they measure the development of higher order thinking skills (American Association for the Advancement of Science, 1998). Educational systems should build stronger bridges between research, policy and practice and should actively involve students and parents in the formative process to ensure that classroom, school, and system level evaluations are linked and are used formatively to shape improvements at every level of the system.

2.2.6 Links between formative and summative assessment

Finally, the links between formative and summative assessment could be strengthened by drawing on advances in the cognitive sciences to strengthen the quality of formative and summative assessment (Shepard, 2000 and references therein), by developing curriculum-embedded or 'on-demand' assessments, by taking advantage of technology, by using population instead of census sampling (Chudowsky & Pellegrino, 2003), by developing complementary diagnostic assessments for students at lower proficiency levels to identify specific learning difficulties (Looney, 2011), and by ensuring that standards of validity, reliability, feasibility, and equity are met (American Association for the Advancement of Science, 1998). Moreover, teachers' assessment roles should be strengthened (see assessment literacy above). Heritage, Kim, Vendlinski, and Herman (2009) found that teachers are quite competent in identifying the key mathematical principles being assessed and characterizing the students' level of understanding but had problems determining appropriate next instructional steps. As a last point, the strengthening of teacher appraisal is mentioned (Looney, 2011). There are a number of challenges to the development of coherent and valid measures in the formative as-

assessment practice as it involves several steps, including the assessment process, the interpretation of the evidence of students' learning, and the development of next steps for instruction (Herman, Osmundson, & Silver, 2010).

There is some argumentation in the literature about how close the link between formative and summative assessment might – or should – be. In principal, the term 'formative' is not a property of an assessment; the same test could be used for formative or summative purposes (Bloom, 1969; Wiliam, 2006). Harlen and James (1997), however, argue that the requirements of assessment for formative and summative purposes differ in several dimensions (e.g. reliability, reference base, etc.). They thus challenge the assumption that summative judgments can be formed by the simple summation of formative ones. On the other hand, Black, Harrison, and Hodgen (2010) consider a positive link between formative and summative assessment as going beyond the simple formative use of summative tests. This could be achieved by making use of peer- and self-assessment, thus engaging students in a reflective review of the work they have done, encouraging them to set questions and mark answers, and applying criteria to help them understand how their work could improve (Black, Harrison, Lee, Marshall, & Wiliam, 2004). Looney (2011), moreover, states that especially large-scale summative tests often do not reflect the promoted development of higher-order skills such as problem solving, reasoning, and collaboration – which are key competences in IBE. This is supported by William (2008) who finds that assessments such as PISA are usually relatively insensitive to high-quality instruction. This leads to technical barriers to a more close integration of formative and summative assessment because large-scale summative assessment data are often not detailed enough to diagnose individual student needs or they are not delivered in a time frame which enables them to have an impact on the students assessed. Moreover, creating reliable measures of higher-order skills is still a challenge. Related to this, Looney (2011) sees three major challenges: (1) Developing assessments that measure not only 'what' but also 'how to', (2) Reporting results in a 'criterion-referenced' way instead of a 'norm-referenced' way, including the development of focused reporting scales in criterion-referenced systems to provide diagnostic information (especially for weak students), and (3) Finding a balance between generalizability, reliability, and validity (e. g. Wilson & Sloane, 2000).

Nevertheless, in the literature, some attempts to use summative assessment data formatively (or vice versa) can be found. William and Ryan (2000) analysed the performance of 7 and 14 year old students in the 1997 UK mathematics tests. They tried to describe the children's progression in thinking as it related to their test performance; however, the authors found that the items often were not diagnostic enough. An attempt to combine formative and summative assessment in inquiry-learning environments was also made by Hickey et al. (2012) who used the concept of close, proximal, and distal assessment items. Modest empirical evidence was found that improvement in (formative) feedback conversations leads to gains in external (summative) achievement tests. Pellegrino et al. (2001) described examples in which alternative assessment approaches were successfully used to evaluate individuals and programmes in large-scale contexts in the US.

2.2.7 Assessment and inquiry

Some references looking at the relationship between assessment and inquiry could be found. According to Barron and Darling-Hammond (2008), assessment systems that support inquiry approaches share three characteristics. They contain intellectually ambitious performance assessments, evaluation tools such as guidelines and rubrics, and formative assessments to guide the feedback to the students and shape instructional decisions. As types of assessments that could be used in inquiry lessons the authors name: rubrics (must include scoring guides that specify criteria for students and teachers), solution reviews, whole class discussions, performance assessments, written journals, portfolios, weekly reports, and self-assessments. The authors claim that “most effective inquiry approaches use a combination of on-going informal formative assessment and project rubrics that communicate high standards” (Barron & Darling-Hammond, 2008, p. 3); however, no references are given. The Principled Assessment Designs for Inquiry project (PADI) aimed to provide a practical, theory based approach to developing high-quality assessments of science inquiry by combining developments in cognitive psychology and research on science inquiry with advances in measurement theory and technology. The centre of attention was a rigorous design framework for assessing inquiry skills in science which are highlighted in standards but difficult to assess (Mislevy et al., 2003; SRI International, 2007). The difficulty of assessing inquiry skills is also addressed by Hume and Coll (2010) who conclude that standards-based assessments using planning templates, exemplar assessment schedules and restricted opportunities for full investigations in different contexts tends to reduce student learning about experimental design to an exercise in ‘following the rules’.

The relation between inquiry-based science education (IBSE) and assessment, especially formative assessment, was the focus of a conference held in York in 2010 titled “Taking IBSE into secondary education”. As an outcome of the conference, it was stated that “implementation of IBSE will require some fundamental changes particularly in [...] the form and use of assessment and testing” (INQUIRE project, 2010, p. 6). The participants agreed that a full implementation of inquiry will involve the use of formative assessment since the aims of formative assessment and IBSE coincide in helping students to take responsibility for their own learning; however, introducing inquiry-based science education and formative assessment both require a considerable change in pedagogy (INQUIRE project, 2010). The shared potential of formative assessment and inquiry to develop understanding through students taking charge of their own learning is also stressed by Harlen (2009). Delandshere (2002) argues that formative assessment itself can be understood as a form of inquiry (e.g. asking questions, defining criteria, interpreting data, coming to conclusions, communicating results, etc.). In their investigation of problem and project based learning, Barron and Darling-Hammond (2008) eventually state that formative assessment might provide a kind of scaffolding that supports student learning. Scaffolding is defined as a “process that helps a child or novice to solve a problem, carry out a task, or achieve a goal which would be beyond his unassisted efforts” (Barron & Darling-Hammond, 2008, p. 276).

3. Objectives of the literature review

The first phase of ASSIST-ME, including WP 2, focused on producing the knowledge base necessary for a research-based design of assessment methods, followed by a trial implementation of these methods. Therefore, the development of a baseline definition of IBE in STM (see D 2.5 'A definition of inquiry-based STM education and tools for measuring the degree of IBE') and the identification of a set of assessment methods suitable for enhancing inquiry-based learning in STM were the starting point, as described above. The literature review takes up on these definitions and aims to answer the following research questions:

- Which aspects of IBE are investigated by empirical studies in STM?
- What formative and summative assessment methods are used in STM with respect to the aspects of IBE?
- How are these methods used?

Thus, this report is a review of existing knowledge about the formative and summative assessment of knowledge, as well as the competences and/or attitudes in IBE in STM. It focuses on the findings of empirical studies which are related to the research questions mentioned above. The report presents the findings from a comprehensive analysis of existing research on how the summative and formative assessment of knowledge, and the competences and/or attitudes in STM can be linked to aspects of IBE. The focus lies on methods which improve students' outcomes.

Table 2 shows the intended objective. On the one hand, there are aspects of IBE (see also Table 1) and, on the other hand, there are different formative assessment methods. The question is: Which formative assessment methods are suitable for the assessment of specific aspects of IBE? For example, portfolios are used for the assessment of the aspect 'planning investigations' or 'constructing prototypes' in order to understand the procedure which the students use (Dori, 2003; Samarapungavan, Mantzicopoulos, & Patrick, 2008; Samarapungavan, Patrick, & Mantzicopoulos, 2011; Williams, 2012).

Table 2: Starting point for the identification of possible connections between IBE and formative assessment

Inquiry-based education	Connections between inquiry-based education and assessment methods	Formative assessment
Diagnosing problems	?	Concept maps
Critiquing experiments		Mind maps
Distinguishing alternatives		Portfolios
Planning investigations		Science notebooks
Researching conjectures		Multiple-choice
...		...

To reach this objective, a literature review was conducted. Its search strategies are presented in section 4. Procedure of the literature review. By categorizing the publications found, information was gathered about IBE and formative and summative assessment. Possible connections will be discussed in report D 2.6 'Report of outcomes of the expert workshop on assessment in STM and IBE' and recommended in report D 2.7 'Recommendation report from D 2.1 – D 2.6'.

4. Procedure of the literature review

The starting point of the literature review was – as described in D 2.2 ‘Synopsis of the literature review’ – the appointment of appropriate keywords. However, a systematic search using keywords faces several challenges.

Above all, these challenges are caused by the diversity of terms and instructional or teaching approaches that include characteristics of IBE. A literature search just using ‘inquiry’ as the keyword would, on the one hand, miss a lot of relevant publications. On the other hand, it would find an unmanageable number of publications. Besides, not only IBE comes under a variety of terms and approaches, but also some of the outcome variables like formative assessment. Therefore, relatively open keyword approaches do not seem to be feasible for the work in the ASSIST-ME project.

For this reason and due to the experience gained in the synopsis (see D 2.2 Synopsis of the literature review), a large number of relevant keywords were defined. Then, three different search strategies were applied to conduct the literature review:

1. Searches in data bases,
2. Searches in relevant journals,
3. Searches in reference lists.

These searches yielded approximately 200 results as a final extract which was managed in a Citavi-project file and evaluated in an Excel file (see 5. Results of the literature review). The following sections describe how these nearly 200 publications were extracted and how the searches were carried out. In addition, an expert survey was realized in order to validate the results and in order to receive recommendations of further relevant and/or influential publications in the field of formative and summative assessment as well as in IBE or problem-solving in STM.

The search concerning ICT-assisted assessment was conducted and documented by Pearson Education International as their contribution to the work of WP 2 in the ASSIST-ME project. The results are presented in part II of this report.

4.1 Searches in data bases

The search in databases allows for the systematic and simultaneous search in a collection of most of the important journals within a specific field of interest. According to the ASSIST-ME proposal (Dolin, 2012), two data bases were selected for this literature review. The first one is ‘Web of Science’ provided by Thomson Reuters. Web of Science includes the ‘Science Citation Index Expanded’ covering over 8500 major journals across 150 disciplines (including education in the scientific disciplines) from 1900 to present as well as the ‘Social Sciences Citation Index’ covering over 3000 journals across 55 social science disciplines (including education and educational research) as well as selected items from 3500 of the world’s leading scientific and technical journals from 1900 to present. Within the Social Sciences Citation Index, the following journals are e.g. listed:

- Review of Educational Research
- Learning and Instruction

- American Educational Research Journal
- Journal of the Learning Sciences
- Educational Researcher
- Journal of Research in Science Teaching
- Science Education

These journals have impact factors that are among the top ten in the 2012 Thomson Reuters Journal Citation Reports (JCR) Social Science Edition. "Journal Citation Reports® is a comprehensive and unique resource that allows for evaluating and comparing journals using citation data drawn from over 11000 scholarly and technical journals from more than 3300 publishers in over 80 countries. It is the only source of citation data on journals, and includes virtually all areas of science, technology, and social sciences" (Thomson Reuters, 2012).

Other journals included in the Web of Science database are e.g. in the field of technology education:

- Journal of Engineering Education,
- Journal of Science Education and Technology,
- International Journal of Technology and Design Education,
- International Journal of Engineering Education,

and in the field of mathematics education:

- Journal for Research in Mathematics Education,
- Educational Studies in Mathematics,
- International Journal of Science and Mathematics Education.

The second database that was used is 'Education Resources Information Center' (ERIC). In contrast to Web of Science that presents a broad range of science journals, ERIC focuses specifically on the field of general education and provides access to education literature and resources. It contains more than 1.4 million records and links to more than 337.000 full-text documents from ERIC.

For the literature review, the last 15 years, from April 1st 1998 till April 1st 2013, were chosen as the time span. The selection of the keywords was based on the collection of definitions in the ASSIST-ME project proposal (Dolin, 2012) and on a first unsystematic literature review which is described in D 2.2 'Synopsis of the literature review'. Furthermore, a first list of keywords was presented and discussed with the project partners at the WP 2 workshop during the ASSIST-ME kick-off conference in Copenhagen on January 26th 2013. The feedback was considered when the final list of keywords was built. Then, one expert from each subject approved the list. Afterwards, the keywords were grouped into six topics. Each topic is related to an aspect of ASSIST-ME (see Table 3). For example, topic 1 is related to the aspect of IBE. Furthermore, topics 1 and 2 cover domain-specific aspects by considering subject-specific keywords for IBE and alternative keywords for mathematics, science or technology education.

Table 3: Keywords for searches in data bases

Topics	Keywords		
	Science	Technology	Mathematics
Topic 1: inquiry	Inquiry-based learning OR inquiry OR collaborative learning OR discovery learning OR cooperative learning OR constructivist teaching OR problem-based learning OR argumentation	inquiry OR design OR problem-based learning OR project-based learning OR argumentation OR collaborative learning	inquiry OR didactical learning OR didactical situations OR open approach OR problem based-learning OR problem centred learning OR "realistic mathematics education" OR argumentation
Topic 2: subject	science education OR science instruction OR science teaching and learning	technology education OR engineering education OR technology instruction OR technology teaching OR technology learning	mathematics education OR mathematics instruction OR mathematics teaching OR mathematics learning
Topic 3: school	classroom OR teacher OR student	classroom OR teacher OR student	classroom OR teacher OR student
Topic 4: objective	assessment OR evaluation OR validation OR achievement OR feedback	assessment OR evaluation OR validation OR achievement OR feedback	assessment OR evaluation OR validation OR achievement OR feedback
Topic 5: type of assessment	formative OR embedded OR summative	formative OR embedded OR summative	formative OR embedded OR summative
Topic 6: method of assessment	discourse OR effective questioning OR assessment conversations OR accountable talk OR quizzes OR self-assessment OR peer-assessment OR portfolio OR learn log OR mind map OR concept map OR rubrics OR science notebook OR multiple-choice OR constructed-response OR open-ended response	discourse OR effective questioning OR assessment conversations OR accountable talk OR quizzes OR self-assessment OR peer-assessment OR portfolio OR learn log OR mind map OR concept map OR rubrics OR science notebook OR multiple-choice OR constructed-response OR open-ended response	discourse OR effective questioning OR assessment conversations OR accountable talk OR quizzes OR self-assessment OR peer-assessment OR portfolio OR learn log OR mind map OR concept map OR rubrics OR science notebook OR multiple-choice OR constructed-response OR open-ended response

For the searches in the data bases, the topics were combined to achieve a high correlation between the content of the literature found and the objectives of the ASSIST-ME project. The five combinations are presented in Table 4. The first search resulted in a very large number of references. By checking the content of the literature found, it became obvious that most of the publications did not meet the aims of the ASSIST-ME project. Therefore, the search strategy was changed. In order to focus on the intended objectives, the keywords of topic 5 were added (search 2). As a result, the number of references substantially decreased which increased the danger of missing relevant

publications. Thus, topic 5 was exchanged for topic 6 (search 3) and the explicit mentioning of the terms formative and summative was avoided. The third search strategy led to a better result in view of relevant literature. Searches 4 and 5 were carried out in order to verify the search strategy. By deleting the keywords of topic 1, the literature found once again did not meet the objectives of the ASSIST-ME project. Thus, search strategy 3 was used for the data base searches. With regard to the WP 2 time frame, it led to a manageable number of publications while, at the same time, yielded results that are relevant with respect to the project objectives.

The results of the searches were refined in the data bases by the following categories: 'education educational research', 'education scientific disciplines', 'education special', 'computer science interdisciplinary applications', 'psychology educational'. In addition, the chosen document types were articles, book chapters or reviews.

There is an overlap between the results of the two data bases within a subject. However, it is quite low. Therefore, these findings confirm that carrying out a search in two different data bases was worthwhile. Ultimately, 331 publications in science, 88 in mathematics and 68 in technology were found. The references were imported to a Citavi-project file.

Table 4: Results of the searches in data bases

Search		Variations					Results				
		Topic 1	Topic 2	Topic 3	Topic 4	Topic 5	Topic 6	S	M	T	
Web of Science											
1	Inquiry-based learning OR ...	science education OR ...	classroom OR ...	assessment OR ...			790	171	249		
2	Inquiry-based learning OR ...	science education OR ...	classroom OR ...	assessment OR ...	formative OR ...		69	11	25		
3	<i>Inquiry-based learning OR ...</i>	<i>science education OR ...</i>	<i>classroom OR ...</i>	<i>assessment OR ...</i>		<i>discourse OR ...</i>	<i>163</i>	<i>34</i>	<i>50</i>		
4		science education OR ...	classroom OR ...	assessment OR ...		discourse OR ...	513	181	64		
5		science education OR ...	classroom OR ...			discourse OR	1253	423	105		
Education Resources Information Center											
1	Inquiry-based learning OR ...	science education OR ...	classroom OR ...	assessment OR ...			1105	482	220		
2	Inquiry-based learning OR ...	science education OR ...	classroom OR ...	assessment OR ...	formative OR ...		82	23	17		
3	<i>Inquiry-based learning OR ...</i>	<i>science education OR ...</i>	<i>classroom OR ...</i>	<i>assessment OR ...</i>		<i>discourse OR ...</i>	<i>+183</i>	<i>+56</i>	<i>+25</i>		
4		science education OR ...	classroom OR ...	assessment OR ...		discourse OR ...	749	526	49		
5		science education OR ...	classroom OR ...			discourse OR	1255	888	84		
Search 3: Results of both data bases											
						Duplicates	-15	-2	-7		
						Total	= 331	= 68	= 68		

4.2 Searches in relevant journals

In addition to the searches in the data bases, searches in relevant journals were conducted as a result of the discussion about the search strategies at the ASSIST-ME Kick-off meeting in Copenhagen. The journals in Table 5 were considered as relevant in view of the objectives of the ASSIST-ME project or even as the most important for each subject or research field. If available, the impact factors of each journal are presented for the last year and the last five years, indicating their importance. Those journals that have an impact factor are also included in the Science Citation Index or in the Social Science Citation Index and are thus regarded by searches in the data base Web of Science.

However, the impact factors were not the only criterion for the selection of the journals. In addition, publications about the importance of journals were considered. For example, Johnson and Daugherty (2008) asked key leaders in the field of technology education to identify what they consider the top research-focused journals in the field. "The following four technology education journals were consistently mentioned by the panel of experts: (a) the International Journal of Technology and Design Education (ITDE), (b) the Journal of Industrial Teacher Education (JITE), (c) the Journal of Technology Studies (JTS), and (d) the Journal of Technology Education (JTE). This is essentially the same list of refereed journals that Zuga analysed in her 1994 study. The only difference is that Zuga included 'The Technology Teacher' while this study included the 'International Journal of Technology and Design Education'." Journals focusing on teachers or teacher education were excluded because ASSIST-ME focuses mainly on students.

Table 5: Relevant journals and their impact factors

Subjects	Journals	Impact factor ¹	
		Last year	Last five years
Science	Journal of Research in Science Teaching	2.55	3.23
	Science Education	2.38	2.71
Technology	Int. Journal of Technology and Design Education	0,34	0.42
	Journal of Technology Education	-	-
	Journal of Technology Studies	-	-
Mathematics	Educational Studies in Mathematics	0.77	-
	Int. Journal of Science and Mathematics Education	0.46	-
	Journal for Research in Mathematics Education	1.55	2.08
Assessment	Applied Measurement in Education	0.58	0.74
	Assessment in Education	-	-
	Educational Assessment	-	-

¹(according to Thomson Reuters, 2013)

Both methods led to the list of journals in Table 6. The articles of all issues published during the last 10 years were scanned by using the homepages of the publishers and the two data bases mentioned above. Compared to the search in the data bases, the numbers of references were much lower. But, the differences between the subjects were also much smaller. Thus, this search was able to improve the quantity and quality of the literature basis.

Table 6: Results of the searches in the issues of relevant journals by subject

Subjects	Journals	Results	
		Per journal	Per subject
Science	Journal of Research in Science Teaching	44	63
	Science Education	19	
Technology	Int. Journal of Technology and Design Education	14	24
	Journal of Technology Education	9	
	Journal of Technology Studies	1	
Mathematics	Educational Studies in Mathematics	11	30
	Int. Journal of Science and Mathematics Education	10	
	Journal for Research in Mathematics Education	9	
Assessment	Applied Measurement in Education	9	41
	Assessment in Education	19	
	Educational Assessment	13	
Total		158	158

4.3 Searches in reference lists

To guarantee that important literature with regard to IBE and formative or summative assessment was considered, an additional, more unsystematic search was carried out. Following the pyramid scheme, the reference lists of the literature found were scanned in view of frequently recurring publications which might have a high impact on research on IBE and formative or summative assessment. As well as the publications from the search in relevant journals, the references were added to the Citavi-project file. For science, there were 32 additional references that focused on students in school. For mathematics, there were only 10 publications, and for technology and assessment none.

4.4 Final extract

Finally, the literature collected by the different search strategies and searches was imported into one Citavi-project file. This file contained 732 references. However, 31 duplications resulted from the parallel searches. They were deleted from the project file. In the end, the Citavi-project file contained 701 entries.

Up to this point, a deeper analysis of all publications had not been carried out. Therefore, the titles and abstracts of the publications were read and categorized in order to further identify the relevant literature. Table 7 shows the categories and the numbers of

references for each category by subject. Only the publications in the category 'focus students (school)' should meet the objectives of the ASSIST-ME project. The other publications addressed the learning process of university students or its assessment; others contributed to the research on teacher education or development and some others did not report findings from an empirical study but only theoretical aspects. Therefore, these publications did not meet the core objectives of the ASSIST-ME project at the current stage of the project and were no longer regarded for this review. Nevertheless, the found publications focusing on teachers' professional development should be evaluated at a later stage of the project when teacher training courses will be developed.

Table 7: Categorization of literature

Categories	Science	Mathematics	Technology	Assessment	Total
<i>Focus students (school)</i>	152	44	23	16	235
Focus students (university)	19	4	23	-	46
Focus teacher	57	38	14	5	114
No study ¹	58	12	28	13	111
Review	5	2	1	4	12
Book (Monograph)	15	2	1	-	18
Book (Serial)	11	6	5	-	22
Dissertation	9	6	2	-	17
Proceeding	-	6	2	-	8
Not relevant ²	94	18	3	3	118
Total	420	138	102	41	701

¹e.g. policy or methodological frameworks, description of approaches, theoretical discussions, or presentation of explorative investigations
²The content or focus of the publications is not connected to the objectives of ASSIST-ME.

In order to achieve a deeper analysis of the relevant literature from the category 'focus students (school)', all 235 publications were read and evaluated with a coding scheme. The results were filed in an Excel file. Table 9 shows the titles and contents of each column in the Excel file. First, the aim of this step in the analysis procedure was to gather information about the whole content of the publications. In addition, this step analysed the extent to which the literature met the objectives of the ASSIST-ME project. The second aim was to categorize the results with respect to the research questions:

- Which aspects of IBE are investigated by empirical studies in STM?
- What formative and summative assessment methods are used in STM with respect to the aspects of IBE?
- How are these methods used?

Besides, it was recorded which domain and grade level the studies address. Furthermore, the literature derived from the three assessment journals was reassigned to the three subject domains.

Table 8: Final extract for the literature review

Category	S	M	T	Total
<i>Focus students (school)</i>	148	30	13	191

Even though the literature was categorized by reading the titles and abstracts in advance, 42 references were identified which did not belong to this category but to one of the others. The remaining 191 references are the publications which meet the objectives of the ASSIST-ME project and thus form the final extract for this report (see Table 8). Even though there was a partial selection before, 510 of all 701 publications were excluded. Chapter 5. Results of the literature review summarizes the empirical results of the 191 publications. Obviously, the three search strategies resulted in a huge number of publications in science education but only in a few number of publications in mathematics and especially technology education. Reasons might be that IBE as a teaching and learning approach is best developed and investigated in science education. In technology education there might be less research on IBE as technology is not a common school subject in a lot of countries. In mathematics education there is huge range of different teaching and learning approaches or theories which might include aspects of inquiry (see D 2.5). Therefore, the strongly focused search strategy applied within this review might not reflect this diversity and thus lead to the small number of publications in mathematics.

Some of the aspects of IBE focused on by the interventions and learning environments or by the assessment are conceptually not distinguishable. Therefore, 'considering alternative or multiple solutions', 'searching for alternatives' and 'modifying designs' are combined in one paragraph. The aspects 'formulating hypotheses' and 'researching conjectures' are evaluated in one section as well. Third, 'collecting and interpreting data' and 'evaluating results' are also described within one section.

Table 9: Scheme for the evaluation of the literature

Column	Content
Literature	author(s)
General information about the investigation/ analysis	year
	country
	design (Survey, Intervention, Evaluation, Case Study, Meta-analysis)
	domain (Science, Technology, Mathematics)
	sample(s) size (N)
	sample characteristics: grade (school type)
Content focus of the investigation/ analysis (either as focus of the intervention/learning environment/curricula or as focus of the assessment)	sample characteristics: age
	scientific inquiry/science process skills
	diagnosing problems/ identifying questions
	searching for information
	considering alternative or multiple solutions
	creating mental representations
	constructing and using models
	formulating hypotheses
	planning investigations
	constructing prototypes
	finding structures or patterns
	researching conjectures
	collecting and interpreting data
	evaluating results
	searching for alternatives/ modifying designs
	constructing and critiquing arguments or explanations/ argumentation/ reasoning/ using evidence
	debating with peers/ communication
	searching for generalizations
	dealing with uncertainty
	knowledge/ achievement/ understanding/ conceptual change
problem solving	
other	

Assessment: method/ practice	Multiple-choice
	constructed-response/ open-ended
	concept map
	mind map
	portfolios
	learn log
	notebook
	effective questioning
	discourse/ assessment conversations/ accountable talk
	heuristics
	quizzes
	performance assessment/ experiments
	interviews
	observation/ field notes
	video tapes
audio tapes	
questionnaires	
written materials	
artefacts	
other	
Assessment: character/ type	summative assessment
	formative assessment
	embedded assessment
	computer-based/-assisted assessment
	software or learning environment used or curriculum
Assessment: additional information	feedback
	peer-assessment
	self-assessment
	rubrics
	other
Assessment instru- ments given?	yes
	examples
	no
Rubrics given?	yes
	examples
	no
Important outcome	

4.5 Expert survey

The comparably small number of publications found in the field of mathematics education lead to concerns within the project that mathematics might not be adequately represented in the literature review. In order to validate the results from the review and to ensure that no relevant literature is missing, an expert survey was conducted. Experts from all three subject domains were asked to name those ten publications that they regarded as the most important or relevant in the field of formative and summative assessment or IBE and problem-solving, respectively.

In total, at the end of August 2013 twelve experts were contacted, four from the field of science education, two from the field of technology education and five from the field of mathematics education. Until the beginning of October, four experts had responded to the survey, three from mathematics and one from science.

Most of the recommended publications are theoretical articles, reviews or books within the above mentioned research fields. Only very few publications refer to empirical studies.

In science, almost three quarter of the recommended publications had previously been found in the literature review. The additional publications are all theoretical papers dealing either with certain aspects within the field of IBE (e.g. the role of teachers or model-based inquiry as a new paradigm in school science) or the role of feedback in out of school contexts (management theory, communication networks and decision processes). Another additional paper by William (2007) investigated the relationship between classroom assessment and the regulation of learning and was also recommended by one of the mathematics experts.

Due to time constraints, it was not possible to include the additional empirical studies recommended by the mathematics experts within the results section of this review. They will thus be shortly described in the following. The theoretical publications about IBE or problem-solving are included in D 2.5 'A definition of inquiry-based STM education and tools for measuring the degree of IBE'.

In the field of mathematics education, the majority of recommended papers refers to formative assessment (34 compared to 18 in IBE). Compared to science, a smaller amount of publications had already been found within the literature review (12 papers). However, summarizing all publications, there is also only small agreement among the experts with only five papers being named by more than one expert.

Among the empirical studies, Elia, Gagatsis, Panaoura, Zachariades, and Zoulinaki (2009) investigated three different dimensions of grade 12 students' understanding of the concept of limit and their interrelations. These dimensions are students' conceptions concerning the meaning of the concept of limit; their competence in converting a certain expression of limit from a geometric to an algebraic representation and vice versa, and their problem solving abilities with respect to limits. Since no representation can fully reflect a mathematical construct and each form of representation has its advantages but also its limitations, especially the ability to flexibly use and convert representations is regarded as a prerequisite for the acquisition of conceptual understand-

ing. The assessment instrument consisted of a questionnaire that involved ten tasks related to the above mentioned dimensions of conceptual understanding and their interrelations. The results of the analysis indicated that students who had constructed a conceptual understanding of limit were more likely to accomplish the conversions of limits from the algebraic to the geometric representations and vice versa.

Verschaffel, Corte, and Vierstraete (1999) performed an error analysis to investigate grade five to six students' difficulties in modelling and solving nonstandard additive word problems involving ordinal numbers. The backdrop of their study was that in traditional instructional practice realistic modelling and interpreting are often missing. Students are not aware of the possibly problematic modelling assumption underlying their proposed solutions which leads them to approach arithmetic word problems in superficial, mindless and routine-based ways. The assessment instrument consisted of a 17-item paper & pencil word problem test in which tasks were deliberately formulated in a way that the addition/subtraction of two numbers will give either the correct result or a wrong result that differs ± 1 from the correct response. One example for such a task is e.g.: "In September 1995 the city's youth orchestra had its first concert. In what year will the orchestra have its fifth concert if it holds one concert every year?" (Verschaffel et al., 1999, p. 267). Related to the mathematical structure, the nature of the unknown quantity and the size of the number difference involved, nine different problem types of items were defined. The findings showed that the students had great difficulties in solving the items often resulting from a superficial, stereotyped approach of adding/subtracting two numbers without thinking about the appropriateness of the approach in the given situation.

Rodríguez, Bosch, and Gascón (2008) used the Anthropological Theory of the Didactic to analyse metacognition in problem solving in mathematics. Their theoretical considerations were supported by an empirical study in grade 11 focusing on the problem of comparing mobile phone tariffs which constitutes a complex problem with a multitude of variables. Students were asked to keep a portfolio including the progressive productions of their work; in addition field notes and video tapes were used as assessment instruments. The analysis of the 'didactic moments' in the process revealed that (a) teachers often destroyed them by wanting to make 'progress' and (b) that self- and peer-evaluation appeared naturally during the collaborative course work. At the end of the process, the students were asked to answer an individual written test on the comparison of fixed phone tariffs with some novelties. The results showed that the students were able to approach a question similar to the one previously studied, explain the process followed and use the comparison techniques constructed during their previous work in a flexible way.

Another aspect of problem solving that causes problems even for high performing calculus students was investigated by Moore and Carlson (2012). They looked at students' ability to model relationships between two dynamically varying quantities. This is regarded as a critical reasoning ability for thinking about and representing the quantitative relationships described in a problem statement which in turn provides the basis for future constructions and reflection during the problem solving process. The study focused on undergraduate pre-calculus students at university (age 18-25) which are be-

yond the age range addressed by the ASSIST-ME project. It has to be seen during the future work of the project whether the results are transferable to the school context or not. The students were assessed using structured, task-based clinical interviews. The authors found a positive correlation between the ability to mentally construct a robust structure of the related quantities and the production of meaningful and correct solutions. They concluded that it is critical that students first engage in mental activity to visualize a situation and construct relevant quantitative relationships prior to determining formulas or graphs.

The assessment of mathematical problem solving ability was also the focus of a study by Collis, Romberg, and Jurdak (1986). They reported the developing, administering, and scoring of a set of mathematical problem-solving items – so-called ‘superitems’ – and examined their construct validity using the ‘Structure of the Learned Outcomes – SOLO’ taxonomy. Each superitem included a mathematical situation and a structured set of questions about that situation that reflected the SOLO levels. The items belonged to six content categories (numbers and numeration; variables and relationships; size, shape, and position; measurement; statistics and probability; and unfamiliar) and were designed in a way that within any item a correct response to a question would indicate an ability to respond to the information in the stem at least at the level reflected in the SOLO structure of that question. Two test versions were constructed, one for 17-year-olds and one for nine to thirteen year-olds. The results showed that to construct valid items required input from three significant groups of people: (a) mathematicians, mathematics educators, and mathematics teachers; (b) people with expertise in interpreting the theoretical model in a practical situation and (c) students for whom the finished test was intended. Following this recommendation, however, the SOLO model proved viable for devising a construct valid test in mathematical problem solving suggesting that this kind of response model approach may be very useful for educators and researchers who have the task of describing levels of reasoning on school-related tasks.

The last two empirical studies recommended by the mathematics experts are examples for one of the key findings of the literature review presented in this report: the evaluation of an inquiry-based teaching approach by using standardized achievement measures. Both publications refer to a problem-centred mathematics program in the United States. Within the program, special emphasis was placed on e.g. the development of thinking strategies and the development of algorithms within the instructional activities as well as providing opportunities for collaborative working and whole-class discussions. The first paper by Cobb et al. (1991) compares results for ten grade two classes who had been participating in the program for one year with the results of eight non-program classes. Means for the comparison were two arithmetic competence tests: a standardized achievement test (the state-mandated multiple-choice standardized achievement test – ISTEP) and another arithmetic test developed by the program. Within the latter, items had been constructed in a way that they could be coded for the use of a standard algorithm or that incorrect answers would reveal the use of e.g. a figurative rule. Moreover, students had to fill in a questionnaire about personal goals and beliefs about the reasons for success in mathematics. Results showed that the

levels of computational performance were comparable between program and control group. However, qualitative differences in the use of arithmetical algorithms could be observed. Program students "had higher levels of conceptual understanding; held stronger beliefs about the importance of understanding and collaborating; and attributed less importance to conforming to the solution methods of others, competitiveness, and task-extrinsic reasons for success." (Cobb et al., 1991, p. 3). In a later publication, Wood and Sellers (1997) presented results from a longitudinal analysis of grade three and four students within the same teaching program (and using the same assessment instruments). The study yielded similar results. Compared to students in textbook instruction, students in problem-centred classrooms had significantly higher arithmetic achievement, better conceptual understanding and more task-oriented beliefs.

Summarizing the outcomes of the expert survey, it can be said that for science the literature review seems to reflect the state-of-the-art of formative and summative assessment in IBE. For mathematics, the survey further emphasizes the importance of problem solving and its components in inquiry-based approaches to mathematics education. However, as far as assessment methods are concerned, the applied methods are in line with those identified within the literature review.

5. Results of the literature review

The identified publications were read by four researchers to extract the study's aim, design and results. The analysis focused on three questions:

1. Which aspects of IBE are emphasized or researched in the study?
2. Which types of assessment are employed in the study?
3. Which connections can be found between the emphasis on particular aspects of IBE and specific assessment instruments?

The following two chapters of report D 2.4 will be structured in line with the first two questions. The interrelatedness between the diverse aspects of IBE and assessment will be described in the recommendation report D 2.7 that will be based on all prior reports from WP 2. Then, connections made in the publications will be displayed to show which aspects are often bound and researched together.

When reading the next sections, it is important to keep in mind that in technology and mathematics education the number of found publications is rather low. Therefore, the findings from this literature review cannot be generalized for these two subjects. Nevertheless, in science education a sufficient number of publications was found.

As a kind of disclaimer, it is important to mention two issues for those reading this report. First, in line with the description of both IBE and formative and summative assessment stated above, the findings of the literature review are presented in a rather fragmented way. For instance, the different aspects of IBE are presented one after another, including specific foci and interpretations as extracted from the different papers in this review. Thereby, the interconnections between the different aspects are partly lost.

Second, the following description of findings mainly focuses on details of the different aspects of IBE and assessment instruments. However, for the purpose of better readability, not all studies relevant to a particular aspect are cited each time. We tried to include citations from relevant or representative papers, but no effort is made to achieve a balanced citation of all studies.

5.1 Which aspects of IBE are emphasized or researched in the study?

5.1.1 Diagnosing problems/ Identifying questions

Finding, identifying, and/or formulating a research question are certainly major steps in scientific inquiry processes, whereas diagnosing problems is mostly related to mathematics (e. g. Chang, Wu, Weng, & Sung, 2012) and technology education (e. g. Mioduser & Betzer, 2007). Accordingly, the aspect of diagnosing problems or identifying questions is present in many IBE studies. 44 publications of this review explicitly explored this aspect as part of a learning environment or as part of the assessment.

While the relevance of identifying the research problem and formulating a research question is intuitively clear to every researcher, the manner in which students come to a problem or question of interest makes a difference. Studies explicitly including this step of problem identification focus on/consider instruction that introduces students to a challenging problem (Toth et al., 2002), student-generated problems in science (Zhang & Sun, 2011), or students' ability to identify a situation in technology which demands a design (Mioduser & Betzer, 2007). As can be seen from Table 10, this aspect of inquiry has mainly been investigated in the field of science education. Highlighting personal relevance aims to stimulate students' engagement in the task so that they then take personal ownership of a problem (Silk, Schunn, & Cary, 2009).

For the evaluation of students' ability to diagnose problems and to identify research questions, Ebenezer, Kaya, and Ebenezer (2011) formulated two scoring criteria:

"Criterion 1: 'Define a scientific problem based on personal or societal relevance with need and/or source' means that students ought to identify and accurately define a community-based problem that is meaningful to them. The problem must have personal or societal relevance. Students should defend the problem based on the need for the study or because they have identified the problem from a reliable source.

Criterion 2: 'Formulate a statement of purpose and/or scientific question' means students should write the purpose and state a scientific question with clarity and precision." (p. 102).

Regarding students' ability and results when asked to identify research questions of interest or relevance, different approaches can be identified. Dori and Herscovitz (1999) investigated students' question-posing capability as an alternative evaluation method. They used two case studies (dealing with rain forests and the threat of health hazard problems caused by the ozone layer) and asked students to pose as many questions as possible related to these two cases. The results of both case studies were analysed according to the number of questions posed by each student, the orientation of each question (differentiating between phenomena and/or problem descriptions, descriptions of hazards, and treatment and/or solution), the relation to the case study (establishing whether the answer is provided in the case study, a part of the answer is provided in the case study, or the answer cannot be found in the case study), and the complexity of each question (distinguishing between application and/or analysis, inter-

disciplinary approaches, judgement and/or evaluation, and taking a stance and/or forming a personal opinion).

Similarly, Chin and Osborne (2010) analysed students' questions and derived five categories of questions to classify the kind of questions students came up with: "(a) key inquiry; (b) basic information; (c) unknown or missing information; (d) conditions under which the heating was carried out; and (e) others" (p. 891). Key inquiry questions sought explanations. Basic information questions addressed the most basic, factual information students needed to know. Unknown or missing information questions asked for any information not given in the task sheet but which students felt was necessary. Questions in the conditions category included students' predictive thinking in terms of asking what would happen if the conditions of the experiment were altered.

Aguiar, Mortimer, and Scott (2010) analysed the impact of students' questions on the discourse of the lesson. The authors tried to reveal the 'teaching explanatory structure' (cf. Ogborn, Kress, Martins, & McGillicuddy, 1996) of a lesson, as it provides a way to conceptualize the teaching discourse which the students are responding to with their questions.

In general, students' ability to identify research questions was explicitly addressed in 44 publications (see Table 10). However, the majority of these publications included this introductory step of scientific inquiry processes only as a facet of the learning environment, while less than one third of the publications tried to explicitly assess students' ability in this step.

Table 10: Number of studies investigating 'diagnosing problems/ identifying questions'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	5	21	1	27
Focus on assessment	1	10	1	12
Focus on both	0	5	0	5
Studies per subject [N]	6	36	2	44

5.1.2 Searching for information

Searching for information is an important and relevant step in each inquiry process. Missing information needs to be looked up, to be evaluated, and to be integrated into existing knowledge and inferences. The self-evident relevance of this step might be the reason for why it has only been researched by few studies.

Toth et al. (2002) distinguish between an information search and an evaluation of information. Additionally, the information search measure has two sub-items: "(1) How many topic-relevant information pieces were recorded and (2) How many topic-relevant

information pieces were labelled as data and hypotheses” (p. 274). The scoring revealed a broad use of categories by students, including theory, hypotheses, idea, fact, data, and evidence (Toth et al., 2002).

Regarding the evaluation of information, the amount of topic-relevant inferences was analysed. Three kinds of inferences were differentiated between: Consistency inferences (‘for’ inferences), indicating a supportive relationship between data and hypotheses; inconsistency inferences (‘against’ inferences), indicating disparities between hypotheses and data; and conjunction inferences (‘and’ inferences), indicating that two information pieces should be considered together during reasoning (Toth et al., 2002).

In general, only few studies focused on students’ search for information, especially as a facet of the respective assessment procedures, and they were almost exclusively located in the field of science education (see Table 11).

Table 11: Number of studies investigating ‘searching for information’

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	1	12	0	13
Focus on assessment	0	3	0	3
Focus on both	0	1	0	1
Studies per subject [N]	1	16	0	17

5.1.3 Considering alternative or multiple solutions/ searching for alternatives/ modifying designs

This aspect of IBE can play a role in different points of the inquiry process. Especially if the inquiry tasks involve ill-structured problems, students are required to consider alternative pathways towards a solution at an early stage of the process (e. g. MacDonald & Gustafson, 2004). After conducting the investigation and evaluating the results, however, the necessity to consider alternative solutions might also arise if the results do not yield the desired outcome. Especially in technology education, the improvement of an artefact after its construction is an important aspect (e. g. Hong, Yu, & Chen, 2011; MacDonald & Gustafson, 2004). In any case, the identification or evaluation of alternative or multiple solutions to an inquiry problem is a challenging step.

In addition, considering alternatives also deals with the use of a variety of investigation technologies. Accordingly, students should be able to decide between different tools to support their investigation (e.g., hand tools; measuring instruments and calculators; electronic devices; and computers for the collection, analysis, and display of data; (Ebenezer et al., 2011)). But, the challenges and sacrifices on the side of both the students and the researchers are quite high:

“To make sensible decisions about experimental designs that test the multitude of ideas they hold, learners need to combine their knowledge of combinatorial reasoning and controlling variables with methods for sorting out their disciplinary knowledge and identifying compelling questions. Learners must weigh multiple sources of knowledge to conduct informative experiments” (McElhane & Linn, 2011, p. 748).

These high affordances might be the reason for the small number of studies identified which include this facet of IBE.

In their study within the field of science education, McElhane and Linn (2011) asked students to develop a series of consecutive trials for the same investigation. Each trial was scored using a knowledge integration rubric from zero to five, reflecting the strength of the link between students' investigation goals and their variable choices in several ways. The authors describe three objectives of the rubric as it was used within the study:

“First, the rubric rewards conducting at least two unique trials for a particular investigation question, as comparisons between multiple trials are essential for illustrating variable relationships. Second, the rubric rewards varying the variable that corresponds to the chosen investigation question for that comparison. Third, the rubric rewards controlled comparisons that produce evidence for a variable effect, as measured by achieving opposite outcomes (safe or unsafe).” (McElhane & Linn, 2011, p. 755).

In a similar manner, students in engineering classes in Australia were asked to design a product that would enable someone stranded on a beach with no drinking water to use the power of the sun to produce drinkable water from the sea water (Williams, 2012). The task required students to produce four alternative designs that were supposed to show revised and improved solutions to the problem.

In mathematics, only one study addressed this issue by asking students to find multiple answers or to apply multiple strategies to open-ended questions (Kwon et al., 2006). One example given was that students should choose from a list of numbers one number that was different from the others and explain their choice. They were instructed to try to find as many cases or answers as possible.

In total, 26 studies could be identified that incorporated students dealing with alternative or multiple solutions, either as part of a learning environment or as part of the assessment (see Table 12). Again, this facet of scientific inquiry was mainly incorporated within a learning environment, probably because of the high complexity of the analysis when carried out as part of the assessment.

Table 12: Number of studies investigating 'considering alternative or multiple solutions/ searching for alternatives/ modifying designs'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	0	11	2	13
Focus on assessment	1	5	2	8
Focus on both	0	3	2	5
Studies per subject [N]	1	19	6	26

5.1.4 Creating mental representations

The use of mental representations is a vast research area in itself (cf. Genter & Stevens, 1983). The power of internal and external representations "originates from the unique characteristic of each form of inscription – table, graph, picture – to guide the user's attention towards employing specific strategies of extracting information encoded in these representations" (Toth et al., 2002, p. 266). Hence, the use of representations influences scientific inquiry processes by making ideas perceptually salient (Koedinger, 1992; Larkin & Simon, 1987). In mathematics, this aspect is often closely related to the aspect of finding patterns or structures (see 5.1.9 Finding structures or patterns). For example, Lin, Yang, and Chen (2004) investigated the relationship between reasoning, proving, and understanding proof in a number of patterns. This investigation was closely related to the process of representation, which incorporates exploring and searching for geometric number patterns, and explaining patterns verbally or diagrammatically.

Oh et al. (2012) analysed the impact of using simulation applets to facilitate students' understanding of gas and liquid pressure concepts. The analysis indicated significant improvements in understanding when using the applets compared to didactic instruction. In addition, students were interested in the use of simulation applets and perceived them to be useful.

In general, the use of mental representations seems to be a characteristic feature of mathematics and science education. The studies extracted in these reviews are almost evenly distributed between these two domains, as well as between the adoption of mental representations as part of the learning environment or as part of the assessment (see Table 13).

Table 13: Number of studies investigating 'creating mental representations'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	2	2	0	4
Focus on assessment	1	3	0	4
Focus on both	2	1	0	3
Studies per subject [N]	5	6	0	11

5.1.5 Constructing and using models

Analogous to the creation of mental models, the construction and usage of models is an important part of scientific reasoning. An indicator of students' understanding of scientific models is their ability to apply them to reasoning about scientific phenomena, patterns, and data (Anderson, 2003). In this regard, models can be used to explain or predict patterns or relations.

Schwarz and White (2005) developed curriculum material to foster students' learning about the nature of scientific models and to engage them in the process of modelling, especially by creating computer models that express students' own theories of force and motion, by evaluating their models using criteria such as accuracy and plausibility, and by engaging them in discussions about models and the process of modelling. In an evaluation study, students working with these materials wrote significantly better conclusions in an inquiry test and performed better in some far-transfer problems. In addition, the results suggest that developing knowledge of modelling and inquiry can be transferred to the learning of science content within such a curriculum.

In the field of chemistry, Kaberman and Dori (2009) developed curriculum material that integrates computerised hands-on experiments with molecular modelling. The material was evaluated with regard to its impact on students' higher-order thinking skills of question-posing, inquiry, and modelling. Their findings indicate that the experimental group of students performed significantly better than their comparison peers in all three examined skills. With regard to modelling skills, students in the experimental group significantly improved in making transfers from 3D models to structural formulae. But, in total, only about half of them were able to transfer from formulae to 3D models.

Zhang, Wilson, and Manon (1999) analysed gender differences in problem-solving strategies for two extended constructed-response mathematics questions. The analysis revealed different patterns, e.g. more boys than girls used approaches of higher sophistication, yet, overall, more boys were unsuccessful in accomplishing the task. The girls were more likely to use a visual, more concrete approach, and a lot more girls than boys did not give a sufficient explanation for the strategy used to solve the problem.

In total, students' ability to construct and use models was explicitly addressed in 17 publications (see Table 14). Between the adoption of modelling as part of the learning environment or the assessment, the studies extracted in this review are almost evenly distributed.

Table 14: Number of studies investigating 'constructing and using models'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	1	5	2	8
Focus on assessment	1	4	2	7
Focus on both	0	2	0	2
Studies per subject [N]	2	11	4	17

5.1.6 Formulating hypotheses/ researching conjectures

The formulation of (testable) hypotheses is a major facet of scientific practice (Klahr & Dunbar, 1988; Kuhn, 1962). "In the end, there are a relatively small number of characteristics that define the enterprise we call science. The central ideas involve observation of the world and the constant testing of theories against nature, with the requirement that everything that is to be called science must be testable" (Trefil, 2008, p. 19). In this 'enterprise', meaningful and well-founded hypotheses are at the centre of scientific knowledge and progress.

With regard to students' ability in formulating a testable hypothesis, Ebenezer et al. (2011) expect students to "be able to state a hypothesis that lends itself to testing. Also, the hypothesis should be accompanied by coherent explanation(s)" (p. 103).

Burns, Okey, and Wise (1985) used multiple-choice items to analyse students' ability to identify and select testable hypotheses. Using constructed-response items, Lavoie (1999) examined the effects of adding a prediction or discussion phase at the beginning of a learning cycle. He asked students to individually write out predictions with explanatory hypotheses concerning problems in genetics, homeostasis, ecosystems, and natural selection. By introducing this phase, the authors intended to prompt students to construct and deconstruct their procedural and declarative knowledge. The evaluation of this intervention revealed significant gains in the use of process skills, logical-thinking skills, understanding scientific concepts, and scientific attitudes.

Kyza (2009) examined students' inquiry practices in considering alternative hypotheses. She analysed students' discourse, actions, inquiry products, and interactions with their teacher and peers. Despite significant learning gains when implementing a supportive learning environment, the authors point out several epistemological problems relating to students' perception of the usefulness of examining and communicating alternative explanations, e.g. about what constitutes a convincing explanation of a com-

plex problem or what counts as evidence. Their findings indicate the importance of epistemologically targeted discourse alongside guided inquiry experiences for overcoming these challenges.

The researching of conjectures is explicitly only part of the research by Reiss, Heinze, Renkl, and Groß (2008). The authors refer to three phases: (1) The production of a conjecture is the first step which includes the exploration of the problem leading to the conjecture as well as the identification of arguments to support its evidence; (2) The second step is the precise formulation of a conjecture as a basis for all future activities; (3) The third phase combines the exploration of the (precisely stated) conjecture, the identification of appropriate mathematical arguments for its validation, and the generation of a rough proof idea. In other publications, the researching of conjectures is implicitly part of the aspect 'formulating hypotheses' and is not an aspect by itself (e. g. Gobert, Pallant, & Daniels, 2010; Toth et al., 2002).

In the field of scaffold inquiry, Pine et al. (2006) asked students why an ice cube melts much more slowly in salt water than in tap water. After the replication of an experiment with ice cubes made of tap water coloured with red dye and the subsequent observations of the flow of the coloured melt water, students were asked to try to present/give/offer/provide an initial explanation for the difference in melting times. Furthermore, on successive days, students studied coloured water dropped from an eyedropper into fresh and salt water, and the effect of stirring on the difference in melting times in fresh and salt water. They again were asked to provide an explanation for the difference in melting times observed at the beginning.

In total, students' ability to formulate hypotheses or research conjectures was explicitly addressed in 38 publications (see Table 15). Despite this large number of studies, only a small number of studies disentangled this aspect of inquiry in detail. Additionally, no study in the field of technology education explicitly referred to the formulation of hypotheses as an important step of inquiry. This might be due to the nature of technological inquiry itself. In solving design problems, e.g., students generally do not have to formulate a hypothesis in its classical sense since this hypothesis would be that the design they are proposing will work and will fulfil the specified requirements and constraints.

Table 15: Number of studies investigating 'formulating hypotheses/ researching conjectures'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	0	17	0	17
Focus on assessment	2	12	0	14
Focus on both	0	7	0	7
Studies per subject [N]	2	36	0	38

5.1.7 Planning investigations

Similar to the formulation of hypotheses, planning an investigation is at the core of inquiry, especially in science. To develop appropriate investigations, students need to demonstrate logical connections between their conceptual understanding, their guiding hypothesis, and the research design. This means that "students should identify the scientific concepts and create a conceptual system that will guide the hypothesis and research design" (Ebenezer et al., 2011, p. 103).

The reviewed publications differ - especially with regard to the mode in which students approach the planning of their investigations. For example, McElhany and Linn (2011) used a computer simulation in which students conducted experiments to answer different investigation questions. The questions could be selected from a drop down menu or students could choose an alternative such as 'just exploring'. While students conducted their experiments, the software logged the investigation question and the variable values that the students selected for each trial. Students' choice of an investigation question was used to infer their intentions in each trial.

Other studies used open questions that students had to answer by planning their own, hands-on investigations, or these studies analysed differences between hands-on investigations and surrogates (e.g. simulations) (Baxter, Shavelson, Goldman, & Pine, 1992; Shavelson, Baxter, & Pine, 1991; Williams, 2012). Furthermore, White and Frederiksen (1998) investigated the effect of reflective assessments on inquiry units. Overall, students' performance improved significantly and a controlled comparison revealed that students' learning was greatly facilitated by reflective assessment. Interestingly, adding this metacognitive process to the curriculum was particularly beneficial for low-achieving students: Performance in their research projects and inquiry tests was significantly closer to that of high-achieving students than was the case in the control classes.

In total, the planning of investigations represents a broad research area with many different facets. 39 publications that included planning as part of a learning environment or as part of the assessment were found (see Table 16). Most of these publications stem from the field of science education (in which there is generally a larger number of

publications than in other fields) and reflect the importance of this inquiry aspect for science.

Table 16: Number of studies investigating 'planning investigations'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	2	26	0	28
Focus on assessment	0	10	0	10
Focus on both	0	0	1	1
Studies per subject [N]	2	36	1	39

5.1.8 Constructing prototypes

The construction of prototypes is predominantly addressed in publications from the field of technology education (see Table 17). Eight out of the twelve technology publications that were found investigated this issue, which shows the predominant role that this aspect plays in technological inquiry. MacDonald and Gustafson (2004) describe a project in which the children designed, made, and tested model parachutes. The intention was to analyse the characteristics of the design technology drawings that the children made before entering a construction phase. The results indicate that drawing was conceived by the children solely as representation. It was not used to indicate initial thoughts, to explore and form ideas, or as a vehicle for thinking, but was used exclusively to depict the completed product. Thus, the function of prototypes was not well understood by the children. Gustafson, MacDonald, and Gentilini (2007) extended this study to students' talking and drawing. However, no studies were identified in which students constructed prototypes in hands-on activities.

Table 17: Number of studies investigating 'constructing prototypes'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	0	2	3	5
Focus on assessment	0	0	3	3
Focus on both	0	2	2	4
Studies per subject [N]	0	4	8	12

5.1.9 Finding structures or patterns

As the Mathematical Sciences Education Board states, 'mathematics is a science of patterns and relationships' (Mathematical Sciences Education Board, 1990). Finding patterns or structures is seen by several authors as being closely related to processes of mathematical thinking (Lin et al., 2004; Tzur, 2007), reasoning and proving (Lin et al., 2004), problem solving (Zhang et al., 1999), and to the ability to use mental strategies and to make use of mathematical symbols (Britt & Irwin, 2008). It is considered to play an important role in students' ability to generalize. For example, Britt and Irwin (2008) investigated the use of 'tens frames' in primary mathematics classrooms and found that their use and understanding supported children's generalization ability and thus engaged them in mathematical thinking. Lin et al. (2004) analysed the relation between students' understanding of number patterns and their abilities in proving, reasoning, and algebraic thinking. To assess students' reasoning in geometric number patterns, they used four types of items: understanding the task, generalizing the number pattern, representing this pattern with symbols, and checking if a given number fits into this pattern. The relation between students' ability to identify and generalize patterns was also an important aspect in the study of Zhang et al. (1999). They used two everyday situations (sorting eggs into egg cartons and estimating the number of beans in a jelly jar). Students had to identify the pattern, generalize it, and then apply it to reach the solution.

In science, the publications dealing with the aspect of finding structures or patterns are mostly related to the identification of patterns in data (Gobert et al., 2010; Ketelhut & Nelson, 2010). In the study of Gobert et al. (2010), e.g., students were required to analyse earthquake patterns, use these patterns to explain their data, and relate them to plate interactions.

Wilson, Taylor, Kowalski and Carlson (2010) compared inquiry-based and commonplace science teaching with respect to students' knowledge, reasoning, and argumentation. They used an inquiry unit dealing with sleep disorders that was based on the BSCS 5E model. Within this model, they specifically focused on the 'explore' activity. Students should find patterns and negotiate those with their peers.

The small number of studies addressing this aspect of inquiry (see Table 18) might be due to the fact that it cannot be clearly separated from, e.g., 'searching for generalizations' in mathematics or 'collecting and interpreting data' in science.

Table 18: Number of studies investigating 'finding structures or patterns'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	1	5	0	6
Focus on assessment	1	0	0	1
Focus on both	2	2	0	4
Studies per subject [N]	4	7	0	11

5.1.10 Collecting and interpreting data/ evaluating results

Collecting and interpreting data, thus, the experiment itself, is certainly at the core of inquiry in science. Thousands of articles have been published about the role of the experiment in science education, as well as its benefits and relevance for students' understanding of science. Most of these publications regard the experiment as a fixed procedure; some even talk about THE scientific procedure. In several studies, experimenting means controlling variables. Therefore, fewer studies aim to describe the steps that must be taken in order to collect data that can be interpreted in a scientific way.

Designing and conducting experiments related to a hypothesis requires making a logical outline of methods and procedures, using proper measuring equipment, heeding safety precautions, and conducting a sufficient number of repeated trials to validate the results (Ebenezer et al., 2011). In addition, appropriate tools, methods, and procedures are necessary to collect and analyse data systematically, accurately, and rigorously. In some cases, this can include the use of mathematical tools and statistical software, e.g. to analyse and display data in charts or graphs or to test relationships between variables (Ebenezer et al., 2011).

Several studies in this review aimed to describe the different steps that must be taken in the collection and interpretation of data. Toth et al. (2002) used a 'design experiment' approach to develop an instructional framework that lends itself to authentic scientific inquiry. A technology-based knowledge-representation tool called 'Belvedere' enabled students to relate hypotheses to data by constructing so-called 'evidence maps'. Students formulated scientific statements by using 'hypotheses' (oval shapes) and 'data' (square shapes) and indicated the relation between these with 'for' (support) and 'against' (refutation) links. Additionally, 'and' links could be used to conjoin statements. "The results indicated that in real-life-like classroom investigations designed to teach students how to evaluate data in relation to theories, the use of evidence mapping is superior to prose writing. Furthermore, this superior effect of evidence mapping was greatly enhanced by the use of reflective assessment throughout the inquiry process." (Toth et al., 2002, p. 264).

Lubben, Sadeck, Scholtz, and Braund (2010) investigated the untutored ability of grade 10 students to engage in argumentation about the interpretation of experimental data. The authors analysed students' written interpretations of experimental data and their justifications for these interpretations based on evidence and concepts of measurement. The results revealed an initial low level of argumentation, which was considerably improved through small group discussions unsupported by the teacher. The authors concluded that several factors impact on students' argumentation ability, such as experience with practical work, or students' language ability to articulate ideas.

Further studies focused on interventions to foster students' ability in collecting and interpreting data. Mattheis and Nakayama (1988) investigated the effects of a laboratory-centred inquiry programme on laboratory skills, science process skills, and understanding. The Foundational Approaches in Science Teaching (FAST) programme was compared with a traditional science textbook approach. These results indicate that the FAST instruction especially affects laboratory skills (e.g. measuring height, area, mass, volume displacement, and calculation of density) and specific process skills (e.g. identifying experimental questions, formulating hypotheses, identifying variables), although no significant effects were found on process skills and understanding in general contexts.

Zion, Michalsky, and Mevarech (2005) investigated the effects of four different learning methods on students' scientific inquiry skills. The 2x2-design included metacognitive-guided inquiry vs. unguided inquiry and the usage of asynchronous learning networked technology vs. face-to-face interaction. The study examined general scientific ability and domain-specific inquiry skills in microbiology. The group using metacognitive-guided inquiry within asynchronous learning networked technology outperformed all other groups, while the face-to-face group without metacognitive guidance acquired the lowest scores. The authors concluded that the use of metacognitive training within a learning environment enhances the effects of asynchronous learning networks on students' achievements in science.

After having conducted an experiment, the interpretation of the obtained data is an important step. However, it seems that only few studies focus on students' ability to make logical connections between evidence and scientific explanations. Ebenezer et al. (2011) emphasized that students should be able to connect evidence from their investigations to explanations based on scientific theories.

Ruiz-Primo, Li, Ayala, and Shavelson (2004) analysed students' notebooks in science for, among other things, entries on interpreting data and/or concluding. They interpreted these entries as indicators of students' conceptual understanding. They found high and positive correlations between the derived notebook scores and other performance assessment scores. However, students' communication skills and understanding differed greatly from the expected maximum scores and did not improve over the course of the study that lasted for one school year.

The evaluation of results is included in many publications as a step of inquiry, but often only as a buzzword or by-product of a more general view on inquiry. Most of these pub-

lications stem from the field of science education (in which there is generally a larger number of publications than in other fields) and reflect the importance of this inquiry aspect for science. In total, 81 studies focused on students' ability to collect and interpret data or evaluate results, 73 of them in the field of science education (see Table 19).

Table 19: Number of studies investigating 'collecting and interpreting data/ evaluating results'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	5	45	0	50
Focus on assessment	0	20	1	21
Focus on both	1	8	1	10
Studies per subject [N]	6	73	2	81

5.1.11 Constructing and critiquing arguments or explanations, argumentation, reasoning, and using evidence

Studies including argumentation, explanation, or reasoning as part of an inquiry process make up the largest group of studies in this review, leading to a broad array of theoretical and empirical papers. None of the other aspects is researched in the same detail.

The construct understood as argumentation varies slightly between studies. Two major conceptualizations can be identified: argumentation as students' general use of data and scientific concepts to construct arguments or explanations about the phenomenon under study (e. g. Linn, Songer, & Eylon, 1996; Smith, 1991; Strike & Posner, 1985); and argumentation as students' competitive interaction in which participants present claims, defend their own claims, and rebut the claims of their opponents until one participant (or side) 'wins' and the other 'loses' (e. g. Driver, Newton, & Osborne, 2000; Duschl, 2000; Kuhn, 1962; Latour, 1980; Toulmin, 1972). The difference between these conceptualizations depends upon the question of whether explanation and argumentation are treated as separate categories or as a single practice (Berland & Reiser, 2009).

The process of reasoning is often researched as part of an explanatory and argumentative discourse, often without any differentiation between or definition of these modes of communication (Bielaczyc & Blake, 2006; Hogan, Nastasi, & Pressley, 1999). Scardamalia and Bereiter (1994) refer to this combination as 'knowledge building'. While the combination of explanation and argumentation certainly makes sense in terms of their related goals and processes, it results in a practice with multiple instructional goals, with some of them more challenging for students than others (Berland & Reiser, 2009).

In a theoretical paper, Berland and Reiser (2009) identified “three distinct goals for constructing and defending scientific explanations: (1) using evidence and general scientific concepts to make sense of the specific phenomena being studied; (2) articulating these understandings; and (3) persuading others of these explanations by using the ideas of science to explicitly connect the evidence to the knowledge claims” (p. 29). When emphasizing the goal of persuasion, students are intended to go beyond articulating explanations by engaging with the ideas of others, receiving critiques, and revising their ideas (Driver, Newton, & Osborne, 2000; Duschl, 1990; Duschl, 2000). Thus, the goal of persuasion is to shift classroom interactions involving the practice of constructing and defending scientific explanations from ‘doing school’ to ‘doing science’ (Berland & Reiser, 2009; Jimenez-Aleixandre, Rodriguez, & Duschl, 2000).

In addition, the goal of persuasion signals the overlap to the conceptualization of argumentation as a comparative interaction. In this line of research, most studies refer to Toulmin’s model of argumentation (1958). For example, McNeill (2011) analysed students’ written argumentations and differentiated between a claim (a statement that answers a question or problem), evidence (scientific data that supports the claim), and reasoning (scientific knowledge that is/can be used to solve the problem and to explain why the evidence supports the claim). Toulmin (1958) originally included three more components of an explanation: qualifiers (statements about how strong the claim is), backings (assumptions or reasons to support the claim), and rebuttals (statements that contradict the data, warrants, qualifiers, or backings). These components have also been researched by other authors (Ruiz-Primo, Li, Tsai, & Schneider, 2010).

Studies differ not only with regard to the conceptualization of argumentation, but also with regard to the different methods used to assess students’ abilities in argumentation. While most studies use the verbal data of students’ discourse, many studies focus on students’ written argumentation. Ebenezer et al. (2011) even claim that “students should be able to write a clear scientific paper with sufficient details so that another researcher can replicate or enhance the methods and procedures” (p. 103).

A major difficulty in analysing students’ argumentations is the differentiation between the structure and components of argumentation and its accuracy. McNeill (2011) used four different codes (argument, just claim, informational text, personal narrative) to evaluate the writing style of students’ arguments. These codes were used regardless of the accuracy of the science content. Similarly, Ruiz-Primo et al. (2010) coded the accuracy of a claim as a separate measure. In addition, the authors analysed the focus (whether the claim addressed the main issues of the investigation question), and three aspects of the quality of the evidence (type: what type of evidence the student provided - anecdotal, concrete examples, or investigation-based; nature: did the student focus on patterns of data or isolated examples?; and sufficiency: did the student provide enough evidence to support the claim?) (Ruiz-Primo et al., 2010).

Toth et al. (2002) put an emphasis on analysing students’ reasoning and their final conclusions. The authors scored students’ written conclusions based on three components: (1) whether the information in the conclusion was based on information previously explored, (2) whether the conclusion contained any data to support the main hy-

pothesis, and (3) whether the conclusion indicated evidence 'going against' the accepted hypothesis (p. 275). The authors detailed different strategies the students used to structure their reasoning process. Several groups of students approached the inquiry problem by listing all the hypotheses they could think of or all the hypotheses they found in the web-based materials, and then continued with exploring data ('reasoning from hypothesis' approach to scientific reasoning). "Other groups started with data recording, and only after they had collected several data pieces did they start recording hypotheses, indicating a strategy resembling a 'reasoning from data' approach to scientific reasoning." (Toth et al., 2002, p. 280).

Wilson et al. (2010) investigated students' ability to construct and critique arguments. The authors used standardized open-ended interviews, in which students were asked to develop explanations for patterns in given data, as well as critique given explanations for those patterns. The results of a control-group comparison indicated

"that students receiving inquiry-based instruction reached significantly higher levels of achievement than students experiencing commonplace instruction. The superior effectiveness of the inquiry-based instruction was consistent across a range of learning goals (knowledge, scientific reasoning, and argumentation) and time frames (immediately following the instruction and 4 weeks later)" (Wilson et al., 2010, p. 292).

A further approach used to foster students' engagement in argumentation and explanation is to put student explanations in opposition to each other so that they are in positions to persuade one another (e. g. Bell & Linn, 2000; Hatano & Inagaki, 1991; Osborne, Erduran, & Simon, 2004). Using this approach, the role of argumentative discourse is emphasized while scientific explanations are a by-product of this process. Using a control-group design, Osborne, Erduran and Simon (2004) analysed the effect of fostering argumentation in science lessons. Teachers taught the experimental groups a minimum of nine lessons which involved socio-scientific or scientific argumentation. In addition, the same teachers taught similar lessons to a comparison group at the beginning and end of the year. Results from analysing small groups of four students engaging in argumentation over the course of 33 video-taped lessons indicated that there was improvement in the quality of students' argumentation, albeit not significant. In addition to the difficulties in fostering students' ability to engage in high-quality argumentation, the authors also concluded that supporting and developing argumentation in a scientific context is significantly more difficult than enabling argumentation in a socio-scientific context.

In mathematics, reasoning has been investigated in relation to proof competence (Heinze, Cheng, Ufer, Lin, & Reiss, 2008; Reiss et al., 2008). Boesen, Lithner, and Palm (2010) analysed the relation between the proximity of assessment tasks to the textbook and the mathematical reasoning students use. They thereby extended the relationship between reasoning and proof to understanding reasoning as "the line of thought adopted to produce assertions and reach conclusions. Argumentation is the substantiation, the part of the reasoning that aims at convincing oneself or someone else that the reasoning is appropriate". Their results show that when confronted with test tasks that are closely related to tasks in the textbook, students solved them by try-

ing to recall facts or algorithms. Surprisingly, more distant tasks mostly elicited creative mathematically founded reasoning.

All in all, 106 publications included aspects of argumentation, constructing and critiquing arguments or explanations (see Table 20). Among these studies, both the fostering of students' content knowledge by improving their argumentation skill and the fostering of argumentation skills as a merit/value on its own can be found. Again, the majority of publications can be found in the field of science.

Table 20: Number of studies investigating 'constructing and critiquing arguments or explanations, argumentation, reasoning, and using evidence'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	6	24	0	30
Focus on assessment	4	36	1	41
Focus on both	3	31	1	35
Studies per subject [N]	13	91	2	106

5.1.12 Communication/ debating with peers

Scientific knowledge is socially and culturally constructed through negotiation (Alexopoulou & Driver, 1996; Kelly & Green, 1998). "A key element of this negotiation is oral discourse. Group processes therefore are central to understanding how knowledge is created in a science classroom" (Baker et al., 2009). These group processes go beyond the individual construction of conceptual understanding, but also build a scientific community in the classroom (Newton, Driver, & Osborne, 1999).

Cavagnetto, Hand, and Norton-Meier (2010) analysed students' interactions in small groups in a primary school utilising the Science Writing Heuristic approach. Their results indicate that students worked on tasks 98% of the time, engaging in generative talk about 25% and in representational talk about 71% of the time. The authors emphasized that students' talk was dominated by the informative function (i.e. representing one's idea) and that students spent less time on the heuristic function (i.e. inquiring through questions) or on challenging each other's ideas.

Toth et al. (2002) investigated the processes of peer communication in four ninth grade science classrooms. In their study, student groups in different classrooms shared their research results and conclusions with peer groups at the end of their inquiry. Both the peer groups and the teacher used rubrics to score each team's performance as well as the artefacts (evidence maps and reports) they developed during their inquiry. The use of rubrics was a form of reflective assessment used to provide clear expectations for optimal progress throughout the entire process of inquiry. The results showed that the

use of these reflective assessments improved students' performance in evaluating data in relation to theories.

In total, 70 studies included facets of communication processes, although the majority of them only included them as part of the learning environment (see Table 21). Interestingly, several studies which included communication as part of the assessment tended to analyse written artefacts.

Table 21: Number of studies investigating 'communication/ debating with peers'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	5	31	1	37
Focus on assessment	2	21	0	23
Focus on both	0	10	0	10
Studies per subject [N]	7	62	1	70

5.1.13 Searching for generalizations

The facet of generalizing findings and implications as part of the inquiry process has seldom been researched. Only a small number of studies were found that explicitly entailed this step. For example, Woods, Williams, and Mc Neal (2006) analysed students' mathematical thinking as apparent in video-taped classrooms. Students' synthetic-analysing, which is Woods' et al. (2006) category to represent the production of independent generalizations, made up between 0 and 16 % of the time in different classrooms. Further analysis revealed major differences between conventional and reform-oriented classrooms in the quality of mathematical thinking.

In total, only five studies included the facet of searching for generalizations in the learning environment, only one as part of the assessment (see Table 22). However, as can be seen above, the aspect of searching for generalizations is, especially in mathematics, often closely related to the aspect of finding patterns (see 5.1.9 Finding structures or patterns).

Table 22: Number of studies investigating 'searching for generalizations'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	2	3	0	5
Focus on assessment	1	0	0	1
Focus on both	1	1	0	2
Studies per subject [N]	4	4	0	8

5.1.14 Dealing with uncertainty

Similarly, students' dealing with uncertainty has also seldom been researched (see Table 23). Only two studies were identified that included this aspect of inquiry. One example is Liedtke's (1999) study about two projects in Victoria (British Columbia) primary schools that tried to promote positive attitudes towards mathematical tasks and problem solving. The authors used open-ended tasks with multiple solutions to stimulate curiosity, group discussions, and risk taking. The case study revealed positive changes in the classroom behaviour of several students; they became more willing to ask questions and volunteer answers.

Table 23: Number of studies investigating 'dealing with uncertainty'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	1	1	0	2
Focus on assessment	0	0	0	0
Focus on both	0	0	0	0
Studies per subject [N]	1	1	0	2

5.1.15 Problem solving

Problem solving is part of the inquiry process but it affects more than one aspect of IBE. Usually, several aspects are combined within the studies found. For example, in mathematics education, Chang, Wu, Weng, and Sung (2012) investigated students' problem posing by analysing four phases: (1) 'posing problems' (problem-posing activity); (2) 'planning' (verifying self-posed problems and revising self-posed problems according to the teacher's feedback); (3) 'solving problems' (solving posed problems); and (4) 'looking back' (obtaining teacher's feedback and getting new ideas to create new problems). This example illustrates that the process of problem solving covers more than just identifying a problem. The phases originally derive from Polya's (1957)

work which defined the phases: understanding, planning, carrying out the plan and looking back. Other studies also refer to this definition (e. g. Lorenzo, 2005). As students have to learn the complex process of problem solving, research projects investigate the methodological approach of scaffolding (e. g. Simons & Klein, 2007).

In total, 13 studies from mathematics and science education were found (see Table 24). However, none were found in the field of technology education.

Table 24: Number of studies investigating 'problem solving'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	1	0	0	1
Focus on assessment	5	7	0	12
Focus on both	0	0	0	0
Studies per subject [N]	6	7	0	13

5.1.16 IBE and inquiry process skills in general

While many of the reviewed publications focused on the development and evaluation of learning environments for IBE or the assessment of certain aspects of IBE, some studies took a broader perspective on IBE and inquiry process skills. These studies used inquiry as a 'black box' category. The problem is that these approaches do not allow "for distinctions between activities that are guided more by the teacher and those guided more by the student" (Furtak and Seidel et al., 2012, p. 304). While mostly taking inquiry as a single construct, the studies differ in their research intentions.

A central field of research is the question of whether inquiry skills and content knowledge can be separated within a domain. Gobert et al. (2010), for example, designed a supplemental instructional and assessment module for enhancing middle school students' content knowledge and inquiry skills in the domain of geosciences. By using factor analysis, the authors intended to demonstrate the separation of content knowledge and inquiry skills. They found five factors, some reflecting content knowledge exclusively, some representing inquiry skills exclusively, and some including both content and inquiry within the same strand. The authors concluded that content knowledge and inquiry skills can partly be separated, but are also partly interrelated.

Beyond the analysis of the 'construct' inquiry, several publications investigated the comparison of IBE with other forms of teaching, often referred to as 'direct', 'traditional' or 'commonplace' teaching. For instance, Cobern et al. (2010) designed a controlled experimental study which compared inquiry instruction and direct instruction in realistic science classroom situations in middle school grades. The results indicate that "inquiry and direct methods led to comparable science conceptual understanding in roughly

equal instructional times. Gain differences between instructional modes were not statistically significant within the observed natural variation of students, teachers and classrooms.” (Cobern et al., 2010, p. 92).

In contrast, Furtak and Seidel et al. (2012) critique that “insufficient attention has been given to the operationalization of the inquiry construct in the case of prior meta-analyses of inquiry-based teaching and that this has masked important differences in the efficacy of distinct features of this instructional approach” (p. 304). Thus, the generalizability of the inferences one can make after combining effect sizes depends on “the way that the sample of students has been selected, the way that the outcome variable has been measured, and the way that the treatment under investigation has been defined” (Furtak and Seidel et al., 2012, p. 304). Therefore, Ruiz-Primo et al. (2012) present an approach which considered three aspects of quality in terms of the assessment items: (1) representing the curriculum content, (2) reflecting the quality of instruction, and (3) having formative value for teaching.

But, of course, there are studies which provide evidence that IBE has positive effects on students’ learning. For example, Gibson and Chase (2002) concluded that “a 2-week summer science programme which used an inquiry-based approach may have helped middle school students, who had a high level of interest in science, maintain their interest during their years in high school” (p. 704). Additionally, Hofstein, Navon, Kipnis, and Mamlok-Naaman (2005) present evidence that students can improve their ability to ask relevant questions as a result of gaining experience with inquiry-type experiments. Furthermore, students who were involved in these experiences were more motivated to pose questions regarding scientific phenomena. Even if the results are related to the aspect of identifying questions, general process skills are also included in the experiments.

Baker et al. (2009) developed the Communication in Science Inquiry Project which aims to create science classroom discourse communities (SCDCs): “a community of learners who create a culture that reflects literacy practices in science. The culture promotes norms of interaction that foster scientific discourse, use of notebooks, scientific habits of mind, and scientific language acquisition through inquiry. Central to a SCDC are experiences for students to communicate, create, interpret, and critique scientific arguments using scientific principles and data from inquiry activities.” (Baker et al., 2009, p. 260). The evaluation of this project focused on student perceptions of the teacher’s use of instructional strategies (i.e. scientific inquiry, learning expectations, writing, and use of science notebooks).

Further studies analysed the effect of curricular reforms. For example, Reys, Reys, Lapan, Holiday, and Wasman (2003) investigated the impact of standards-based mathematics curriculum material for middle grades on student achievement. The mathematics section/part of the Missouri Assessment Program (MAP) was used to measure students’ achievement. This included aspects of IBE, for example, defending data predictions, recognizing dependent and independent variables, using diagrams, patterns or functions in problem solving, and solving problems by using strategies (Reys et al., 2003). Differences were found between students who used the standards-based mate-

rials for at least 2 years and students from comparison districts who used other materials.

In total, 55 of the reviewed publications included a broader focus on IBE in STM; most of them in science education (see Table 25).

Table 25: Number of studies investigating 'IBE and inquiry process skills in general'

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	0	32	2	34
Focus on assessment	2	14	3	19
Focus on both	0	2	0	2
Studies per subject [N]	2	48	5	55

5.1.17 Knowledge/ achievement/ understanding

There are 96 studies that focused on the assessment of students' knowledge, achievement or understanding in the context of IBE, mainly in science education (see Table 26). This indicates that these variables are seen as control variables or dependent variables which are presumably influenced by any kind of an intervention including inquiry-based learning environments (e. g. Birchfield & Megowan-Romanowicz, 2009; Chen & Klahr, 1999; Santau, Maerten-Rivera, & Huggins, 2011).

The use of central examinations is one example for a frequently used assessment strategy. Schneider, Krajcik, Marx, and Soloway (2002) investigated the effect of a project-based science programme using the twelfth grade 1996 National Assessment of Educational Progress (NAEP) science test. This test includes the assessment of knowledge or understanding, as well as the assessment of aspects of scientific inquiry.

As the assessment of knowledge, achievement, and understanding is strongly related to the assessment methods and instruments, they are presented in Section 5.2 Which types of assessment are employed in the study?

Table 26: Number of studies investigating 'knowledge/ achievement/ understanding

	Mathematics	Science	Technology	Studies per focus [N]
Focus on learning environment	2	0	0	2
Focus on assessment	6	81	5	92
Focus on both	0	2	0	2
Studies per subject [N]	8	83	5	96

5.1.18 Further aspects focused on or assessed by the studies

Despite the broad definition of inquiry which led the focus of this review, several publications included further aspects. Some of these aspects are domain-specific, for example, proof competence as part of inquiry in mathematics education (Heinze et al., 2008; Lin et al., 2004; Reiss et al., 2008). Representing data by graphs (Burns, Okey, & Wise, 1985; McElhaney & Linn, 2008), visualizing data, drawing, and graphing (Gober et al., 2010; Ruiz-Primo & Furtak, 2007), or using visualizations in general (Hamilton, Nussbaum, & Snow, 1997) are also partly linked to mathematics but, without doubt, these aspects are relevant for the domains of science and technology too.

In addition, epistemological aspects were also addressed in several publications. Epistemic understanding was either regarded as domain-specific, e.g. the nature of science (Akerson & Donnelly, 2010; Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999; Khishfe, 2008; Vellom & Anderson, 1999), or as more general, e.g. epistemic understanding (Ryu & Sandoval, 2012) or the nature of modelling (Schwarz & White, 2005).

Interdisciplinary relevance is also significant for abilities such as divergent thinking and creativity (Doppelt, 2009; Kwon, Park, & Park, 2006) or critical thinking (Kim et al., 2012). However, these aspects are not only limited to the domains of STM. In fact, they are more closely related to aspects of general cognitive abilities.

Beyond these cognitive abilities, affective aspects are also addressed in certain publications, although to a smaller extent. Enjoyment, interest, value, self-efficacy (Schukajlow et al., 2012), motivation (Butler & Lumpe, 2008; Shavelson et al., 2008), and confidence (Klahr, Triona, & Williams, 2007), but also attitudes towards science (Burghardt, Hecht, Russo, Lauckhardt, & Hacker, 2010; Gibson & Chase, 2002; Lavoie, 1999; Mislter Jackson & Songer, 2000; White & Frederiksen, 1998) are analysed in relation to different aspects of inquiry.

5.2 Which types of assessment are employed in the study?

First of all, for the analysis of the assessment practices, the frequency of the assessment types used was compared between science, technology and mathematics. Table 27 shows the results. In three quarters of all studies, methods of summative assessment were employed. Methods of formative assessment were not very common among the empirical studies found, especially in science education. However, nearly 15% of the studies in science combined methods of summative and formative assessment. Furthermore, in science education, some studies dealt with embedded assessment (see Table 28). Peer- and self-assessment played a subordinate role. In combination with IBE, neither was explored very often. In contrast, rubrics were a common instrument used for the evaluation and analysis of varying assessment situations.

When comparing the results, one has to keep in mind that there were only 13 studies in technology and 30 in mathematics, but 148 in science. This made it difficult to determine subject-specific main focuses, especially in technology and mathematics.

Table 27: Assessment practices by subject

Type of assessment	Science		Technology		Mathematics	
	N	%	N	%	N	%
Summative assessment	108	73.0	10	76.9	23	76.7
Formative assessment	9	6.1	2	15.4	6	20.0
Summative and formative assessment	22	14.8	1	7.7	-	-
Neither summative nor formative assessment	9	6.1	-	-	1	3.3
Total	148	100.0	13	100.0	30	100.0

Table 28: Character of the assessment

Character of assessment	Science		Technology		Mathematics	
	N	%	N	%	N	%
Embedded assessment in combination with summative assessment	5	3.4	1	7.7	1	3.3
Embedded assessment in combination with summative and formative assessment	8	5.4	-	-	-	-
Feedback	12	8.1	-	-	2	6.7
Peer-assessment	8	5.4	1	7.7	1	3.3
Self-assessment	11	7.4	1	7.7	4	13.3
Rubrics	51	34.5	6	46.2	5	16.7

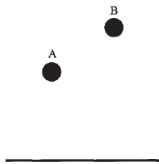
In view of the objectives, it is important to know which assessment methods are frequently employed in the studies and which assessment methods are less common. Furthermore, the purpose of the assessment methods is of importance. In the following three chapters, these aspects are addressed for every subject by analysing the purpose of each assessment method exemplarily. One has to note that the focus of the search strategy was on IBE and assessment methods. Therefore, most of the studies

using assessment methods have to be seen against the background of IBE and related aspects and competences.

5.2.1 Science

Multiple-choice items and constructed-response or open-ended items used as a summative assessment tool dominate the assessment methods in research on IBE in science education (see Table 30). The reasons are obvious as these items have many advantages. In particular, the analysis of multiple-choice items is more objective and the results are easier to compare and to interpret than other more complex assessment methods. Figure 1 shows an example from a research project in physics education by White and Frederiksen (1998) which combined both item formats for the assessment of physics knowledge.

Imagine that you drop two identical balls from different heights. Both balls are dropped at exactly the same time.



Which ball hits the floor first? (circle your choice below)

- (A) The lower ball.
- (B) The higher ball.
- (C) Both balls hit the floor at the same time.

Explain the reasons for your choice: _____

Which ball is going faster when it hits the floor? (circle your choice below)

- (A) The lower ball.
- (B) The higher ball.
- (C) Both balls are going the same speed when they hit the floor.

Explain the reasons for your choice: _____

Figure 1: A sample gravity problem from a physics test (White & Frederiksen, 1998, p. 60)

However, even though the items have advantages in view of summative assessment, they are less frequently used for formative assessment. Four studies used multiple-choice items and five studies constructed-response or open-ended items. Hickey and Zuiker (2012) provided an example of open-ended items supporting feedback conversations (see Figure 2). The explanations were the basis of the following conversations in biology learning.

Section 3A: Assessment
From Offspring Phenotypes to Mode of Inheritance I

In dragons, a single gene with two possible alleles determines visual ability. Use what you know about pedigrees to help you figure out these other things about visual ability.

female sighted

male sighted

female blind

male blind

PEDIGREE FOR VISUAL ABILITY IN DRAGONS

- 1.1 Do the alleles for visual ability show complete dominance or incomplete dominance?

- 1.2 Explain what it is about the pedigree that distinguishes between complete and incomplete dominance.
- 2.1 Is the allele for blindness dominant, recessive, or incompletely dominant to the sighted allele?
(Hint: use the circled part of the pedigree.) _____
- 2.2 Explain what it is about the circled part of the pedigree that tells you the answer, and explain why the parents and offspring that were not circled do not tell you the answer.

Figure 2: Formative assessment item on dominance relationships (Hickey & Zuiker, 2012, p. 24)

To assess students' understanding of key concepts, concept maps instead of items are often used for a summative assessment. For example, Brandstatter, Harms, and Groschedl (2012) investigate concept maps as an assessment tool for system thinking in biology education. As the process of the concept map development is quite complex, some approaches use computer-assisted methods (e. g. Schaal, Bogner, & Girwidz, 2010).

On the other hand, concept maps can be used for formative assessment. In this case, the focus lies on checking students' progress in understanding key concepts at several times during a treatment (e. g. Furtak et al., 2008). The analysis of concept maps can be organised by rubrics as shown in Table 29 (e. g. Nantawanit, Panijpan, & Ruenwongsa, 2012).

In general, it is important to train students in the procedure of making a concept map (Nantawanit et al., 2012). One possible way is the think-pair-share method: First, students make an individual map, then, they build a map in a small group, and finally, they construct a concept map as a class (e. g. Furtak et al., 2008). Another common method is to give the concepts and linking words to the students (see Figure 3). Both approaches have a more formative than summative character.

Table 29: Holistic concept mapping scoring rubric (Nantawanit et al., 2012)

Score	Content	Logic and Understanding	Presentation
5	All relevant concepts (14) of plant responses to biological factors are correct with multiple connections.	Understanding of facts and concepts of plant responses to biological factors is clearly demonstrated by correct links.	Concept map is neat, clear, and legible, has easy-to-follow links and has no spelling errors.
4	Most relevant concepts (10-13) of plant responses to biological factors are correct with multiple connections.	Understanding of facts and concepts of plant responses to biological factors is demonstrated by a few error links.	Concept map is neat, clear, and legible, has easy-to-follow links and has some spelling errors.
3	Few relevant concepts (6-9) of plant responses to biological factors are correct with two or more connections.	Understanding of facts and concepts of plant responses to biological factors is demonstrated but with some incorrect links.	Concept map is neat, legible but with some links difficult to follow and has some spelling errors.
2	Few relevant concepts (3-5) of plant responses to biological factors are correct with no connection.	Poor understanding of facts and concepts of plant responses to biological factors with significant errors.	Concept map is untidy with links difficult to follow and has some spelling errors.
1	1-2 relevant concepts are linked via the linking words.		

<u>Set of given concepts:</u>	<u>Set of linking words:</u>
Blue mussel	Becomes
Byssus	Develops
Egg	Eats
Eider duck	Protects
Human	Displaces
Larvae	Breeds
Mussel breed	Sticks together
Oyster	Lives in
Sea star	Builds
Young mussel	Warms
Worm	Pulls

Figure 3: Given concepts and linking words for the construction of a concept map in biology (Brandstädter et al., 2012, p. 2167)

The publication about the advantages of mind maps does not report any empirical data (Goodnough & Long, 2006). However, the authors state that mind mapping is a tool that can be used to ascertain students' developing ideas about scientific concepts. Furthermore, similar to concept mapping, the technique makes the exploration of prior knowledge possible, as well as an assessment of students' overall performance from the viewpoint of specific learning outcomes.

Notebooks are a science-specific assessment method used in formative assessment. They are supposed to monitor and facilitate students' understanding of complex scientific concepts and especially inquiry processes. To achieve this, the method includes the collection of student writing before, during, and after hands-on investigations (Aschbacher & Alonzo, 2006). As notebooks are an embedded part of the curriculum, they can obtain information about students' understanding at any point without needing additional time and expertise to create quizzes.

Baxter, Shavelson, Goldman, and Pine (1992) were able to confirm that notebooks are a valid tool for a summative assessment of hands-on activities. They compared the analysis of notebooks with results from an observation and from multiple-choice items. However, field observations are a more reliable tool than notebooks.

As well as notebooks or science journals, portfolios summarize the inquiry process, for example, in a laboratory or learning environment (Dori, 2003; Zhang & Sun, 2011). Portfolios are normally compiled individually to measure knowledge growth over a certain period of time. Thus, they are used for summative assessment.

Hands-on activities like experiments are often used as for performance assessment in a summative manner. They are supposed to be an alternative to more traditional paper and pencil assessment methods (Shavelson et al., 1991). However, in comparison to these methods, performance assessment requires more complex scoring or evaluation systems. Baxter et al. (1992) recommend field observations instead of notebooks.

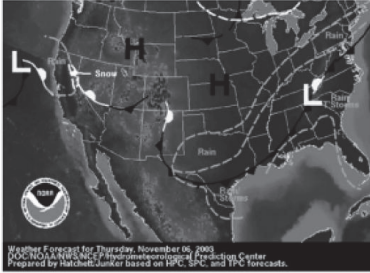
For example, Hofstein, Navon, Kipnis, and Mamlok-Naaman (2005) investigated the ability of students to ask questions related to their observations and findings in an inquiry-type experiment. Providing students with opportunities to engage in inquiry-type experiments in the chemistry laboratory improved their ability to ask high-level questions, to hypothesize, and to suggest questions for further experimental investigations (Hofstein et al., 2005). In this case, the experiments were a method to provoke a more realistic assessment situation. The purpose of the study of Kelly, Druker, and Chen (1998) was quite similar; they investigated the reasoning processes students use while solving electricity performance assessments (Kelly et al., 1998). In contrast, Ruiz-Primo, Li, Tsai, and Schneider (2010) conducted a study on various types of assessment and their advantages compared to others. With regard to performance assessment, students were asked to design and conduct an investigation to solve a problem with given materials.

There was one study which really meets the objectives of ASSIST-ME (Pine et al., 2006). By conducting a performance assessment, the inquiry skills 'planning an inquiry', 'observation', 'data collection', 'graphical and pictorial representation', 'inference' and 'explanation based on evidence' were measured.

Among the publications, quizzes were only used by one research group (Cross, Taasoobshirazi, Hendricks, & Hickey, 2008; Hickey et al., 2012; Taasoobshirazi & Hickey, 2005; Taasoobshirazi, Zuiker, Anderson, & Hickey, 2006). Ultimately, the quizzes developed by Hickey, Taasoobshirazi and Cross (2012) were a combination of multiple-choice and open-ended items (see Figure 4). Each quiz consisted of three to four two-part items, with the first part requiring a short answer, and the second part requiring an explanation to support that answer. Students completed the quizzes individually. Then, pairs of students joined with other pairs to engage in a structured argumentation review routine to discuss the answers. The questions focused on activities completed during several units of a software-based learning environment. Each quiz was aligned to the specific activities the students had completed for that particular unit.

Figure 5 shows guidelines for the feedback conversation which structured the argumentation process.

In *Weather or Not?*, you predicted the weather using satellite images and other kinds of weather maps. The weather map below shows the weather forecast for Thursday, November 6, 2003. The temperature on that day was 73°. Using the map, predict the weather in northern Georgia for **Friday, November 8, 2003**.



1a What will the weather be like on Friday?

- a low pressure system is moving in with warm temperatures
- a high pressure system is moving in with warm temperatures
- there will be a low pressure system with the possibility of rain
- there is the possibility of a cold front but it should be sunny

1b Explain your answer:

Figure 4: Activity-oriented quiz (Hickey et al., 2012, p. 1247)

Usually, conversations or discussions are carried out to enhance students' argumentation, reasoning or communication skills. Mainly, the discussions take place in small groups. These students' discussions indicate an alternative didactical approach in contrast to the more traditional discourse where the teacher dominates classroom dialogue mainly to transmit information and requires students to use oral discourse only to show acquired knowledge. In order to distinguish between the approaches, it is important to know that the term 'discourse' includes a broader set of practices than the language-intensive ones usually associated with discussion or argumentation (van Aalst & Mya Sioux Truong, 2011).

Feedback conversation guidelines as shown in Figure 5 support collective discourse (Hickey et al., 2012; Hickey & Zuiker, 2012). This approach suggests that the most valuable function of feedback is fostering participation in discourse. Furthermore, formative discussions can help students in IBE. For example, the consideration of multiple solutions can be followed by a classroom discussion in which students present their solutions, share information, reflect on things, raise questions, and receive feedback on their proposed solutions (Valanides & Angeli, 2008).

FOR EACH QUIZ ITEM

- 1. EXPLAIN AND COMPARE EACH ANSWER:**
Everybody should *share* what they wrote (provide claims) and explain why they wrote it **and** how they knew it (warrant claims using data).
- 2. REACH INITIAL CONSENSUS:**
Through evaluation of the warrants, the group should try to agree on the most sensible claim, agree to disagree, or agree that for some questions there could be multiple answers. Everyone should understand why one (or more) claims are sensible.
- 3. REVIEW ANSWER EXPLANATION:**
As a group, read aloud the answer explanation sheet. Use the written explanation and the *language of science* to provide warrants and data to help your group agree on the most sensible claims.
- 4. CONFIRM GROUP UNDERSTANDING:** Everyone should understand and agree on a final sensible claim. Take your time! It's more important that everyone understands than to finish quickly.

Figure 5: Feedback conversation guidelines (Hickey et al., 2012, p. 1248)

Apart from a formative character, one can use discussions with a more summative character with regard to the assessment. One evaluating study used students' small group discussions to address four aspects of IBE: "(a) expressing and comparing prior knowledge on a specific phenomenon or situation to create a common ground for the collaborative construction of knowledge; (b) formulating and comparing hypotheses before performing an experiment; (c) examining empirical data in the light of previous predictions; (d) and making a shared synthesis to propose a final explanation for an examined phenomenon" (Mason, 2001, p. 315). A qualitative analysis of the collected data was then carried out to analyse the collaborative discourse-reasoning.

In biology education, students are trained in discussing socio-scientific issues – such as whether to allow human gene therapy (Nielsen, 2012). This kind of issue calls for a discussion about what to do and not merely about what is true. Socio-scientific issues seem to be a good theme or opportunity for discussions. The first and final lessons of an intervention by Osborne et al. (2004) were devoted to the discussion of whether zoos should be permitted, whereas the remaining lessons were devoted solely to discussion and arguments of a scientific nature. The authors used a generic framework for the materials that supported and facilitated argumentation in the science classroom. The starting point was a table of statements on a particular topic in science which was given to students. They were asked to say whether they agreed or disagreed with the statements and argue for their choices. Based on this starting point, one can build discussions and initiate IBE learning.

Ruiz-Primo's and Furtak's (2006) approach to exploring teachers' questioning practices is based on viewing whole-class discussions as assessment conversations. Assessment conversations consist of four-step cycles: 1. The teacher elicits a question; 2. The student responds, 3. The teacher recognizes the student's response; 4. The teacher uses the information collected to assist/initiate student learning. Thus, these kinds of conversations permit teachers to gather information about the status of students' con-

ceptions, mental models, strategies, language use, or communication skills and enable them to use these to guide instruction.

Closely related to discourses, assessment conversations or accountable talks can also be employed as assessment methods, just like field notes or video tapes. As well as observations or field notes, video and audio tapes are mostly conducted as a form of summative assessment. These methods are used with a variety of purposes because they allow the measurement of certain constructs and the description of learning and teaching processes in retrospect.

Communication processes are often observed, for example, to assess students' argumentation within discussions or classroom interaction (e. g. Abi-El-Mona & Abd-El-Khalick, 2006; Lavoie, 1999). Moreover, observations provide records of the order in which students carried out certain activities in learning environments and the time they spent on these activities (e. g. Hamilton et al., 1997; Kubasko, Jones, Tretter, & Andre, 2008). For some reasons, it is necessary to combine both purposes. For example, in the study of Harskamp, Ding and Suhre (2008) the observers' task was to use observation log files to document and log individual student's time on the task, as well as cooperative actions and the type of interaction.

The application of video and audio tapes aims more at the observation and analysis of learning and teaching processes than at the assessment of learning or teaching outcomes (Valanides & Angeli, 2008), even though they are generally used for summative assessment. Moreover, they are used as a further tool in addition to other research methods or in explicit combination with other tools, e.g. field notes, written materials or multiple-choice pre- and post-tests (e. g. Vellom & Anderson, 1999). Which tool is used depends on the objectives and design of the study.

The time scale of video or audio-taped classroom or learning environment interaction varies. Some studies collected data daily from whole class sessions for longer periods. However, some studies only collected data from selected student groups for a few hours (e. g. Southerland, Kittleson, Settlege, & Lanier, 2005).

In order to achieve a deeper analysis, video or audio tapes are usually transcribed using repeated viewings or hearings of video or audio segments (e. g. Aguiar et al., 2010). Sometimes, annotations about important contextual factors such as actions, gestures, and other classroom interactions were added to the transcripts (e. g. Vellom & Anderson, 1999).

One major purpose of video and audio tapes is the observation of class or group interaction, discussions or dialogues (Schnittka & Bell, 2011; Southerland et al., 2005). For example, Shemwell and Furtak (2010) investigated the quality of argumentation in classroom discussion by analysing the support of argumentation by evidence. In another study, McNeill (2009) analysed the instructional practices teachers use to introduce scientific explanations by videotaping classroom interaction. Another purpose is the observation of students' performance in a certain task (Sampson, Grooms, & Walker, 2011).

In cases in which only audio tapes were used, the focus was on the talk especially on the amount of on/off task talk and the categorization of task talk (Cavagnetto et al., 2010). Chin and Teou (2009) audiotaped conversation from one group to provide a record of students' thinking in a form that was accessible to the teacher for monitoring and feedback purposes. This is an example of a formative use of audio tapes. Students' assertions and questions had formative potential as they encouraged discourse by drawing upon each other's ideas.

Even though there are so many publications that include video and audio tapes, the purpose of their use and the way in which they can be analysed often remain unclear (e. g. Harris, McNeill, Lizotte, Marx, & Krajcik, 2006; Tytler, Haslam, Prain, & Hubber, 2009). Obviously, video and audio tapes provide background information that is not described and explained in detail.

In addition, field notes are a method which combines both observations and video or audio tapes. For instance, they provide general descriptions of the most salient instructional events during an observed session (e. g. Abi-El-Mona & Abd-El-Khalick, 2006) or provide information about events that occur outside the range of a video camera (e. g. Ryu & Sandoval, 2012). Furthermore, field notes can be taken as events unfold, and recorded with time indices for later matching with video segments (e. g. Vellom & Anderson, 1999). However, in view of performance assessment, notebooks are a reliable tool that can be used for formative teacher feedback (Ruiz-Primo et al., 2004).

Appendix A. Interview questions that elicited argument

Actual questions from interview transcripts included:

- What do you think about biotechnology?
- Can you tell me about any problems that might come from biotechnology?
- What are your feelings about cloning?
- Can you see any other problems with cloning?
- What about cloning of extinct animals or endangered species?
- Can you tell me about any problems with genetics engineering?
- What do you feel about genetically modified (GM) foods?
- Do you have any views on forensic testing?

Figure 6: Examples of questions for a semi-structured interview (Dawson & Venville, 2009, p. 1445)

Similar to any kind of observation, the objectives of interviews are also manifold and, similar to field notes, they are an additional tool that is usually combined with other methods such as observation, video tapes (e. g. Berland, 2011) or audio tapes (e. g. Dawson & Venville, 2009). Interviews are an assessment and research method that is usually qualitatively analysed. Therefore, in most of the studies, only some students from the total samples were interviewed in order to acquire additional information on the explored aspects. For example, after responding to a questionnaire, students were asked to explain their answers in order to gather information about existing misconceptions (White & Frederiksen, 1998). Furthermore, pre- and post-interviews provide another possibility for evaluating the intervention part of a case study (Berland, 2011).

A possibility which makes interviews and especially their content more comparable is the realization of semi-structured interviews, as they were conducted by Dawson and Venville (2009) who, for example, asked questions about students' understanding and views of biotechnology, cloning, and genetic testing for diseases.

Ash (2008) gives an example of how interviews can be used as a kind of formative assessment. An interviewer provided biological dilemmas as thought experiments, described the context, and then asked questions. The formative character was introduced by further questions or hints: After the student had answered, the interviewer provided a hint if the student was on the wrong track or a challenge if the student gave an appropriate answer. The hint determined what a student might achieve with appropriate help, while the challenge helped determine whether understanding was robust. The goal was to measure students' competence in solving biological dilemmas (Ash, 2008). Unfortunately, the purposes of the interviews were often not explained in detail within the publications (e. g. Tytler et al., 2009). Therefore, it is difficult to provide a detailed overview.

Artefacts are used quite rarely as an assessment method for research on IBE in STM. Only two publications referred to their use when collected as written material (Harris et al., 2006; Kyza, 2009).

Rubrics are a common tool for the analysis of several assessment methods, as described above. Figure 7 shows another example which illustrates the use of rubrics in students' self-assessment to enhance students' self-reflection with regard to the learning process.




RUBRIC FOR SELF ASSESSMENT (ACTIVITY 13 – INITIAL IDEA GENERATION) My name and surname: _____ Date of self assessment: _____ Be honest with yourself and indicate if you could do activity 13. Cross (X) the dog of your choice. The first dog indicates that you could easily do the work. The second dog indicates that the work was a bit difficult but that you completed it satisfactory. The third dog indicates that you could not do the work at all.			
Stage outcomes for activity 13 Consider as many as possible solutions for the problem (Specifically look at the three possible solutions you have generated)	I assess myself		
			
RUBRIC FOR SELF ASSESSMENT (ACTIVITY 13 – INITIAL IDEA GENERATION) My name and surname: _____ Date of self assessment: _____ Be honest with yourself and indicate if you could do activity 13. Cross (X) the face of your choice. The meaning of each face is explained with each statement.			
I assess myself			
Consider as many as possible solutions for the problem (Specifically look at the three possible solutions you have generated)			
No solutions for the problem is considered ☹	One or two good solutions for the problem are considered 😐	One, two or three excellent solutions for the problem are considered 😊	

Figure 7: Assessment rubric for self-assessment (van Niekerk, Piet Ankiewicz, & Swardt, 2010, p. 213)

Table 30: Frequency of assessment methods in the studies from the field of science education

Assessment method	SA [M]	References	FA [M]	References
Multiple-choice	63	<p>Acar & Tarhan, 2007; Baxter et al., 1992; Blanchard et al., 2010; Burns, Okey, & Wise, 1985; Chen & Klahr, 1999; Cobern et al., 2010; Cross et al., 2008; Ding & Harskamp, 2011; Dori & Herscovitz, 1999; Ebenezzer et al., 2011; Furtak & Ruiz-Primo, 2008; Geier et al., 2008; Gerard, Spitulnik, & Linn, 2010; Gibson & Chase, 2002; Gijlers & Jong, 2005; Gotwals & Songer, 2009; Hamilton et al., 1997; Harris et al., 2006; Hickey et al., 2012; Hmelo, Holton, & Kolodner, 2000; Jang, 2010; Ketelhut & Nelson, 2010; Kyza, 2009; Lavole, 1999; Lee & Liu, 2010; Lee, Brown, & Orrill, 2011; Linn, 2006; Liu, Lee, & Linn, 2011; Liu, O. L., Lee, H.-S., & Linn, M. C., 2010a; Liu, O. L., Lee, H.-S., & Linn, M. C., 2010b; Mattheis & Nakayama, 1988; McNeill & Krajcik, 2007; McNeill, 2009; Mistler Jackson & Songer, 2000; Nantawanit et al., 2012; Oh et al., 2012; Osborne, Simon, Christodoulou, Howell-Richardson, & Richardson, 2013; Pfiarre, 2010; Pine et al., 2006; Repenning, Ioannidou, Luhn, Daetwyler, & Repenning, 2010; Rivet & Kastens, 2012; Rivet & Krajcik, 2004; Ruiz-Primo & Furtak, 2006; Ruiz-Primo & Furtak, 2007; Ruiz-Primo et al., 2010; Ruiz-Primo et al., 2012; Ryu & Sandoval, 2012; Schneider et al., 2002; Schnittka & Bell, 2011; Schwarz & White, 2005; Shavelson et al., 1991; Shavelson et al., 2008; Shymansky, Yore, & Anderfson, 2004; Silk et al., 2009; Simons & Klein, 2007; Spires, Rowe, Mott, & Lester, 2011; Steinberg, Cormier, & Fernandez, 2009; Taasobshirazi & Hickey, 2005; Taasobshirazi et al., 2006; Tsai, Hwang, Tsai, Hung, & Huang, 2012; Wilson et al.,</p>	4	<p>Aschbacher & Alonzo, 2006; Birchfield & Megowan-Romanowicz, 2009; Hickey et al., 2012; White & Frederiksen, 1998</p>

		2010; Wong & Day, 2009; Young & Lee, 2005; Zion et al., 2005		
Constructed-response / Open-ended	65	Acar & Tarhan, 2007; Brown et al., 2010; Ding & Harskamp, 2011; Dori, 2003; Dori & Herscovitz, 1999; Furtak & Ruiz-Primo, 2008; Geier et al., 2008; Gerard et al., 2010; Gijlers & Jong, 2005; Gobert et al., 2010; Gotwals & Songer, 2009; Hamilton et al., 1997; Harris et al., 2006; Harskamp et al., 2008; Hickey et al., 2012; Hickey & Zuiker, 2012; Hmelo et al., 2000; Jang, 2010; Kaberman & Dori, 2009; Khishe, 2008; Kubasko et al., 2008; Kyza, 2009; Lee & Liu, 2010; Lee et al., 2011; Lin & Mintzes, 2010; Linn, 2006; Liu et al., 2011; Liu, O. L. et al., 2010a; Liu, O. L. et al., 2010b; Lorenzo, 2005; Lubben et al., 2010; Mason, 2001; Mattheis & Nakayama, 1988; McElhanev & Linn, 2008; McNeill & Krajcik, 2007; McNeill, 2009; McNeill, 2011; Mistler Jackson & Songer, 2000; Pifarre, 2010; Rivet & Kastens, 2012; Rivet & Krajcik, 2004; Ruiz-Primo et al., 2010; Ryu & Sandvoal, 2012; Schneider et al., 2002; Schwarz & White, 2005; Shavelson et al., 1991; Shavelson et al., 2008; Shermwell & Furtak, 2010; Shymansky et al., 2004; Siegel, Hynds, Siciliano, & Nagle, 2006; Simons & Klein, 2007; Stecher et al., 2000; Steinberg et al., 2009; Tsai et al., 2012; Valanides & Angelli, 2008; van Aalst & Mya Sioux Truong, 2011; Veal & Chandler, 2008; Wilson & Sloane, 2000; Wilson et al., 2010; Winters & Alexander, 2011; Wirth & Klieeme, 2003; Wong & Day, 2009; Yoon, 2009; Young & Lee, 2005; Zion et al., 2005	5	Hickey et al., 2012; Hickey & Zuiker, 2012; van Niekerk et al., 2010; White & Frederiksen, 1998; Wilson & Sloane, 2000
Concept map	8	Brandstädter et al., 2012; Brown et al., 2010; Butler & Lumpe, 2008; Dori, 2003; Nantawanit et al., 2012; Schaal et al., 2010; Vasconcelos, 2012; Yin, Vanides, Ruiz-Primo, Ayala, & Shavelson, 2005	3	Furtak & Ruiz-Primo, 2008; Furtak et al., 2008; Okada & Shum, 2008; Yin et al., 2005

Mind map	1	Goodnough & Long, 2006	-	-
Portfolios	2	Dori, 2003; Zhang & Sun, 2011	-	-
Notebook	8	Baxter et al., 1992; Kelly et al., 1998; Ruiz-Primo et al., 2004; Ruiz-Primo, Shavelson, Hamilton, & Klein, 2002; Ruiz-Primo et al., 2010; Shavelson et al., 1991; Simons & Klein, 2007; So, 2003	4	Aschbacher & Alonzo, 2006; Tyler et al., 2009; van Niekerk et al., 2010; White & Frederiksen, 1998
Effective questioning	-	-	2	Chin & Teou, 2009; Wong & Day, 2009
Discourse / assessment conversations/ accountable talk	10	Lyon, Bunch, & Shaw, 2012; Mason, 2001; Nielsen, 2012; Osborne, Erduran, & Simon, 2004; Reyes, 2008; Ruiz-Primo & Furtak, 2006; Ruiz-Primo & Furtak, 2007; van Aalst & Mya Sioux Truong, 2011; Winters & Alexander, 2011; Zhang & Sun, 2011	4	Chen & Klahr, 1999; Hickey et al., 2012; Hickey & Zuiker, 2012; Valanides & Angeli, 2008
Quizzes	1	Cross et al., 2008	3	Hickey et al., 2012; Taasobshirazi & Hickey, 2005; Taasobshirazi et al., 2006
Performance assessment / experiments	13	Baxter et al., 1992; Hofstein et al., 2005; Kelly et al., 1998; Lyon et al., 2012; McElhaneey & Linn, 2011; Pine et al., 2006; Ruiz-Primo et al., 2002; Ruiz-Primo et al., 2010; Schneider et al., 2002; Shavelson et al., 1991; Shavelson et al., 2008; Stecher et al., 2000	2	Chen & Klahr, 1999; Sampson et al., 2011
Interviews	24	Acar & Tarhan, 2007; Akerson & Donnelly, 2010; Berland & Reiser, 2009; Berland, 2011; Carruthers & Berg, 2010; Dawson & Verville, 2009; Gibson & Chase, 2002; Gijlers & Jong, 2005; Gotwals & Songer, 2009; Hamilton et al., 1997; Himelo et al., 2000; Jang, 2010; Khistife, 2008; Kim & Song, 2006; Lin & Mintzes, 2010; Mistler Jackson & Songer, 2000; Schnittka & Bell, 2011; Schwarz & White, 2005; Sutherland et al., 2005; van Niekerk et al., 2010; Veal & Chandler, 2008; Vellom & Anderson, 1999; White & Frederiksen, 1998; Wilson et al., 2010	3	Ash, 2008; Goodnough & Long, 2006; Tyler et al., 2009

Observation / field notes	13	Abi-Ei-Mona & Abd-Ei-Khalick, 2006; Aguiar et al., 2010; Carruthers & Berg, 2010; Hamilton et al., 1997; Harskamp et al., 2008; Kubasko et al., 2008; Lavoie, 1999; Mistler Jackson & Songer, 2000; Ryu & Sandoval, 2012; Southerland et al., 2005; Valanides & Angeli, 2008; van Niekerk et al., 2010; Vellom & Anderson, 1999	3	Goodnough & Long, 2006; Harris et al., 2006; Tyler et al., 2009
Video tapes / audio tapes	25	Abi-Ei-Mona & Abd-Ei-Khalick, 2006; Aguiar et al., 2010; Berland & Reiser, 2009; Berland, 2011; Birchfield & Megowan-Romanowicz, 2009; Cavagnetto et al., 2010; Chen & Klahr, 1999; Chen & Looi, 2011; Chin & Osborne, 2010; Erduran, Simon, & Osborne, 2004; Harris et al., 2006; Kelly et al., 1998; Kim & Song, 2006; Kubasko et al., 2008; Kyza, 2009; McNeill, 2009; Mistler Jackson & Songer, 2000; Ryu & Sandoval, 2012; Sampson et al., 2011; Schnittka & Bell, 2011; Shemwell & Furtak, 2010; Southerland et al., 2005; Taasobshirazi & Hickey, 2005; Valanides & Angeli, 2008; Vellom & Anderson, 1999	6	Ash, 2008; Chin & Teou, 2009; Furtak & Ruiz-Primo, 2008; Furtak et al., 2008; Tyler et al., 2009; White & Frederiksen, 1998
Questionnaires	8	Brandstädter et al., 2012; Butler & Lumpe, 2008; Kim & Song, 2006; McNeill, 2009; Mistler Jackson & Songer, 2000; Shavelson et al., 2008; Southerland et al., 2005; Winters & Alexander, 2011	-	-
Artefacts	2	Harris et al., 2006; Kyza, 2009	-	-

5.2.2 Technology

In total, empirical studies on IBE and assessment methods in technology education are rare. Obviously, in contrast to science and mathematics education, this research field is not particularly dominant. One reason is that technology is not a common subject in European schools (see D 2.3, National reports of partner countries reviewing research on formative and summative assessment in their countries) or in American schools.

Table 31: Frequency of assessment methods in the studies from the field of technology education

Assessment method	SA [N]	References	FA [N]	References
Multiple-choice	3	Burghardt et al., 2010; Doppelt, 2003; Klahr et al., 2007	-	-
Constructed-response / Open-ended	6	Burghardt et al., 2010; Doppelt, 2003; Fox-Turnbull, 2006; Klahr et al., 2007; Mioduser & Betzer, 2007; Merrill, Custer, Daugherty, Westrick, & Zeng, 2008	-	-
Portfolios	2	Doppelt, 2009; Williams, 2012	3	Barak & Doppelt, 2000; Doppelt, 2003; Hong et al., 2011
Discourse / assessment conversations / accountable talk	1	MacDonald & Gustafson, 2004	-	-
Performance assessment / experiments	2	Mioduser & Betzer, 2007; Williams, 2012	-	-
Interviews	1	Davis et al., 2002	2	Barak & Doppelt, 2000; Doppelt, 2003
Observation / field notes	2	Doppelt, 2003; Doppelt, 2009	1	Barak & Doppelt, 2000
Audio tapes	1	Gustafson et al., 2007	-	-
Questionnaires	1	Doppelt, 2003	-	-

With regard to summative assessment, the most important methods are, similar to science education, constructed-response or open-ended items and multiple-choice items (see Table 31). In most cases, they were used for the assessment of knowledge, achievement or understanding. Furthermore, they measured students' motivation or attitudes towards technology (Burghardt et al., 2010; Doppelt, 2003; Klahr et al., 2007).

When looking at formative assessment, the most important methods are portfolios and interviews (see Table 31). Obviously, the advantage of portfolios is their ability to reconstruct a process when solving a problem or designing a prototype (Barak & Doppelt, 2000; Doppelt, 2003; Hong et al., 2011).

Interviews should usually follow guidelines. Davis, Ginns and McRobbie (2002, p. 39) give examples of questions designed to probe the students' understandings of materials and stability:

- "Tell me as much as you can about this object, what it is, how it is made, and what it is made out of. (At the same time students were shown an artifact such as a model bridge constructed out of wood.)
- If you were building this bridge [type] to carry cars and/or pedestrians, what material(s) would you build it out of and why?
- Is this bridge stable? If not, explain how you would make it more stable.
- How do the changes you have suggested make the bridge more stable?"

One major field of research is problem- or project-based learning. In the first case, the starting point is the presentation of a technical problem (see Figure 8). Students have to find an answer and consider alternative solutions (Fox-Turnbull, 2006). In the second case, the starting points are the presentation of a target setting and of materials which can be used to reach this target (see Figure 9). One of the studies focused on the comparison between a hands-on and a virtual construction of a prototype (Klahr et al., 2007).

Help Me Peel

The photo shows a person who's wanting to peel a potato.
It is very hard because the person can only use one hand.
The other hand is in plaster.
This person needs to have a way for making it easier to peel a potato.

1. Draw a plan of your idea for something to make it easier to peel a potato.
2. On your plan, write how your idea makes it easier to peel a potato.




Figure 8: Help me peel task and photo (Fox-Turnbull, 2006, p. 59)

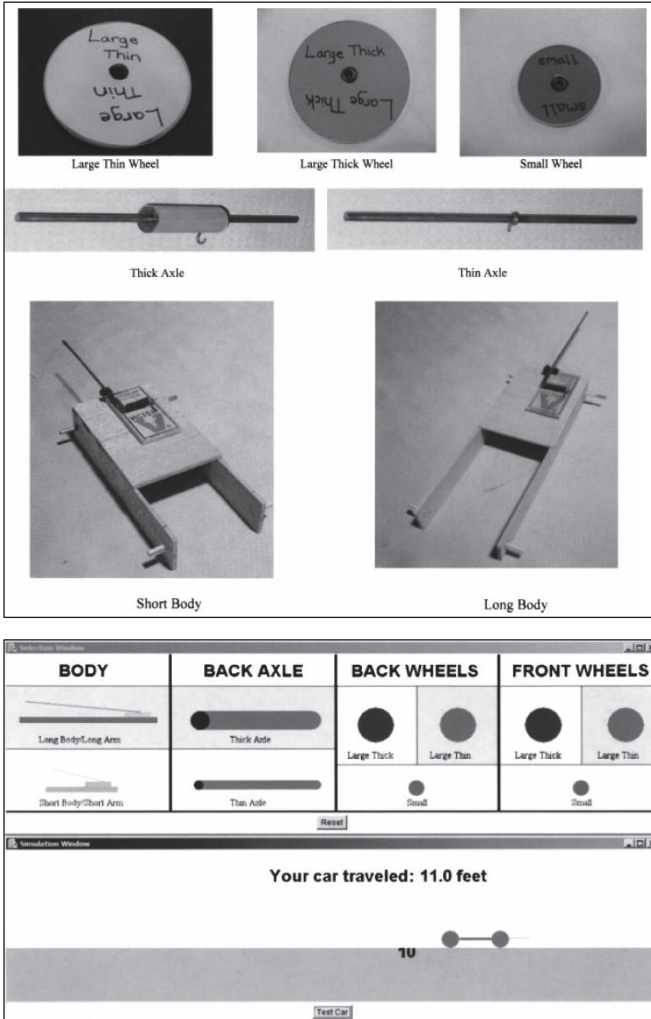


Figure 9: Hands-on and virtual mousetraps (Klahr et al., 2007, pp. 188–189)

The reported studies did not use the methods concept map, mind map, learn log, notebook, effective questioning, heuristics, quizzes, video tapes, written materials, or artefacts.

5.2.3 Mathematics

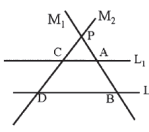
In mathematics, the emphases lay on constructed-response or open-ended items - especially for a summative assessment (see Table 32). The purpose of the items was often the evaluation of an intervention by a pre-post-design. The items ascertained students' reasoning or problem-solving skills and their mathematical knowledge.

Table 32: Frequency of assessment methods in the studies from the field of mathematics education

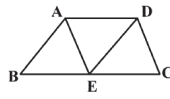
Assessment method	SA [N]	References	FA [N]	References
Multiple-choice	2	Bouck & Kulkarni, 2009; Reys et al., 2003	1	Cross, 2009
Constructed-response / open-ended	14	Boesen et al., 2010; Bouck & Kulkarni, 2009; Britt & Irwin, 2008; Chang et al., 2012; Heinze et al., 2008; Knuth, Alibali, McNeil, Weinberg, & Stephens, 2005; Kwon et al., 2006; Liedtke, 1999; Lin et al., 2004; Reiss et al., 2008; Reys et al., 2003; Rubel, 2007; Wood & Sellers, 1997; Zhang et al., 1999	3	Phelan et al., 2012; Ross, Hogaboam-Gray, & Rolheiser, 2002; Tzur, 2007
Portfolios	1	Koretz, 1998	-	-
Discourse / assessment conversations / accountable talk	3	Martin, McCrone, Bower, & Dindyal, 2005; Pijls, Dekker, & van Hout-Wolters, 2007; Woods et al., 2006	1	Tzur, 2007
Performance assessment / experiments	1	Linn, Burton, DeStefano, & Hanson, 1995	-	-
Interviews	1	Boaler, 1998	1	Ai, 2002
Observation / field notes	1	Boaler, 1998	2	Ai, 2002; Tzur, 2007
Video tapes / audio tapes	2	Chiu, 2008; Webb, Nemer, & Ing, 2006	2	Tzur, 2007; Woods et al., 2006
Questionnaires	3	Boaler, 1998; Chiu, 2008; Schukajlow et al., 2012	-	-
Artefacts	-	-	1	Tzur, 2007

The use of constructed-response or open-ended items is not surprising as, in mathematics education, students usually have to calculate and write down the calculation or prove and explain a given problem. Among the studies, Heinze et al. (2008) gave examples of test items which measure students' proof competence (see Figure 10). Knuth et al. (2005) also gave examples of test items (see Figure 11). Both studies illustrate the character of this assessment method. The example from Schukajlow et al. (2012) focused more on the assessment of problem-solving skills (see Figure 12).

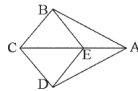
In contrast to science and technology education, multiple-choice items are less common in mathematics education. It is assumed that they would simplify the tests by providing different answer options. Therefore, they are not suitable for the assessment of problem-solving skills.



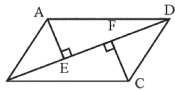
11. L_1 is parallel to L_2 . M_1 intersect L_1 and L_2 at A, B. M_2 intersect L_1 and L_2 at C, D. M_1 intersect M_2 at P, and $PA=PC$. Prove that $AB=CD$



12 Line BC. ABE is congruent to DEC. Prove that AB is parallel to DE.



13 A, E, C lies on a line. $\triangle ABC$ is congruent to $\triangle ADC$. Prove that $BE=DE$



14 In the parallelogram ABCD. AE is perpendicular to BD and CF is perpendicular to BD. Prove that $AE=CF$

Figure 10: The items of the pre-test (Heinze et al., 2008, p. 448)

Is the number that goes in the the same number in the following two equations? Explain your reasoning.

$2 \times \square + 15 = 31$ $2 \times \square + 15 - 9 = 31 - 9$

Figure 11: Using the concept of mathematical equivalence (Knuth et al., 2005, p. 70)

Football Pitch

Trainer Manfred would like to carry out a diagonal run with his team. To do so he would like to know how long the diagonal of the football pitch is. Can you help him?

Calculate the length the diagonal of the football pitch.

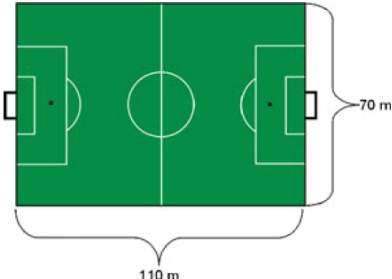


Figure 12: "Dressed up" world problem "football pitch" (Schukajlow et al., 2012, p. 225)

Another emphasis lay on the observation of lessons or learning situations by observations, field notes, video tapes and audio tapes. The application of these methods was not described in detail. As these methods were used in a more qualitative way, the focus of the respective publications was on the description of the observed learning or teaching processes (e. g. Boaler, 1998). Other studies focused on the analysis of discourse, assessment conversations or accountable talk in connection with collaborative learning (e. g. Pijls et al., 2007).

The methods concept map, mind map, learn log, notebook, effective questioning, heuristics, quizzes and written materials were not used within the context of the studies found. Admittedly/In fact/Indeed, these methods are more suitable for a formative assessment (s. Chapter 2). Obviously, there is a need for more research on formative assessment in connection with IBE in mathematics learning.

The GPAR reflection sheets are different from all other methods. They ask students to write responses to the questions presented in Figure 13 (Brookhart, Andolina, Zuza, & Furman, 2004). Students have to reflect on their learning process. Therefore, this method is useful in view of formative assessment.

GOAL – What did you want to learn? [space provided] LOCATION – Right now I can do ___ facts in five minutes. PLAN – My goal is to get ___ /100 facts on my next test. I need to improve in [space provided] ACTION – When will you begin? Starting ___ I will use these study strategies to improve (study flashcards, play multiplication games, study with parents, etc.) [space provided] I will use these problem-solving strategies to improve (write a number sentence, use repeated addition, draw a picture, make a model, array) [space provided] RESULTS – Did you follow through with your plan? What happened? Did you see improvements? [space provided]
Plan for Learning Multiplication Facts My last test score was ___ /100 Reflection To learn my multiplication facts last week, I [space provided] How well did this plan work for me? terrible not well o.k. pretty well great Why did or didn't my plan work? Prediction I want to try to score ___ /100 next week. This week to help me improve I will use these strategies: [space provided] This face shows how I feel about multiplication: (draw a face below) [space provided]

Figure 13: Goals, Plan, Action and Reflection sheet in original and revised version (Brookhart et al., 2004, pp. 216–217)

6. Perspectives

This report is intended to give an overview of the current state of the art in formative and summative assessment in IBE in STM. Instruments for the summative and formative assessment of IBE are described for each subject as far as they have been found by the different search strategies, as far as they exist and as far as they have been investigated. The results of this literature review are limited by the chosen keywords and search strategies. For example, IBE is not a common approach in mathematics education. This might be the reason why there are only few publications in mathematics education. Another reason might be that the common approach of problem-solving is not included as a keyword in the list of relevant keywords. This is a serious restriction which has to be made.

Nevertheless, the literature review reveals some subject-specific emphases, especially in science education. For this subject, half of the publications found report the use of multiple-choice items. Constructed-response and open-ended items are used by half of the empirical studies. However, in both cases, the only purpose of the methods is summative assessment. All other assessment instruments are only used in science education research quite rarely. Subject-specific instruments are mapping techniques like concept mapping.

In technology education, as well as in mathematics education, the emphases lay on constructed-response and open-ended items. In technology education, portfolios were also used. They play an important role in assessing constructing processes.

In view of the assessment type, the emphasis lies on summative assessment. Compared to summative assessment, formative assessment is an aspect that is only investigated in a few studies. All in all, there is not much variation observed with respect to the employed assessment instruments.

In a certain way, there is also not much variation observed in view of IBE. In order to make this result visible, a network for each subject was created with R (R Core Team, 2013) and the *igraph* package (Csardi & Nepusz, 2006). Figure 14, Figure 15 and Figure 16 show the relations between several aspects of IBE. The size of the circles thereby represents the number of publications investigating a certain aspect of IBE. The figures thus allow for the identification of the so-called 'hot spots' of inquiry for each subject. Obviously, the aspect 'constructing and critiquing arguments or explanations, argumentation, reasoning, and using evidence' is the aspect that is most often focused on or investigated in the field of IBE. In science education, it is followed by 'debating with peers and communication', 'collecting and interpreting data', 'planning investigations', 'diagnosing problems and identifying questions', 'evaluating results' and 'formulating hypotheses'. Thus, these are the core aspects of scientific inquiry whereas 'considering alternatives' is less significant.

In technology education, IBE covers fewer aspects. The considered ones are much more knotted than in science education because the net looks much more regular and has not a single dominating node. In mathematics education, 'searching for generaliza-

tions', 'creating mental representations' and 'evaluating results' are the most prominent aspects of IBE.

Furthermore, the results of the literature review and the three figures indicate that there are 'blind spots'. These are aspects of IBE or methods of formative and summative assessment that are more or less not assessed at all or they are assessment methods that are used very seldom.

However, because the specific focus of the ASSIST-ME project is on the relation between aspects of inquiry and assessment methods, further research within the project is necessary to investigate these 'blind spots'. The three figures give a first impression of the content of the prospective recommendation report. The forthcoming report D 2.7 will – on the basis of all previous reports of WP 2 – emphasize this issue by answering the following questions: Do aspects of inquiry exist that should be preferably assessed by a specific assessment method? Or, vice versa, are certain assessment methods particularly suited for assessing certain aspects of inquiry? Thus, D 2.7 will present the connections between aspects of IBE in STM and formative and summative assessment methods.

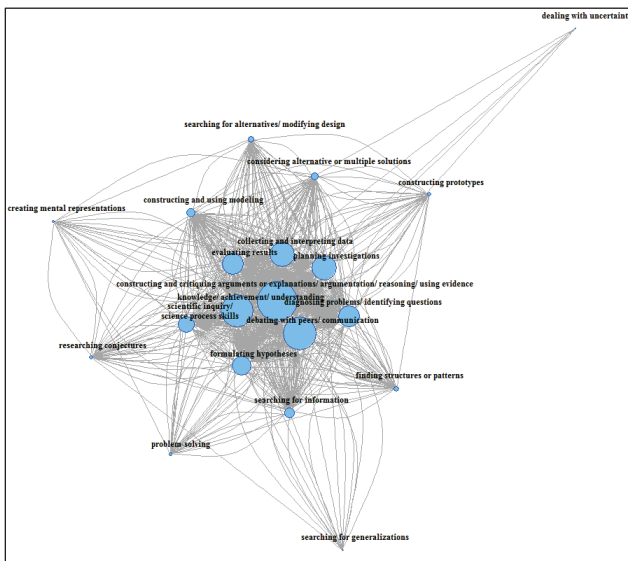


Figure 14: 'hot spots' of inquiry in science education

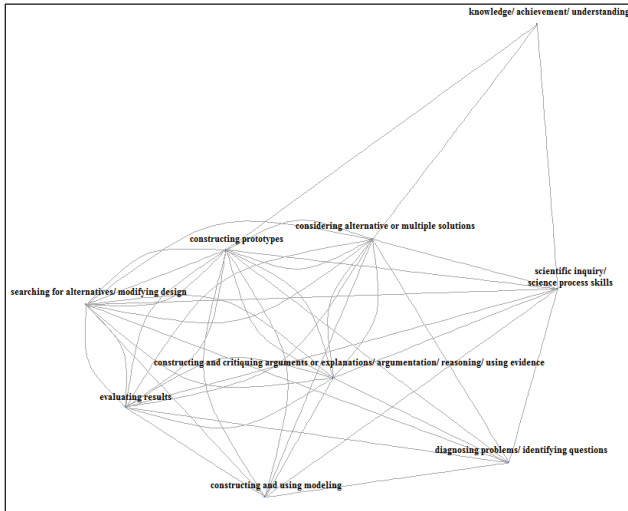


Figure 15: 'hot spots' of inquiry in technology education

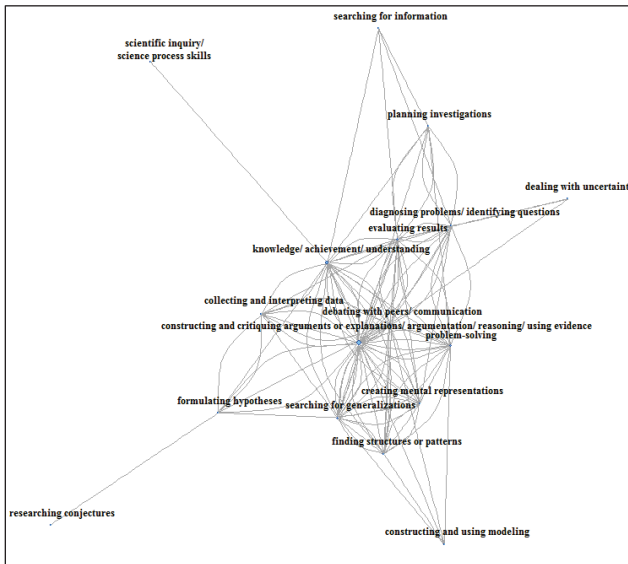


Figure 16: 'hot spots' of inquiry in mathematics education

7. Appendix

7.1 Frameworks of inquiry competences and/or assessment

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7.2 Computer-supported inquiry learning environments and computer-based assessment tools

Name	Description	Reference(s)
Web of Inquiry (WOI)	Selection of web inquiry projects (WIPs); no special focus on assessment	Herrenkohl, Tasker, & White, 2011; Molebash, no date
Web-based Inquiry Science Environment (WISE)	e.g. provides electronic student notebooks; learners are asked at several points to think about questions that challenge them to reflect more deeply, to see things from another perspective, or to apply knowledge built in the preceding section; the student answers about the project are saved in the notebook and can be reviewed as a whole at any time by the student or by the teacher for assessment purposes; includes different assessment tools (pre/post, embedded) to assess interpreting and constructing graphs, reasoning using data/evidence, explaining, and experimentation strategy (using log files); empirical study showed large, significant gains for WISE students	Bell, Urhahne, Schanze, & Ploetzner, 2010; Linn, Clark, & Slotta, 2003; McElhaney & Linn, 2008; University of Berkeley, 2013
Modeling Across the Curriculum (MAC)	e.g. BioLogica, a hypermodel, interactive environment for learning genetics; traces of students' actions and responses to computer-based tasks are electronically collected (log files) and systematically analysed	Buckley et al., 2004
Collaborative Laboratories across Europe (Co-Lab)	e.g. self-evaluation by process displays/prompts; reflective notebooks; long instructional Co-Lab units allow teachers to evaluate the inquiry process skills of individual students more effectively	van Joolingen, Jong, Lazonder, Savelsbergh, & Manlove, 2005; Urhahne, Schanze, Bell, Mansfield, & Holmes, 2010
ThinkerTools Curriculum	Overview of computer-supported learning environments inquiry curriculum centres around a metacognitive model of research, called the Inquiry Cycle, and a metacognitive process, called Reflective Assessment, in which students reflect on their own and each other's inquiry	Bell et al., 2010 White & Frederiksen, 1998

DIAGNOSER	analyses facets of students' thinking; description of facets can be used as scoring guide	Pellegrino, Baxter, & Glaser, 1999; Pellegrino, Chudowsky, & Glaser, 2001
SimScientist	simulation-based science assessments designed to serve formative purposes during a unit and to provide summative evidence of end-of-unit proficiencies; evidence-centred assessment design and model-based learning shaped assessments; IRT analyses demonstrated the high psychometric quality (reliability and validity) of the assessments and their discrimination between content knowledge and inquiry practices. Students performed better in the interactive, simulation-based assessments than in static, conventional items in a post-test. Importantly, gaps between the performance of the general population and English language learners and the students with disabilities were considerably smaller in the simulation-based assessments than in the post-tests	Quellmalz & Pellegrino, 2009; Quellmalz, Timms, Silbergliitt, & Buckley, 2012
Calipers project: Using Simulations to Assess Complex Science Learning	developed assessment designs and prototypes that can take advantage of technology to bring high-quality assessments of complex performances into science tests with either accountability or formative goals	Quellmalz et al., 2007; Quellmalz, Timms, & Buckley, 2010
	Role of games and simulations in science assessments; description of several interactive environments, e.g. SimScientist, Calipers II, IMMEX (Interactive Multimedia Exercises), River City, Crystal Island	Honey & Hilton, 2011

Viten	e.g. provides electronic student notebooks; learners are asked at several points to think about questions that challenge them to reflect more deeply, to see things from another perspective, or to apply knowledge built in the preceding section. The student answers about the project are saved in the notebook and can be reviewed as a whole at any time by the student or by the teacher for assessment purposes; allows teachers to give electronic feedback to students via an assessment tool judged helpful by teachers and students; students are asked to show communication/argumentation skills by a role-play debate in a TV discussion programme; communication data is logged thus offering teachers the possibility to look it up later for coaching or assessment purposes	Bell, Urrhahne, Schanze, & Ploetzner, 2010; Jorde, Strømme, Sorborg, Erlfien, & Mork, 2003
Multi-User Virtual Environment (MUVE) River City	In this environment, middle school students collaboratively solve problems about disease in a virtual town called River City; results indicate that students were able to conduct inquiry in virtual worlds and were motivated by that process; however, results from assessments vary depending on the assessment strategy employed; also assessment of student engagement and influence of student self-efficacy on inquiry	e.g. Kettelhut, Nelson, Clarke, & Dede, 2010; Kettelhut & Nelson, 2010; Kettelhut, 2007
ASSISTments	ASSISTments is a free online platform that allows teachers to write and select questions, students to get immediate and useful tutoring, and teachers to receive instant reports to help inform their classroom instruction	Worcester Polytechnic Institute, 2013
	validity of computer-automated scoring	Clauser, Kane, & Swanson, 2002

	intelligent argumentation assessment system for computer-supported cooperative learning: is effective in classifying and improving students' argumentation level and assisting the students in learning the core concepts at primary school	Huang et al., 2011
Berkeley Evaluation and Assessment research (BEAR) – assessment system		Wilson & Scalise, 2003; Wilson & Sloane, 2000
Formative Assessment in Science Teaching (FAST) homepage	Hosts output from the FAST project, e.g. case studies, resources, and investigative tools (e.g. feedback coding scheme, assessment experience questionnaire)	Brown, 2008; The Open University & Sheffield Hallam University, 2008
Principled Assessment Designs for Inquiry (PADI) homepage	Uses evidence-centred design framework; aims to provide a practical, theory-based approach to developing quality assessments of science inquiry by combining developments in cognitive psychology and research on science inquiry with advances in measurement theory and technology	SRI International, 2007

7.3 Assessment instruments

Name	Description	Reference(s)
Measuring up. Prototypes for mathematics assessment.	Collection of assessment tasks that bring standards to life and thus offer children opportunities to demonstrate the full range of their mathematical power, including such important facets as communication, problem solving, inventiveness, persistence, and curiosity; focuses on grade 4	Mathematical Sciences Education Board & National Research Council, 1993
Discovery Inquiry Test in Science (DIT)	Instruments to assess technology literacy consists of released NAEP items that measure students' abilities to analyse and interpret data, to extrapolate from one situation to another, and to utilize conceptual understanding; was, e.g., used in study to assess impact of effective teaching	Gairmire & Pearson, 2006 Johnson, Kahle, & Fargo, 2007; Program in Education, no date
Competence Scale for Learning Science	Questionnaire assessing competence scale for learning science regarding competencies in scientific inquiry and communication; 29 self-report, Likert-type items	Chang et al., 2011
Number Knowledge Test	test to assess mathematical understanding of whole numbers	Griffin, 2005
Indicators and Instruments in the Context of Inquiry-based Science Education	Instruments to assess IBST identified within the EU project S-TEAM	Heinz, 2012
Practical Tests Assessment Inventory	Instrument to assess inquiry practical examinations in biology	Tamir, Nussinovitz, & Friedler, 1982
McGill Inventory of Student Inquiry Outcomes (MISIO)	23-item, criterion-referenced; student outcomes include knowledge and skills, intrinsic motivation, and development of expertise	Saunders-Stewart, Gyles, & Shore, 2012

Assessment of inquiry or science process skills		
Test of the Integrated Science Process Skills	Develop a reliable and valid instrument to measure integrated science process skills	Dillashaw & Okey, 1980
Test of Inquiry Process Skills (TIPS II)	Provides a reliable instrument for measuring the process skill achievement of middle and high school students	Burns, Okey, & Wise, 1985
Test of Science Process Skills		Molitor & George, 1976
Test of science processes		Tannenbaum, 1971
	Test items for four integrated science processes	McLeod, Berkheimer, Fyffe, & Robison, 1975
	questionnaire with 15 constructed-response (CR) type items and one hands-on task to assess science process skills; grade 9	Temiz, Taşar, & Tan, 2006
Test of enquiry skills	Development and validation of a content free test of enquiry skills	Fraser, 1980
Processes of biological investigations test	Easily administered, reliable p&p test for high school biology students that measures the science process skills developing hypotheses, making predictions, identifying assumptions, analysing data, and formulating conclusions	Germann, 1989

Assessment of reasoning	
Evidence-Based Reasoning in Science Classroom Discourse	Instrument is intended to provide a means for measuring the quality of evidence-based reasoning in whole-class discussions, capturing teachers' and students' co-constructed reasoning about scientific phenomena; coding system for assessing argumentation in science classroom discourse is developed
Raven's Progressive matrices	measures general mental ability and offers information about someone's capacity for analysing and solving problems, abstract reasoning, and the ability to learn; an earlier version (Raven's progressive test of non-verbal reasoning) used to assess scientific reasoning
Assessment of attitudes and affect	
Views of Nature of Science (VNOS)	Questionnaire for NOS
Views of Scientific Inquiry (VOSI)	
Views of Scientific Inquiry – primary school (VOSI-P)	
Test of Science Related Attitudes (TOSRA)	
"Learning how to learn"-project	A Project of the ESRC Teaching and Learning Research Program; presents e.g. self-evaluation questionnaires
	Questionnaire for assessing students' motivation

Furtak, Hardy, Beinbrech, Shavelson, & Shemwell, 2010

Mercer, Dawes, Wegerif, & Sams, 2004

Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002

Schwartz, Lederman, & Lederman, 2008

Program in Education, no date

Fraser, 1981;

Fraser & Butts, 1982;

Program in Education, no date

Learning how to Learn Project, 2002

Nolen, 2003;

Osborne et al., 2013

	Questionnaire for assessing students' attitudes towards science in grades 1-5	Pell & Jarvis, 2001; Osborne et al., 2013
	Questionnaire for assessing four dimensions of epistemic beliefs (source, certainty, development, justification) in primary school	Conley, Pintrich, Vekiri, & Harrison, 2004; Osborne et al., 2013
	MC test to assess development of epistemological understanding (absolutist, multipist, evaluativist)	Kuhn, Cheney, & Weinstock, 2000; Osborne et al., 2013
	Overview of existing instruments to assess affective measures in mathematics	Chamberlin, 2010
Attitudes towards mathematics inventory (short version)		Lim & Chapman, 2013
Assessment of assessment literacy		
Teacher assessment literacy questionnaire	psychometric properties of the teacher assessment literacy questionnaire	Alkharusi, 2011
Classroom assessment literacy inventory	35 items related to the seven Standards for Teacher Competence in the Educational Assessment of Students; Some of the items are intended to measure general concepts related to testing and assessment; other items are related to knowledge of standardized testing and the remaining items are related to classroom assessment	Mertler, no date

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The EU project ‘Assess Inquiry in Science, Technology and Mathematics Education’ (ASSIST-ME) investigates formative and summative assessment methods to support and improve inquiry-based approaches in European science, technology and mathematics (STM) education.

In the first step of the project, a literature review was conducted in order to gather information about the current state of the art in formative and summative assessment in inquiry-based education (IBE) in STM. Searches were conducted in databases, in the most important journals in the field of STM education, and in the reference lists of relevant publications. This report describes the search strategies used in detail and presents the results of the empirical studies described in the found publications in this field.



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