

Moving towards engaged learning in STEM domains; there is no simple answer, but clearly a road ahead

Ton de Jong 

Department of Instructional Technology,
Faculty of Behavioral, Management and Social
Sciences, University of Twente, Enschede, The
Netherlands

Correspondence

Ton de Jong, Department of Instructional
Technology, Faculty of Behavioral,
Management and Social Sciences, University
of Twente, PO Box 217, 7500 AE Enschede,
The Netherlands.

Email: a.j.m.dejong@utwente.nl

Funding information

European Union, Grant/Award Numbers:
317601, 731685 and 781012; NWO/TYF,
Grant/Award Number: 409-15-209

Abstract

What is the best approach to educating students is, evidently, the pivotal question in educational research. In the general debate on this question, clear positions are often taken—for example, whether teacher-led instruction or more student-directed approaches should be followed. In the current narrative review, this central question and the different stances taken are explored for a specific field of learning, STEM (science, technology, engineering, and mathematics) domains. The current article starts with an argument as to why the traditional, more directive teacher-led educational approach to STEM learning may not always lead to deep conceptual knowledge and proposes exploring more engaged forms of learning. More specifically, a particular arrangement for engaged learning, inquiry learning, is taken as an example in this exploration. It is argued that the effects of educational methods are influenced by a multitude of (interacting) factors related to student and teacher characteristics, context, domain, frequency of use, timing, and probably more. Therefore, this article tries to outline a more nuanced and balanced stance towards choosing educational approaches. A picture is presented to show that adopting and combining different approaches, at both the lesson and the curricular levels, may be necessary to reach optimal levels of learning. Existing and upcoming technologies may play a decisive role in realizing this more complex, but also more realistic view of learning in STEM.

KEYWORDS

engaged learning, inquiry learning, online laboratories, scaffolding, STEM, technology-based learning

1 | INTRODUCTION

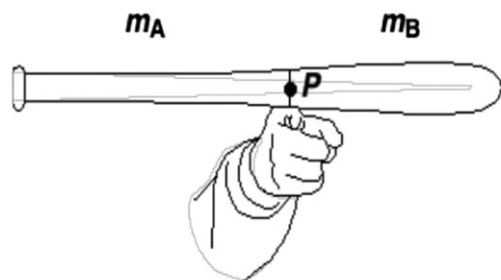
Conceptual knowledge is at the heart of understanding a domain and is most often the central goal that teachers aim to reach with their students. Conceptual knowledge may be defined as knowledge that captures structural relations between concepts, principles, and/or procedures in the domain and enables (causal) inferences (see, e.g., Bennet & Bennet, 2008; de Jong & Ferguson-Hessler, 1996; Pines & West, 1986; Viennot, 2008). Acquiring conceptual knowledge at this deep level requires time and effort and is related to expertise, flexibility of

use, intuition, and transfer. Many studies have shown clear advantages of more “active” or “engaged” learning¹ over direct instruction for acquiring deep conceptual knowledge (e.g., Freeman et al., 2014; Hake, 1998, see also later); others, however, have reported that direct instruction leads to better learning outcomes (e.g., Stockard, Wood, Coughlin, & Khoury, 2018). In consequence, there is still a debate as to which of the two forms of learning or instruction should prevail.

¹Although both terms are used interchangeably in the literature, to simplify things, in this paper, engaged learning is used exclusively, even if the original author used active learning as a term.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2019 The Authors. *Journal of Computer Assisted Learning* Published by John Wiley & Sons Ltd



Compare the mass to the left and right of the balance point. Explain.

FIGURE 1 Physics problem (from Ortiz et al., 2005, p. 546)

With that debate in mind, it is of great potential interest to consider that technology is now entering the classroom. Most often, however, this involves technologies that do not change the traditional pedagogy, for example, whiteboards that replace blackboards, (adaptive) online tests that replace paper and pencil tests, learning management systems that replace written schedules, and, specifically in higher education, massive open online courses that replace in-person lectures. Clearly, these technologies have obvious advantages in terms of efficiency, reach, personalization, and quick updating, but they leave the instructive pedagogy in the classroom basically untouched (see also, e.g., Cuban, 2009). To some degree, this may even explain why these technologies are so popular. There is also a set of technologies that elicit cognitive engagement, for example, in the form of inquiry learning or collaborative learning. The pedagogical approaches or methods these technologies represent are also not new, as students have been doing inquiry in hands-on laboratories and have collaborated in project work for a long time; however, the new technologies enable the application of these approaches in a larger, more efficient, more personalized, and effective way. In addition, technologies introduced in this article offer an opportunity to combine different approaches to learning and instruction and introduce new, interactive, and adaptive options for guidance. This makes engaged forms of learning more manageable and combinable with other instructional approaches within classroom situations.

These developments may turn the ongoing debate into a discussion of how to make the most advantageous combinations of instructional approaches, and move research away from the traditional “which is the best?” question to more subtle and nuanced questions concerning what is best for whom for what domain and at what moment in time. The current paper explores this issue as a “narrative review” with an emphasis on inquiry learning for STEM (science, technology, engineering, and math) domains, at the secondary school level.

2 | THE NEED FOR A CHANGE IN STEM EDUCATION AND ENGAGED LEARNING

In a classic study, Ortiz, Heron, and Shaffer (2005) presented undergraduate students (first-year engineering, physics, math, and computer science students with high school physics experience)

with simple and straightforward physics problems such as the one depicted in Figure 1.²

Students were informed that the baseball bat was in balance and they had to indicate whether mass A was larger than, smaller than, or equal to mass B. Because the centre of mass A is clearly further away from the balance point than the centre of mass B, the correct answer is that mass B must be larger than mass A. Despite this being basic physics knowledge on which the students in the study by Ortiz et al. (2005) had received instruction, only 20% gave the correct answer; most students answered that both masses should be the same. In his EARLI 2015 presidential address, Constantinou (2015) presented figures that showed that university students and teachers from different levels had trouble giving the correct answer to this problem, often reaching percentages lower than the 20% reported by Ortiz et al. (2005). Other studies have shown that such a lack of basic conceptual understanding is apparent for many different science fields, including other physics topics, chemistry, and astronomy (see, e.g., Bodner, 1991; Burgoon, Heddle, & Duran, 2010; Cros, Chastrette, & Fayol, 1988; Gunstone & White, 1981; Kruger, Summers, & Palacio, 1990; H. Lin, Cheng, & Lawrenz, 2000; McDermott, 1984; Nakhleh, 1992; Smith & Metz, 1996; Trouille et al., 2013; Trowbridge & McDermott, 1980; Viennot, 1979). These consistent findings could indicate that (deep) conceptual knowledge of science topics may often be lacking.

Many scholars and instructional designers seek to solve the problem of a lack of deep conceptual knowledge by introducing methods of engaged learning. In traditional, direct, instruction, students may also interact deeply with the domain, such as when they practice solving problems after the direct instruction has been delivered, but in engaged forms of instruction, the involvement in the content is at the core of the approach. Engaged learning can be seen as a form of learning in which students perform meaningful activities with the content offered, which means that they modify or elaborate the content (by interpreting, exemplifying, classifying, inferring, differentiating, or organizing) or reflect upon it by themselves or in discussion with others (Prince, 2004). Central to this definition is that students go beyond the information that is offered to them. Engaged learning may take place at different levels of intensity (see, e.g., Chi & Wylie, 2014, to be detailed later) and may entail many forms of learning, such as problem-based learning, project-based learning, peer tutoring, collaborative learning, and, the focus of this article, inquiry learning.

There are clear indications that engaged learning indeed leads to a higher level of conceptual knowledge than traditional, direct, instruction. Hake (1998) compared the outcomes of 62 introductory physics courses (involving more than 6,500 students), 14 of which were characterized as traditional and 48 as following interactive-engagement (IE) methods. The latter were defined as courses that were “designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors” (Hake, 1998, p. 65). All courses involved standardized tests that were intended to measure conceptual

²Reproduced from Ortiz et al. (2005). Student understanding of static equilibrium: Predicting and accounting for balancing. *American Journal of Physics*, 73, 545–553, with the permission of the American Association of Physics Teachers.

knowledge of Newtonian mechanics. The results of the study by Hake showed that students whose course was based on interactive engagement achieved an average gain in conceptual knowledge that was close to two standard deviations above that of the students who took a traditional course. In his work, Hake (1998) also found that some IE courses scored at the low end, making this approach not a panacea, but the overall results led him to conclude that: "The conceptual and problem-solving test results strongly suggest that *the use of IE strategies can increase mechanics course effectiveness well beyond that obtained with traditional methods.*" (Hake, 1998, p. 71, author's emphasis).

In a later meta-analysis, Freeman et al. (2014) confirmed that engaged learning has clear advantages over more direct, expository, forms of learning. In their analysis of 225 studies, they found a difference of 0.47 SD in favour of engaged forms of learning, and students in traditional classes failing 1.5 times as often as students participating in engaged forms of learning. The definition used for engaged learning by Freeman et al. was rather broad, and included: "occasional group problem-solving, worksheets or tutorials completed during class, use of personal response systems with or without peer instruction, and studio or workshop course designs" (Freeman et al., 2014, p. 8410). Although this definition is indeed very broad, the study by Freeman et al. indicates that mobilizing students one way or another makes sense, which is also supported by more personal and qualitative testimonials (e.g., Falconer, 2016).

The studies by Hake (1998) and Freeman et al. (2014) presented results over all different kinds of engaged learning, but if we also zoom in on specific forms of engaged instruction, large-scale studies or meta-analyses have shown large and consistent advantages of forms of engaged learning over traditional forms of instruction, as is the case for peer tutoring, for example (see, e.g., Crouch & Mazur, 2001). To explicate this phenomenon and to be able to give specific details, in the current article, I focus on one specific form of engaged learning: inquiry learning.

3 | INQUIRY LEARNING AS A FORM OF ENGAGED LEARNING

The definition of engaged learning given above, students who are processing material in a meaningful way and reflecting on what they are doing, still sees engaged learning as a rather open concept that embraces many different forms of learning, including, for example, solving exercise problems in a traditional curriculum. Going one step further, engaged learning can involve drawing inferences from and adding commentaries to material offered, found, or shared, as often occurs in problem-based or collaborative learning. A next level of activity can be introduced by not offering all of the information to students and presenting them with situations they need to manipulate to create the information themselves; basically, this is what happens in *inquiry learning*. There are many different views on inquiry learning, but here, we see inquiry learning as characterized with situations in which students are presented with or have to design a scientific question. They must find an answer to that question by performing investigations and/or collecting data, for example, in real or online laboratories. In most cases, inquiry activities for students concern questions for which the answer is already known in the literature, but they can also address questions without known answers. In any case, in inquiry learning,

students themselves have to make inferences in the domain. Compared with traditional instruction, in inquiry learning, the emphasis is on students taking the initiative. In traditional instruction, the usual (simplified) sequence is that the teacher explains and students read the theory in the book, and then students do exercises. In inquiry learning, still based on the necessary preconditional surface knowledge, students first carry out explorations and then create concepts and laws together with their teachers. Schuster, Cobern, Adams, Undreiu, and Pleasants (2018) called this *ready-made science* versus *science in the making*. In traditional learning settings, experiments that students perform are meant to confirm what they have been learning in their lessons, whereas in inquiry learning, the lab exercises are meant not only to confirm knowledge but also to construct meaning (Trout, Lee, Moog, & Rickey, 2008).

The interactive, constructive, active, and passive (ICAP) framework designed by Chi (2009) and Chi and Wylie (2014) is relevant to further position inquiry learning as a form of engaged learning. The ICAP taxonomy categorizes (overt) activities that students can perform such as listening and observing (passive), making notes or highlighting (active), creating artefacts such as concept maps (constructive), or collaborating with others (interactive). These overt activities are related (not necessarily on a one-to-one basis) to cognitive activities by students that show increasing levels of engagement: storing (passive), integrating (active), inferring (constructive), and coinfering (interactive; Chi & Wylie, 2014, p. 225). Based on other studies and on their own work, Chi and Wylie (2014) concluded that students perform best with instruction that stimulates interactive learning, which is better than both approaches focusing on constructive learning and passive methods, which are least effective. In inquiry learning, all of the different ICAP levels are present. Students are *active* in manipulating a lab or simulation (de Jong, Linn, & Zacharia, 2013), they are *constructive* in such work as creating hypotheses and making inferences (Eysink & de Jong, 2012), and this is often performed together with peers, which stimulates *interactivity* (Osborne, 2010). When students receive instruction alongside of the inquiry (see later), the *passive* mode of learning is also present.

4 | TECHNOLOGY FOR INQUIRY LEARNING

Instructional implementations of inquiry do not necessarily involve specific technologies, but technology can be an essential component of active or engaged learning (see, e.g., National Academies of Sciences Engineering Medicine, 2018) and of inquiry learning in particular. In a recent paper, de Jong, Lazonder, Pedaste, and Zacharia (2018) summarized technologies for inquiry learning, such as simulations and online laboratories, (certain types of) games, and modelling environments. There are many variations within these categories, but essentially, these technologies allow learners to interact with a computational model that represents a domain. In this interaction, students in essence manipulate values of independent variables and observe values of output variables. In doing so, they try to put their existing ideas, which could be misconceptions, to the test. They can also explore relations they become aware of and infer new knowledge, and then test these newly acquired ideas by doing new experiments. Students may also try to find out the conditions under which their ideas hold (see, e.g., de Jong & van Joolingen, 1998).

Web-based applications have created a situation in which these technologies have become readily available for usage in classrooms or at home. Examples of repositories of online labs or simulations that are very widely used in science education are the PhET (Moore & Perkins, 2018; Wieman, Adams, & Perkins, 2008), Amrita/OLabs (Achuthan et al., 2011; Nedungadi, Malini, & Raman, 2015; Nedungadi, Ramesh, Pradeep, & Raman, 2018), Molecular Workbench (Xie et al., 2011), Physics Aviary (MacIsaac, 2015), Physlet Physics (Christian & Belloni, 2003), and ChemCollective (Yaron, Karabinos, Lange, Greeno, & Leinhardt, 2010) collections. The Go-Lab sharing platform (www.golabz.eu, see, e.g., de Jong, Sotiriou, & Gillet, 2014) is an example of a platform in which labs from different repositories are brought under one umbrella. Virtual laboratories that include virtual reality techniques mimicking the hands-on laboratory as closely as possible can also be found, for example, in (commercial) repositories such as Labster (Bonde et al., 2014). Many websites offering a larger set of smaller games (often for children) can be found, and more advanced games can be found in general repositories such as merlot.org. A larger set of modelling tools (based on different principles) is also available, with some of the best known examples being NetLogo (Wagh, Cook-Whitt, & Wilensky, 2017) and Scratch (Resnick et al., 2009), as well as newer developments such as SageModeller (Damelin, Krajcik, McIntyre, & Bielak, 2017) and SimSketch (Heijnes, van Joolingen, & Leenaars, 2018).

The technologies mentioned in this section provide students with a platform for engaging with a domain and extending their knowledge in a self-directed way. Compared with doing inquiry with real materials, the use of technologies offers practical advantages, such as no waste of chemical substances or 24/7 lab availability (Alessi & Trollip, 2001), and it may enable access to data that are not available in traditional instruction (Lee & Wilkerson, 2018). The pedagogical advantages are also important. Because inquiry learning is a complex process, especially when first starting out, students need to be supported by different forms of guidance. Technology allows the possibility of offering this guidance in a way that is integrated with the inquiry approach and, as is seen more and more, in a way that is adaptive.

5 | COMBINING INQUIRY WITH (TECHNOLOGY-BASED) PEDAGOGICAL GUIDANCE

Inquiry learning requires students to actively plan their actions and to monitor their plan and their development of knowledge. Leaving this process entirely up to the student (certainly for the novice student) will not lead to productive learning (Mayer, 2004). Therefore, inquiry learning needs to be well guided, which can be done in several ways. In the next sections, various ways of providing students with guidance are discussed, after which some examples are presented of how technology may enact the different types of guidance.

5.1 | Giving students the right level of control

Activities such as generating questions or hypotheses, designing and running experiments, and interpreting data are pivotal in the inquiry

process. In a full inquiry setting, the initiative for all of these activities lies with the student (who, e.g., creates a hypothesis), but the initiative can also lie more with the teacher or system (by providing the student with a ready-made hypothesis), or any situation in between (e.g., partially stated hypotheses to be completed by the student).

In the literature, many authors have elaborated on this idea of different levels of inquiry, with level referring to the degree of freedom or initiative on the part of the students versus the teacher (or system). Bonnstetter (1998), for example, distinguished increasing levels of autonomy for the student: traditional hands-on, structured, guided, student-directed, and student-research inquiry. In the most open form of inquiry, students are in control of all inquiry aspects including the design of the research question, whereas in the most closed form, control is on the side of the teacher, who provides the students with the research questions, a step-by-step data collection procedure, and so forth. The latter form comes very close to what happens in traditional, more recipe-like, hands-on laboratory exercises, in which the role of the experiment is simply to confirm the theory presented by the teacher. Protosaltis et al. (2013) cited earlier work that used similar distinctions (Herron, 1971; Schwab & Brandwein, 1962; Tafoya, Sunal, & Knecht, 1980). More recently than these, Banchi and Bell (2008) also worked through this concept, showing that the idea of introducing different levels of control for inquiry has a permanent place in the science education literature. De Jong and Lazonder (2014) presented ways of guidance that differ in the control they give to students. For example, dashboards only provide students with information on their activities or learning products, process constraints limit the options for students, and prompts or heuristics point students to certain activities to follow.

Although in inquiry, the control should be ideally in the hands of the student, research has suggested that greater system/teacher control is advantageous for learning outcomes. For example, in a meta-analysis, Furtak, Seidel, Iverson, and Briggs (2012) found higher effect sizes for different forms of teacher-led inquiry compared with traditional instruction than for student-led discovery against traditional instruction. Analyses of different rounds of PISA (Programme for International Student Assessment, see www.oecd.org/pisa) data have shown that although the more open forms of inquiry are better for gaining a positive attitude towards science, the more closed, teacher-led forms of inquiry are associated with higher knowledge scores (Cairns & Areepattamannil, in press; Jiang & McComas, 2015). The optimal division of control, however, may depend on student characteristics and other factors. One starting point for deciding on this division could be the “zone of proximal development” for students. This holds for both their knowledge of the domain and their command of inquiry activities. In this context, Perez et al. (2017) found that students who learned more from a simulation on electrical circuits created much less complex circuits than students who did not gain knowledge after working with the simulation. Obviously, the more successful students were able to recognize their limitations and stayed within their zone of proximal development. More adaptive forms of guidance (see later) should be able to make the level of control more flexible, also making it possible to start with more system control for novice students when need to get used to the inquiry process, and leaving more control to the student in later stages. Finding the balance between

student and system (teacher) control is also clearly related to results from work on self-regulated learning, in which providing students with control enhances motivation but may also lose its effect on learning results, when students (come to) lack the skills to regulate their own learning (see, e.g., Gorissen, Kester, Brand-Gruwel, & Martens, 2015).

5.2 | Providing students with scaffolds

Supporting students in the inquiry process can be done by giving them scaffolds. Offering scaffolds can help students to perform processes that they are not as yet able to perform well enough by themselves, because scaffolds can be integrated into the dynamics of a process and offer students structures and elements of the task they must perform (de Jong & Lazonder, 2014). Students can be scaffolded at the overall level of inquiry (the inquiry cycle) or at level of the more detailed inquiry processes within the different phases of an inquiry cycle.

Inquiry is a process with a number of steps that can be placed in a certain (not necessarily sequential) order. Pedaste et al. (2015) reviewed the literature on “inquiry cycles” and summarized them in a framework including phases such as orientation, question or hypothesis stating, investigation, conclusion, and communication and reflection, with a number of relevant subprocesses. Providing students with such a predefined cycle helps them with keeping an overview of actions to be completed and with planning and monitoring their learning process. Manlove, Lazonder, and de Jong (2007) compared two groups of students learning with a physics simulation on Torricelli’s law, with one group following a computerized inquiry cycle and the control group working without this structure. They found that the group with the inquiry cycle produced better reports at the end of the inquiry process.

Scaffolding the entire inquiry process can be done by providing students with an inquiry cycle, but specific difficulties may also appear at each step of the process, such as in setting up hypotheses or drawing conclusions, as well as in processes such as planning and monitoring of the inquiry process (de Jong & van Joolingen, 1998). In a recent study, Woolley et al. (2018) asked more than 300 undergraduate students 80 open questions on scientific reasoning strategies, based on classifications of inquiry processes such as the one developed by the National Science Foundation (2000). Based on their analyses of the students’ answers, Woolley et al. (2018) could identify a large set of common mistakes students made, including not identifying the independent variable, not associating the right data with the right hypothesis, and swapping ratios and units. At a more specific level, Chinn and Brewer (1993) listed six less desirable typical student reactions to anomalous data when having to draw conclusions, including ignoring or reinterpreting anomalous data.

In a meta-analysis of over 144 studies, Belland, Walker, Kim, and Lefler (2017) found a consistent positive effect of computer-based scaffolding on cognitive outcomes. This conclusion held over a series of more open, problem-centred learning approaches, including inquiry learning. In a meta-analysis of over 77 studies specifically focusing on inquiry learning, Lazonder and Harmsen (2016) also found a positive effect on learning outcomes from adding scaffolds. Similar results were reported by d’Angelo et al. (2014), who reported an added effect on learning performance from guidance for inquiry learning from

computer simulations. In contrast and a bit puzzling, when looking at within-subject differences, the effects of using scaffolds for inquiry learning do not seem to be evident (Belland, Walker, & Kim, 2017).

5.3 | Balancing instruction and inquiry

Despite the fact that well-designed (guidance included) inquiry learning has repeatedly been found to be a relatively effective instructional method, meta-analyses and the work on which they are based often do not sketch the full picture. One important factor that is often not considered is the context in which this type of teaching takes place, and, more particularly, its positioning within the curriculum (see also Rutten, van Joolingen, & van der Veen, 2012). For example, the two recent meta-analyses in this field that were mentioned above (Belland et al., 2017; Lazonder & Harmsen, 2016) discussed quite a number of mediating variables (e.g., domain, duration, type of guidance, learner characteristics, assessment level, and scaffolding characteristic), but not the point during the curriculum in which the learning took place. This timing of inquiry, however, seems to be of importance. Hattie and Donoghue (2016), who performed a meta-synthesis of a large series of meta-analyses comprising a total of close to 19,000 individual studies, explicitly mentioned that some more engaged forms of learning and instruction show less favourable effect sizes when they are introduced in the curriculum at a point when the necessary surface knowledge that is needed as a starting point for gaining (deep) conceptual knowledge has not yet been acquired. Schneider and Preckel (2017) also presenting a meta-synthesis, likewise found that prior instruction (and the associated prior knowledge) is a moderator variable for the effectiveness of engaged forms of learning such as problem-based learning and inquiry learning. It seems, therefore, that inquiry learning needs to be preceded (or accompanied) by direct instruction. This triggers the need for a subtle timing of inquiry activities and for a balance of direct instruction of prerequisite knowledge and inquiry activities.

The combination of instruction and inquiry can be implemented in the context of an entire curriculum, but this combination can also be realized in a single learning session. There are a number of studies that have investigated this issue; some work has indicated that inquiry before instruction is most beneficial (Brant, Hooper, & Sugrue, 1991) or that exploring before instruction is the best (DeCaro & Rittle-Johnson, 2012; Weaver, Chastain, DeCaro, & DeCaro, 2018). Most work, however, has indicated that instruction of domain knowledge prior to learning with a simulation or lab leads to better results for domain knowledge than the reverse order, either on an immediate test (Barzilai & Blau, 2014) or over a longer term (Wecker et al., 2013). Lazonder, Wilhelm, and van Lieburg (2009) found indications that having some knowledge of relations between variables is also necessary to profit from a subsequent inquiry process. In a study with a simulation on a fictitious domain, Lazonder, Hagemans, and de Jong (2010) found that having surface information available during learning may be a good alternative or addition to the presentation of information before the simulation. Kant, Scheiter, and Oschatz (2017) found that for scientific reasoning skills, presenting direct information (in this case as a video) was also better done before than after an inquiry task.

5.4 | How technology can enable guided inquiry

Guidance for inquiry can be given by the teacher, peers, or technology (Kim & Hannafin, 2011). Focusing on technology, inquiry learning systems can change the level of control. Some examples include providing students with automatic prompts or heuristics, presenting partially completed scaffolds, or building in process constraints, such as by embedding model progression (an online lab become successively more complex). The use of combinations of sources to provide students with guidance can also be found, for example, when dashboards showing student activities help teachers to guide students in the inquiry process (see, e.g., Roschelle, Martin, Ahn, & Schank, 2017). Technology can also help in providing students with scaffolds. One example of the integration of an inquiry cycle in a technology-based platform is the Go-Lab ecosystem. Inquiry spaces created with this ecosystem follow a set of phases that present an inquiry cycle. These phases are shown by means of tabs in the environment; designers/teachers can change these tabs and thus the cycle according to their own wishes (de Jong, 2015). An example of a more specific scaffold (for an overview, see Zacharia et al., 2015) is an experiment design tool that breaks down the process of experiment design: selecting variables; categorizing them as independent, dependent, or control; assigning values to them; and deciding on the number of trials. An experiment design tool can even suggest specific experimentation strategies such as vary one variable at the time (van Riesen, Gijlers, Anjewierden, & de Jong, 2018b). Finally, combining direct instruction and inquiry can also be supported by technology. Direct instruction can be offered prior to or following the inquiry process or in an adaptive or student-controlled way during the inquiry, for example, by having pop-ups explain variables during experiment design. The latter example also shows that different types of guidance can be combined in a specific tool. In designing adequate guidance, an important aspect is not to “overscript,” so that there remain challenges for students and students can still feel the benefits of having to repair their own mistakes, in line with approaches such as productive failure (Kapur & Bielaczyc, 2012) or desirable difficulties (Linn, Chang, Chiu, Zhang, & McElhane, 2010).

Most individual offerings and some collections of technology-based learning material offer single online labs that can be used by a teacher as demonstration material or can be embedded in offline supporting material. In many cases (e.g., PhET, ChemCollective, Physlets, and OLABs), virtual labs are offered together with materials such as activities, tutorials, and tests, often as offline material. The WISE software began offering the possibility of embedding virtual labs into online learning environments, offering authoring possibilities to teachers with the possibility of including a number of interactive scaffolds (Slotta & Linn, 2009). The Go-Lab software (de Jong et al., 2014; Gillet, Rodríguez-Triana, de Jong, Bollen, & Dikke, 2017, July) offers a large collection of more than 550 online (virtual and remote) labs, including labs from the repositories listed above, and offers extensive authoring facilities, including a large set of interactive, teacher-configurable scaffolds. The combination of labs, scaffolds, and multimedia materials in what are called inquiry learning spaces (ILSs) that follow a (configurable) inquiry cycle means that ILSs enable the combination of online labs with all types of guidance mentioned in this

section. Still, other repositories (e.g., Inq-ITS; Gobert, Moussavi, Li, Sao Pedro, & Dickler, 2018) offer a (much more limited) set of online labs with an integrated set of highly adaptive tools.

6 | EFFECTIVENESS OF (TECHNOLOGY-BASED) INQUIRY LEARNING

Many studies have shown an advantage for inquiry learning over other forms of (direct) instruction for acquiring (conceptual) knowledge (see, e.g., Furtak et al., 2012; Minner, Levy, & Century, 2010; Schroeder, Scott, Tolson, Huang, & Lee, 2007; Shymansky, Hedges, & Woodworth, 1990). Often, however, analysis has shown that positive results of inquiry only hold or hold in a stronger form when the inquiry process is guided, as explained in the previous section. Alfieri, Brooks, Aldrich, and Tenenbaum (2011) found an effect size of -0.38 for unguided and 0.30 for guided inquiry (Alfieri et al., 2011; Cohen's d). A meta-analysis by Lazonder and Harmsen (2016) confirmed that combining inquiry with guidance indeed led to improved learning outcomes, but these authors could not find differential effects of different forms of guidance. In the same context, Furtak et al. (2012) concluded that when inquiry was more teacher led, positive results were more pronounced. When looking into the results for technology-supported inquiry learning (e.g., learning with virtual labs or simulations), the results here also have consistently shown that inquiry learning does better compared with more direct forms of instruction for acquiring (conceptual) knowledge (see, e.g., Rutten et al., 2012), but again, effects are more pronounced when guidance is present (e.g., d'Angelo et al., 2014; Smetana & Bell, 2012). These results are reported for the acquisition of (conceptual) knowledge as an outcome variable, but positive results are often reported as well for interest in science (Cairns & Areepattamannil, in press; Laine, Veermans, Lahti, & Veermans, 2017; OECD, 2016).

Another approach to assessing the relative impact of inquiry learning comes from studies of the actual use of learning strategies in the classroom as related to student performance. The most recent figures in this respect come from the PISA 2015 studies (OECD, 2016). These PISA 2015 data seem to show a different picture than the meta-analyses listed above; based on this analysis, it was concluded that, “After accounting for students' and schools' socio-economic profile, in 56 countries and economies, greater exposure to enquiry-based instruction is associated with lower scores in science” (OECD, 2016, p. 36). This was further confirmed in a further analysis of the PISA 2016 data by Cairns and Areepattamannil (in press), who also concluded that more frequent use of inquiry activities was related to lower scores on the PISA science test.

So we seem to be left with two contrary conclusions from two different sources of information and different types of studies. There are, however, a few distinguishing factors that may explain these seemingly contradictory conclusions.

What obviously influences the effectiveness of instruction, and thus also the effectiveness of inquiry-based instruction, is the actual quality of the instruction, which also concerns the quality of the teacher (see also Rutten et al., 2012). In experimental studies, this quality is often more under control than in the instruction included

in the PISA studies. In experimental studies, the inquiry instruction is often the experimental condition that in most cases has been meticulously designed and documented by the researcher and delivered by a teacher (or the experimenter), who most probably will be motivated to deliver this type of instruction well. In the PISA studies, much less is known about the instruction, instruction is categorized as inquiry-based according to students' self-reports, and basically, no further quality data are available. There are, however, indications that in the actual classroom, inquiry learning is often not realized as intended by the designer. For instance, Plass et al. (2012) analysed how a course on chemistry inquiry that they designed was implemented in 35 classrooms after the experimenters left, and found that half of the teachers involved made adaptations, ranging from spreading the units of the course over a longer period of time to making pedagogical changes that did not comply with the course intentions. Van Dijk, Eysink, and de Jong (submitted) conducted a study in which 30 elementary schools implemented the same inquiry method in their curriculum and found large variations in actual usage of the method. Chinn and Malhotra (2002), in an extensive analysis of practical inquiry learning situations, concluded that most of the inquiry methods used in schools tend to be the more restricted approaches with very little freedom for the learner. These authors also noticed that the "simple inquiry tasks" used at school use very basic and unidimensional experimental situations that are distant from authentic tasks.

Next, in studies using the PISA 2016 data, a relation between frequency of inquiry activities and achievement was observed, while experimental studies often evaluate a one-time intervention. This means that these are basically two different types of results. In this context, a very recent study by Teig, Scherer, and Nilsen (2018) showed that, based on 2015 Norwegian TIMSS data, there is a curvilinear relation between frequency of inquiry activities and achievement, meaning that inquiry learning positively affected achievement until a certain level of frequency of occurrence in the curriculum, such that a high frequency of inquiry activities instead hampered achievement. If these conclusions hold, it may indicate that there is no contradiction in the results. Experimental studies, in which inquiry lessons are often implemented only once, often find better learning outcomes for inquiry. The Teig et al. (2018) results could imply that there is still room to enlarge the effect beyond such a single implementation, but only up until a certain threshold level of implementation of inquiry has been reached.

This being true, there are some caveats to be noted regarding positive results for inquiry learning. First, as is true for all results from (educational) science, there is a tendency to publish only studies in which a "favourable" outcome was found (the "file drawer problem," see Rosenthal, 1979); it can be assumed that scholars investigating inquiry tend to favour this form of learning. Second, it seems hard, especially in educational science where there are dozens of decisions to be made between developing a theoretical idea and its actual implantation in the classroom, to draw general conclusions about "inquiry learning," "traditional instruction," "scaffolds," and so forth. All of these general concepts, as already indicated above, have many different implementations, which makes it almost impossible to lump all these results together under one common denominator. What is called inquiry on the surface can in effect represent many different

approaches. Third, in education, there are many variables that may determine the effectiveness of an intervention. The two most frequent mediators for inquiry learning are the *quality of the teacher* and the *prior knowledge of the students*.

In relation to *teacher quality* and involvement, Waldrop (2015, p. 274), wrote:

One faculty member, who asked not to be named so that she could speak freely about her institution, tells the story of a chemistry instructor who told his students to "work together," and then spent the rest of the class time reading. "Active learning done badly is worse than a good lecture."

This illustrates, as already indicated above, that the role of the teacher in the (inquiry) learning process can be indispensable (see, e.g., Andrews, Leonard, Colgrove, & Kalinowski, 2011; Auerbach, Higgins, Brickman, Andrews, & Labov, 2018; Furberg, 2016), yet this role is neglected in many experimental studies. In the best case, the same teacher teaches the inquiry and the control conditions, but most often, there is hardly any information on the quality of the teaching process. In a qualitative study, Fang and Hsu (2017) made detailed observations of two teachers teaching the same inquiry unit. They found profound differences in approach, resulting also in differences in students' knowledge acquisition and command of inquiry skills. Indirectly, such a relation can also be inferred from a study by Shymansky et al. (1990), who investigated the effectiveness of inquiry reforms in the 1960s and 1970s. They found that overall, these programmes were effective, but programmes in which teachers had received dedicated in-service training were far more effective than programmes in which teachers did not receive such training. A study by Andrews et al. (2011) suggested that teachers who did not receive extra training did not have the expertise to implement engaged learning in an adequate way; in their study, they found no relation between the number of engaged learning activities and conceptual knowledge gain for a set of randomly selected teachers who were not specifically trained.

Student prior knowledge has long been considered as one of the main determinants of the success of learning (Ausubel, 1968). This also holds for inquiry learning. We have already noted that before going into inquiry, students need some surface knowledge of basic concepts from the domain involved. Recently, several studies have also indicated that there is a subtle interplay between the nature of the guidance offered and its effectiveness in relation to the student's prior knowledge. The typical assumption is that lower prior knowledge students should and would profit most from any guidance that is offered, because they would be most in need of this. van Riesen, Gijlers, Anjewierden, and de Jong (2018a), for example, found that lower prior knowledge students profited from a tool that helped them to design experiments, which was not the case for higher prior knowledge students. This is in line with the expertise reversal principle (Kalyuga, 2007). However, in a recent study, Brenner et al. (2017) found that in some cases, low prior knowledge students profited from guidance, but in other cases, they did not. A recent meta-analysis by Belland et al. (2017) indicated that students performing below and above average profited equally from computer-based scaffolding (of ill-structured problem-based curricula in STEM), whereas in other

studies, more recent and focusing on inquiry learning, it was found that the higher prior knowledge students used the guidance most and profited most from it (Roll et al., 2018; van Dijk, Eysink, & de Jong, 2016; van Riesen et al., 2018a; Zhu et al., 2017). The explanation for these findings is that a certain level of knowledge is necessary to be able to use the guidance (Roll et al., 2018; van Riesen et al., 2018a). All of these results point to the existence of a potential subtle interplay between student characteristics, use of guidance, and learning outcomes.

Despite all caveats about differences in implementation and mediating variables, there is sufficient evidence to conclude that (technology-based) inquiry learning can contribute to a learning process that helps to foster conceptual knowledge. To further improve students' results, there are a few potential new developments in which technology plays a central role.

7 | THE NEXT STEPS IN TECHNOLOGY-BASED GUIDANCE OF THE INQUIRY PROCESS

Students who learn in a technology-based inquiry environment (such as a Go-Lab ILS; Gillet et al., 2017, July) produce a series of data. They leave a trace of their learning process (e.g., variables varied in a simulation or online lab, inquiry phases visited, time spent in an inquiry phase, etc.), and they produce all kinds of electronic artefacts (e.g., hypotheses created, experiments designed, and conclusions filled in). These data can be used to further shape and support the learning process in a number of different ways.

7.1 | Dynamically adaptive guidance

The holy grail of technology-supported education is the development of truly adaptive systems that reach the level of one-on-one tutoring (Chi, Siler, Jeong, Yamauchi, & Hausmann, 2001). For simple approaches such as drill-and-practice, automated instruction may have reached this level (Luik, 2007), for higher level learning approaches that (often) involve complex domains and open (inquiry) learning approaches, the situation is more complex.

For example, getting a hold on students' inquiry skills (e.g., their capacity to design sound experiments) and inferring these from their interaction behaviour is difficult because there is not a sequential learning path and effective behaviours can be very different (Fratamico, Conati, Kardan, & Roll, 2017). However, the situation is improving, and several systems that give individualized and adaptive guidance have now been developed. Käser, Hallinen, and Schwartz (2017) described a system that could classify students' knowledge and skills, and found that the joint classification of knowledge and skills could predict students' learning success in a simulation-based game. Sao Pedro, Baker, Gobert, Montalvo, and Nakama (2013) described a set of "detectors" that could fairly reliably detect whether a student was performing controlled or uncontrolled experiments, whether the student's experiment was testing a hypothesis or not, and whether students were planning their behaviour (see also Gobert, Kim, Sao Pedro, Kennedy, & Betts, 2015; Gobert, Sao Pedro,

Raziuddin, & Baker, 2013). Liu, Rios, Heilman, Gerard, and Linn (2016) assessed the validity of a tool called c-rater-ML for the automatic scoring of students' open-ended responses and found good agreement between the automatic and human expert ratings.

These improved diagnostic techniques may form the basis for adoptive scaffolding. Kardan and Conati (2015), for example, diagnosed differences in behaviour between low and high learners in an interactive simulation, designed prompts for learners to stimulate them to change their way of learning if necessary, and found that this positively influenced their learning results. Zhu et al. (2017) used c-rater-ML as a basis in providing students with automatic feedback on open-ended written scientific explanations they gave for their choices in online multiple-choice quizzes related to a virtual laboratory on climate change. These authors found that the great majority of students improved their argumentation after receiving the feedback. In a similar vein, Tansomboon, Gerard, Vitale, and Linn (2017) used the c-rater technology to provide students with dedicated prompts to improve their scientific reasoning. Ryoo and Linn (2016) automatically assessed the quality of student concept maps and generated guidance based on assessment outcomes. Kroeze, van den Berg, Veldkamp, Lazonder, and de Jong (in press) created automatic feedback on hypotheses that students stated in a Go-Lab hypothesis scratchpad (van Joolingen & de Jong, 1993) and found that students indeed improved their hypotheses when they used this feedback option. Science classroom inquiry simulations (Peffer, Beckler, Schunn, Renken, & Revak, 2015) have been claimed to customize prompts for conclusions based on students' choice and justification of hypotheses. Gobert et al. (2018) presented Inq-ITS, a system in which students receive adaptive prompts based on an automatic analysis of their inquiry skills using the "detectors" described above.

Until recently, scaffolding by computers lacked the dynamic diagnostic skills of teachers; in a computer situation, scaffolding is often based on a predetermined plan or self-selection. As shown above, new techniques have begun to enable the introduction of computer-based adaptive guidance. However, results from a recent review study by Belland et al. (2017) showed that when scaffolds were adapted to student performance, this was equally as effective as using a fixed schedule, self-selection, or no customization. Belland et al. (2017) also found that giving scaffolds in a generic way was as effective as presenting them in a contextual (linked into the domain) way. These results show that providing (automatically generated) adaptive scaffolds is still an open research field.

7.2 | Student reflection support

Data gathered from students' interaction with a technology-based inquiry environment may also be used to support reflection, which is another important, but often not completed, learning process. Reflection is a process "in which people recapture their experience, think about it, mull it over and evaluate it" (Boud, Keogh, & Walker, 2013, p. 19). Reflection is intended to draw lessons from what has been done and to improve performance (Land & Zembal-Saul, 2003; X. Lin, Hmelo, & Kinzer, 1999). Based on the seminal work by Schön (1987), a distinction is often made between reflection *in action* (in

which a reflective component is used to improve the ongoing action, such as learning) and reflection *on* action (in which reflection is seen as the basis for the improvement of a similar performance later).

Reflection may also play an important role in inquiry learning. Recently, by analysing the online behaviour of students while working with a simulation on electrical circuits and comparing low prior knowledge students who learned a lot (LH students) with low prior knowledge students who did not gain much knowledge (LL students), Perez et al. (2017) found that the LH students inserted pauses in their learning process much more than the LL students, obviously to reflect upon experiments they had done (and to plan for experiments to come). A similar effect was reported by Fratamico et al. (2017); Bumbacher, Salehi, Wierzchula, and Blikstein (2015) also reported that inserting a delay between experiments was related to being successful on a domain knowledge test after an inquiry session.

In inquiry learning, learning analytics data can be used as a basis for reflection (Specht et al., 2012). Reflection can concern a process (e.g., how to create a concept map) or a product (e.g., the concept map itself). In reflection, a comparison is often made to a “norm,” this norm can be an expert’s process or product, a peer’s process or product, or general (theoretical) rules that determine the quality of the process or product. To stay with the example of a concept map, we may present to students as a basis for comparison and reflection: (a) an expert concept map to which students can compare their own concept map), (b) an (automatically generated) aggregated concept map by fellow students, or (c) an automatically calculated measure of a quality aspect of their concept map (e.g., a parsimony measure of a concept map). An example can be found in the work by Hagemans, van der Meij, and de Jong (2013), who provided students with an online real-time graphical overview of how much of the underlying domain they had covered in their inquiry process. Hagemans et al. (2013) found that this opportunity to reflect on their own progress influenced students’ route taken through the domain and led to better learning results. In the Go-Lab software, LA (learning analytics) tools are developed that present students with overviews of their own processes and products in relation to a specified norm, such as a tool that shows students their own concept map in relation to the aggregated concept map of their classmates (see above) or a tool that shows students their time spent in inquiry phases compared with their peers’ average time or a teacher norm.

7.3 | Collaborative inquiry learning

Inquiry learning and the associated inquiry cycle give a good basis for collaborative learning, because the inquiry cycle offers a number of concrete points at which students need to make common decisions in order to continue (e.g., what hypothesis to test and which experiment to perform). These common decision-making points provide natural anchors for discussion and collaboration (Kaartinen & Kumpulainen, 2002). Sun, Looi, and Xie (2017) analysed students’ interactions when working collaboratively in a simulation-based inquiry environment and found that students were highly engaged, while the low prior knowledge students profited especially from the interaction. Gijlers and de Jong (2013), studying students in a

collaborative online learning environment around a simulation on one-dimensional kinematics, found that students’ integration-building exchanges were positively related to their knowledge gains. In a recent study, however, Chang et al. (2017) found that not all collaborative groups learning with an online simulation were able to engage in a productive collaboration process; obviously, collaboration between students also needs to be trained or supported. In a recent study on learning with a simulation of energy transport systems, Eshuis et al. (in press) compared students who received instruction about collaboration with students who received this instruction plus a tool that visualized their own assessment of the collaboration process and that prompted them to reflect on their collaboration. These authors found that the latter group outperformed the first on a number of central collaboration processes and on a resulting knowledge test. Another way that collaboration can support the inquiry process is by having students create collaborative artefacts, such as models or concept maps. Schwartz (1995) found that collaborative groups were able to create representations at a greater level of abstraction than the individual representations, whereas Gijlers and de Jong (2013) found that creating concepts maps during the inquiry process helped students to enact better collaborative processes. A different mechanism for letting students profit from each other’s expertise is to have them give online feedback on inquiry products, such as hypotheses or experiment designs (Dmoshinskaia, Gijlers, & de Jong, in preparation). Due to its (technical) complexity, research into (online) collaborative inquiry learning is still rather scarce, but it is clear that different modes of collaboration and support for this collaboration exist, each with different effects on the quality of the collaboration and the resulting learning performance (Duque, Gómez-Pérez, Nieto-Reyes, & Bravo, 2015). Student data (e.g., the analysis of student dialogues) can also be used to determine the composition of collaborative groups or to shape adaptive collaboration scripts (Diziol, Walker, Rummel, & Koedinger, 2010; Rodríguez-Triana, Martínez-Monés, Asensio-Pérez, & Dimitriadis, 2015).

7.4 | Blended learning

A very promising development in the educational landscape is the use of blended forms of learning in which technological and human (teacher and peer) support are combined, as well as a flip-the-classroom approach that combines (online) learning outside with discussion inside the classroom. In these approaches, which have often been reported to be successful, the general method is to replace the traditional lectures with video lectures that students view outside the classroom and to use the time in the classroom for more engaged forms of learning, including group discussions (see, e.g., Bazalais & Doleck, 2018). In relation to inquiry learning, blended learning is often seen as combining hands-on and virtual laboratories (Toth, Ludvico, & Morrow, 2014), but students can also prepare for the in-class experience by performing experiments with online laboratories, possibly embedded in supportive ILSs. The data that are generated there (such as the process and artefact data discussed above) can form the input for the teacher to shape the in-class interaction. Presenting these (individual and group) data to the teacher can be done in the form of

teacher dashboards that summarize and visualize the students' behaviour and products (Rodríguez-Triana et al., 2017). How these dashboards should be designed and what role they can play in class discussion is currently the subject of study (see, e.g., Sarikaya, Correll, Bartram, Tory, & Fisher, in press; Schwendimann et al., 2017; Verbert, Duval, Klerkx, Govaerts, & Santos, 2013).

8 | CONCLUSION

Data on conceptual knowledge acquisition by students participating in traditional STEM education, as presented at the start of this article, show that, despite what sometimes is claimed, we cannot just sit on our hands and continue following a purely expository mode of instruction. Instead, a change is needed. In this article, I have tried to indicate the direction in which this change should go: engaged learning with the help of technology, as well as how to implement this move: not radically, but in combination with other forms of learning, and what developments to expect for the future: the use of learning analytics to make interaction with the learner more adaptive and enable smart combinations with other forms of instruction, as in flip-the-classroom kinds of approaches.

Engaged learning basically means that students are cognitively stimulated and aided to elaborate on the content that is offered to them so that they mould, extend, or annotate this content. In this paper, I have taken inquiry learning as an example, but the same arguments used here could hold for other forms of engaged learning such as problem-based learning, learning by self-explanation, and peer tutoring. Technology in the form of online (virtual and remote) laboratories that give students the affordances to perform investigations can play an important role in enabling inquiry learning, but dedicated technologies are also available for other forms of engaged learning, such as peer tutoring, explanation-based learning, and problem-based learning (see, e.g., de Jong et al., 2012; C. Hsu, Tsai, & Wang, 2016; T. Hsu, 2018; Kim & Hannafin, 2011; Sansone, Ligorio, & Buglass, 2018; Walker, Rummel, & Koedinger, 2011). The use of technology enables the introduction of dedicated situations in the classroom, but it also facilitates the introduction of online dynamic and interactive support as part of the engaged teaching method.

Data from research show that inquiry learning is an effective teaching method when used in combination with appropriate guidance. This, however, does not mean we should introduce (technology-mediated) inquiry learning as the one and only method in the classroom. The outcome of research on the effectiveness of inquiry learning (or in fact any form of [engaged] learning) is often much subtler than a simple "yes" or "no" for a variety of reasons. The teaching and learning process is simply too complex to allow for unconditional statements about the effectiveness of any instructional method; many factors mediate whether a method is effective or not. Recommendations are always based on an average, but that does not mean that what is "evidence based" for the average is universally valid for a specific learner or a specific class with a specific teacher. Student characteristics (e.g., prior knowledge) influence the outcome of implementing a method or support mechanism. A similar argument holds for teacher characteristics; the same intervention may, for example, have

dramatically different effects in the hands of a novice teacher as compared with a very experienced one. There may even be a subtle interaction of the teaching situation with domain characteristics. Bumbacher et al. (2015), for example, found that virtual and physical laboratories had reverse effects on students' learning activities for the domains of electrical circuits and masses and springs. Furthermore, the effectiveness of instructional methods should be considered not only as far as the method per se but also from a curriculum perspective. Intuitively, we can say that a one-sided curriculum is probably not the most attractive and effective, and doing inquiry (or whatever method) all the time does not seem like the right approach. It seems more appropriate that a delicate balance between direct teaching and student-driven learning (such as inquiry) should be sought in the curriculum as a whole. Some content for some students can most probably be better taught by more expository methods, whereas at other points and for other students, more engaged, student-driven approaches are appropriate.

There seems much to be in favour of a diversified teaching approach that makes room for forms of instruction that invite students to be active and engaged, but that balances these forms of instruction with more expository instructional approaches, both in direct combination and in the context of an entire curriculum (Clark, Kirschner, & Sweller, 2012; Schneider & Preckel, 2017; Smetana & Bell, 2012; Teig et al., 2018). A similar argument holds for the use of media. Although technology may be a facilitator of inquiry learning, for instance, it may also have its disadvantages. Bumbacher et al. (2015), for example, found that students using a physical lab applied more systematic inquiry behaviour than students who were using a virtual lab, which was then related to being successful on a domain knowledge post test (see Renken & Nunez, 2013, for similar results). To complicate the case further, Bumbacher, Salehi, Wieman, and Blikstein (2018) found indications that there was a subtle interaction between domain characteristics, the laboratory being virtual or real, and students' experimentation strategies. Similar results have recently been reported by Sullivan, Gnesdilow, Puntambekar, and Kim (2017). In this case also, it therefore seems wise to search for a solution that combines virtual and real laboratories to create a balanced curriculum (see, e.g., Makransky, Thisgaard, & Gadegaard, 2016; Zacharia & de Jong, 2014).

The exploration in this paper started with data showing that traditional education as applied to STEM topics may not lead to deep conceptual knowledge. However, the further analyses led not to a plea to abandon direct instruction, but rather to the recommendation to seek balanced and smart combinations of direct instruction with more engaged forms of learning such as inquiry learning. The availability of interactive learning materials, for example, in the form of online labs, extends the teacher's repertoire; when used with wisdom and in the right dose, such materials may help to leverage students' conceptual understanding of a (science) domain. These are several ways in which technology, and more specifically, learning analytics and adaptive scaffolds, can help to bring engaged learning to the next level.

ACKNOWLEDGEMENTS

This work was partially funded by the European Union in the context of the Go-Lab project (Grant Agreement 317601) under the

Information and Communication Technologies (ICT) theme of the 7th Framework Programme for R&D (FP7) and by the Next-Lab and GO-GA innovation action (Grant Agreements 731685 and 781012) under Research and Innovation H2020 Framework Programme. In addition, this work was partly sponsored by the Netherlands Organisation for Scientific Research (NWO) and TechYourFuture under project number 409-15-209. This document does not represent the opinion of the European Union NWO or TYF, and these organisations are not responsible for any use that might be made of its content. I am grateful to all my colleagues from all these projects for many inspirational project meetings, to Emily Fox for editing the manuscript, and to my colleagues from the Department of Instructional Technology for providing me with very valuable feedback on an earlier draft of this paper.

ORCID

Ton de Jong  <https://orcid.org/0000-0003-0416-4304>

REFERENCES

- Achuthan, K., Sreelatha, K. S., Surendran, S., Diwakar, S., Nedungadi, P., Humphreys, S., ... Mahesh, S. (2011, October–November). The value @ Amrita virtual labs project: Using web technology to provide virtual laboratory access to students. Paper presented at the Global Humanitarian Technology Conference (GHTC), 2011 IEEE.
- Alessi, S. M., & Trollip, S. R. (2001). *Multimedia for learning: Methods and development* (3rd ed.). Boston: Allyn and Bacon.
- Alfieri, L., Brooks, P. J., Aldrich, N. J., & Tenenbaum, H. R. (2011). Does discovery-based instruction enhance learning? *Journal of Educational Psychology, 103*, 1–18. <https://doi.org/10.1037/a0021017>
- Andrews, T. M., Leonard, M. J., Colgrove, C. A., & Kalinowski, S. T. (2011). Active learning not associated with student learning in a random sample of college biology courses. *CBE Life Sciences Education, 10*, 394–405. <https://doi.org/10.1187/cbe.11-07-0061>
- Auerbach, A. J., Higgins, M., Brickman, P., Andrews, T. C., & Labov, J. (2018). Teacher knowledge for active-learning instruction: Expert-novice comparison reveals differences. *CBE Life Sciences Education, 17*, ar12. <https://doi.org/10.1187/cbe.17-07-0149>
- Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. New York: Holt, Rinehart & Winston.
- Banchi, H., & Bell, R. (2008). The many levels of inquiry. *Science and Children, 46*, 26–29.
- Barzilai, S., & Blau, I. (2014). Scaffolding game-based learning: Impact on learning achievements, perceived learning, and game experiences. *Computers & Education, 70*, 65–79. <https://doi.org/10.1016/j.compedu.2013.08.003>
- Bazelais, P., & Doleck, T. (2018). Investigating the impact of blended learning on academic performance in a first semester college physics course. *Journal of Computers in Education, 5*, 67–94. <https://doi.org/10.1007/s40692-018-0099-8>
- Belland, B. R., Walker, A. E., & Kim, N. J. (2017). A Bayesian network meta-analysis to synthesize the influence of contexts of scaffolding use on cognitive outcomes in STEM Education. *Review of Educational Research, 87*, 1042–1081. <https://doi.org/10.3102/0034654317723009>
- Belland, B. R., Walker, A. E., Kim, N. J., & Lefler, M. (2017). Synthesizing results from empirical research on computer-based scaffolding in STEM Education. *Review of Educational Research, 87*, 309–344. <https://doi.org/10.3102/0034654316670999>
- Bennet, D., & Bennet, A. (2008). The depth of knowledge: Surface, shallow or deep? *Vine, 38*, 405–420. <https://doi.org/10.1108/03055720810917679>
- Bodner, G. M. (1991). I have found you an argument: The conceptual knowledge of beginning chemistry graduate students. *Journal of Chemical Education, 68*, 385. <https://doi.org/10.1021/ed068p385>
- Bonde, M. T., Makransky, G., Wandall, J., Larsen, M. V., Morsing, M., Jarmer, H., & Sommer, M. O. A. (2014). Improving biotech education through gamified laboratory simulations. *Nature Biotechnology, 32*, 694–697. <https://doi.org/10.1038/nbt.2955>
- Bonnstetter, R. J. (1998). Inquiry: Learning from the past with an eye on the future. *Electronic Journal of Science Education, 3*.
- Boud, D., Keogh, R., & Walker, D. (2013). *Reflection: Turning experience into learning*. Milton Park (UK): Routledge.
- Brant, G., Hooper, E., & Sugrue, B. (1991). Which comes first, the simulation or the lecture? *Journal of Educational Computing Research, 7*, 469–481. <https://doi.org/10.2190/PWDP-45L8-LHL5-2VX7>
- Brenner, D. G., Matlen, B. J., Timms, M. J., Gochyev, P., Grillo-Hill, A., Luttgen, K., & Varfolomeeva, M. (2017). Modeling student learning behavior patterns in an online science inquiry environment. *Technology, Knowledge and Learning, 22*, 405–425. <https://doi.org/10.1007/s10758-017-9325-0>
- Bumbacher, E., Salehi, S., Wieman, C., & Blikstein, P. (2018). Tools for science inquiry learning: Tool affordances, experimentation strategies, and conceptual understanding. *Journal of Science Education and Technology, 27*, 215–235. <https://doi.org/10.1007/s10956-017-9719-8>
- Bumbacher, E., Salehi, S., Wierzchula, M., & Blikstein, P. (2015). Learning environments and inquiry behaviors in science inquiry learning: How their interplay affects the development of conceptual understanding in physics. In O. C. Santos, J. G. Boticario, C. Romero, M. Pechenizkiy, A. Merceron, P. Mitros, et al. (Eds.), *Proceedings of the 8th international conference on educational data mining* (pp. 61–69). Madrid.
- Burgoon, J. N., Heddle, M. L., & Duran, E. (2010). Re-examining the similarities between teacher and student conceptions about physical science. *Journal of Science Teacher Education, 21*, 859–872. <https://doi.org/10.1007/s10972-009-9177-0>
- Cairns, D., & Aarepattamannil, S. (in press). Exploring the relations of inquiry-based teaching to science achievement and dispositions in 54 countries. *Research in Science Education*. <https://doi.org/10.1007/s11165-017-9639-x>
- Chang, C.-J., Chang, M.-H., Chiu, B.-C., Liu, C.-C., Fan Chiang, S.-H., Wen, C.-T., ... Chen, W. (2017). An analysis of student collaborative problem solving activities mediated by collaborative simulations. *Computers & Education, 114*, 222–235. <https://doi.org/10.1016/j.compedu.2017.07.008>
- Chi, M. T. H. (2009). Active-constructive-interactive: A conceptual framework for differentiating learning activities. *Topics in Cognitive Science, 1*, 73–105. <https://doi.org/10.1111/j.1756-8765.2008.01005.x>
- Chi, M. T. H., Siler, S. A., Jeong, H., Yamauchi, T., & Hausmann, R. G. (2001). Learning from human tutoring. *Cognitive Science, 25*, 471–533. https://doi.org/10.1207/s15516709cog2504_1
- Chi, M. T. H., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist, 49*, 219–243. <https://doi.org/10.1080/00461520.2014.965823>
- Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research, 63*, 1–51. <https://doi.org/10.3102/00346543063001001>
- Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86*, 175–218. <https://doi.org/10.1002/sce.10001>
- Christian, W., & Belloni, M. (2003). *Physlet Physics*. Upper Saddle River, NJ: Prentice-Hall, Inc.
- Clark, R. E., Kirschner, P. A., & Sweller, J. (2012). Putting students on the path to learning: The case for fully guided instruction. *American Educator, Spring*, 6–11.
- Constantinou, C. (2015). Modeling based learning in Science. EARLI 2015 Presidential address retrieved from https://www.researchgate.net/publication/282440831_EARLI_2015_Presidential_Address_Presentation_on_Modeling_Based_Learning_in_Science

- Cros, D., Chastrette, M., & Fayol, M. (1988). Conceptions of second year university students of some fundamental notions in chemistry. *International Journal of Science Education*, 10, 331–336. <https://doi.org/10.1080/0950069880100308>
- Crouch, C. H., & Mazur, E. (2001). Peer instruction: Ten years of experience and results. *American Journal of Physics*, 69, 970–977. <https://doi.org/10.1119/1.1374249>
- Cuban, L. (2009). *Oversold and underused*. Cambridge: Harvard University Press.
- Damelin, D., Krajcik, J. S., McIntyre, C., & Bielik, T. (2017). Students making systems models; an accessible approach. *Science Scope*, 40, 78–82.
- d'Angelo, C., Rutstein, D., Harris, C., Bernard, R., Borokhovski, E., & Haertel, G. (2014). *Simulations for STEM learning: Systematic review and meta-analysis*. Menlo Park, CA: SRI International.
- de Jong, T. (Ed.) (2015). *D1.4: Go-Lab classroom scenarios handbook* Go-Lab Project.
- de Jong, T., & Ferguson-Hessler, M. G. M. (1996). Types and qualities of knowledge. *Educational Psychologist*, 31, 105–113. https://doi.org/10.1207/s15326985ep3102_2
- de Jong, T., & Lazonder, A. W. (2014). The guided discovery principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (second ed.) (pp. 371–390). Cambridge: Cambridge University Press.
- de Jong, T., Lazonder, A. W., Pedaste, M., & Zacharia, Z. C. (2018). Simulations, games and modelling tools for learning. In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.), *International handbook of the learning sciences* (pp. 241–268). Oxford: Routledge.
- de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science*, 340, 305–308. <https://doi.org/10.1126/science.1230579>
- de Jong, T., Sotiriou, S., & Gillet, D. (2014). Innovations in STEM education: The Go-Lab federation of online labs. *Smart Learning Environments*, 1, 1–16. <https://doi.org/10.1186/s40561-014-0003-6>
- de Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research*, 68, 179–202. <https://doi.org/10.3102/00346543068002179>
- de Jong, T., Weinberger, A., Girault, I., Kluge, A., Lazonder, A. W., Pedaste, M., ... Wichmann, A. (2012). Using scenarios to design complex technology-enhanced learning environments. *Educational Technology Research and Development*, 60, 883–901. <https://doi.org/10.1007/s11423-012-9258-1>
- DeCaro, M. S., & Rittle-Johnson, B. (2012). Exploring mathematics problems prepares children to learn from instruction. *Journal of Experimental Child Psychology*, 113, 552–568. <https://doi.org/10.1016/j.jecp.2012.06.009>
- Diziol, D., Walker, E., Rummel, N., & Koedinger, K. R. (2010). Using intelligent tutor technology to implement adaptive support for student collaboration. *Educational Psychology Review*, 22, 89–102. <https://doi.org/10.1007/s10648-009-9116-9>
- Dmoshinskaia, N., Gijlers, H., & de Jong, T. (in preparation). Does peer feedback help student to gain better results in an online-lab based inquiry learning experience?
- Duque, R., Gómez-Pérez, D., Nieto-Reyes, A., & Bravo, C. (2015). Analyzing collaboration and interaction in learning environments to form learner groups. *Computers in Human Behavior*, 47, 42–49. <https://doi.org/10.1016/j.chb.2014.07.012>
- Eshuis, E., ter Vrugte, J., Anjewierden, A., Bollen, L., Sikken, J., & de Jong, T. (in press). Developing vocational students' collaboration skills and knowledge through instruction and joint reflection. *International Journal of Computer-Supported Collaborative Learning*.
- Eysink, T. H. S., & de Jong, T. (2012). Does instructional approach matter? How elaboration plays a crucial role in multimedia learning. *Journal of the Learning Sciences*, 21, 583–625. <https://doi.org/10.1080/10508406.2011.611776>
- Falconer, J. L. (2016). Why not try active learning? *AIChE Journal*, 62, 4174–4181.
- Fang, S. C., & Hsu, Y. S. (2017). Understanding science teachers' enactments of a computer-based inquiry curriculum. *Computers & Education*, 112, 69–82. <https://doi.org/10.1016/j.compedu.2017.05.004>
- Fratamico, L., Conati, C., Kardan, S., & Roll, I. (2017). Applying a framework for student modeling in exploratory learning environments: Comparing data representation granularity to handle environment complexity. *International Journal of Artificial Intelligence in Education*, 27, 320–352. <https://doi.org/10.1007/s40593-016-0131-y>
- Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences*, 111, 8410–8415. <https://doi.org/10.1073/pnas.1319030111>
- Furberg, A. (2016). Teacher support in computer-supported lab work: Bridging the gap between lab experiments and students' conceptual understanding. *International Journal of Computer-Supported Collaborative Learning*, 11, 89–113. <https://doi.org/10.1007/s11412-016-9229-3>
- Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching. *Review of Educational Research*, 82, 300–329. <https://doi.org/10.3102/0034654312457206>
- Gijlers, H., & de Jong, T. (2013). Using concept maps to facilitate collaborative inquiry learning. *Journal of the Learning Sciences*, 22, 340–374. <https://doi.org/10.1080/10508406.2012.748664>
- Gillet, D., Rodríguez-Triana, M. J., de Jong, T., Bollen, L., & Dikke, D. (2017, July). Cloud ecosystem for supporting inquiry learning with online labs: Creation, personalization, and exploitation. Paper presented at the Experiment@ International Conference.
- Gobert, J. D., Kim, Y., Sao Pedro, M. A., Kennedy, M., & Betts, C. G. (2015). Using educational data mining to assess students' skills at designing and conducting experiments within a complex systems microworld. *Thinking Skills and Creativity*, 18, 81–90. <https://doi.org/10.1016/j.tsc.2015.04.008>
- Gobert, J. D., Moussavi, R., Li, H., Sao Pedro, M. A., & Dickler, R. (2018). Real time scaffolding of students' online data interpretation during inquiry with Inq-ITS using educational datamining. In A. K. M. Azad, M. Auer, A. Edwards, & T. de Jong (Eds.), *Cyber-physical laboratories in engineering and science education* (pp. 191–219). Cham (Switzerland): Springer.
- Gobert, J. D., Sao Pedro, M. A., Raziuddin, J., & Baker, R. S. (2013). From log files to assessment metrics: Measuring students' science inquiry skills using educational data mining. *Journal of the Learning Sciences*, 22, 521–563. <https://doi.org/10.1080/10508406.2013.837391>
- Gorissen, C. J. J., Kester, L., Brand-Gruwel, S., & Martens, R. L. (2015). Autonomy supported, learner-controlled or system-controlled learning in hypermedia environments and the influence of academic self-regulation style. *Interactive Learning Environments*, 23, 655–669. <https://doi.org/10.1080/10494820.2013.788038>
- Gunstone, R. F., & White, R. T. (1981). Understanding of gravity. *Science Education*, 65, 291–299. <https://doi.org/10.1002/sci.3730650308>
- Hagemans, M. G., van der Meij, H., & de Jong, T. (2013). The effects of a concept map-based support tool on simulation-based inquiry learning. *Journal of Educational Psychology*, 105, 1–24. <https://doi.org/10.1037/a0029433>
- Hake, R. H. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, 66, 64–74. <https://doi.org/10.1119/1.18809>
- Hattie, J. A. C., & Donoghue, G. M. (2016). Learning strategies: A synthesis and conceptual model. *Npj Science Of Learning*, 1, 16013. <https://doi.org/10.1038/npjscilearn.2016.13>
- Heijnes, D., van Joolingen, W. R., & Leenaars, F. A. J. (2018). Stimulating scientific reasoning with drawing-based modeling. *Journal of Science*

- Education and Technology*, 27, 45–56. <https://doi.org/10.1007/s10956-017-9707-z>
- Herron, M. D. (1971). The nature of scientific enquiry. *The School Review*, 79, 171–212. <https://doi.org/10.1086/442968>
- Hsu, C., Tsai, C., & Wang, H. (2016). Exploring the effects of integrating self-explanation into a multi-user game on the acquisition of scientific concepts. *Interactive Learning Environments*, 24, 844–858. <https://doi.org/10.1080/10494820.2014.926276>
- Hsu, T. (2018). Behavioural sequential analysis of using an instant response application to enhance peer interactions in a flipped classroom. *Interactive Learning Environments*, 26, 91–105. <https://doi.org/10.1080/10494820.2017.1283332>
- Jiang, F., & McComas, W. F. (2015). The effects of inquiry teaching on student science achievement and attitudes: Evidence from propensity score analysis of PISA data. *International Journal of Science Education*, 37, 554–576. <https://doi.org/10.1080/09500693.2014.1000426>
- Kaartinen, S., & Kumpulainen, K. (2002). Collaborative inquiry and the construction of explanations in the learning of science. *Learning and Instruction*, 12, 189–213. [https://doi.org/10.1016/S0959-4752\(01\)00004-4](https://doi.org/10.1016/S0959-4752(01)00004-4)
- Kalyuga, S. (2007). Expertise reversal effect and its implications for learner-tailored instruction. *Educational Psychology Review*, 19, 509–539. <https://doi.org/10.1007/s10648-007-9054-3>
- Kant, J. M., Scheiter, K., & Oschatz, K. (2017). How to sequence video modeling examples and inquiry tasks to foster scientific reasoning. *Learning and Instruction*, 52, 46–58. <https://doi.org/10.1016/j.learninstruc.2017.04.005>
- Kapur, M., & Bielaczyc, K. (2012). Designing for productive failure. *Journal of the Learning Sciences*, 21, 45–83. <https://doi.org/10.1080/10508406.2011.591717>
- Kardan, S., & Conati, C. (2015). Providing adaptive support in an interactive simulation for learning: An experimental evaluation. Paper presented at the Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.
- Käser, T., Hallinen, N. R., & Schwartz, D. L. (2017). Modeling exploration strategies to predict student performance within a learning environment and beyond. Paper presented at the Proceedings of the Seventh International Learning Analytics & Knowledge Conference.
- Kim, M. C., & Hannafin, M. J. (2011). Scaffolding problem solving in technology-enhanced learning environments (teles): Bridging research and theory with practice. *Computers & Education*, 56, 403–417. <https://doi.org/10.1016/j.compedu.2010.08.024>
- Kroeze, K., van den Berg, S., Veldkamp, B., Lazonder, A. W., & de Jong, T. (in press). Automated feedback on hypotheses; towards flexible tools for adaptive scaffolding of on-line inquiry learning. *Frontiers in Education*.
- Kruger, C. J., Summers, M. K., & Palacio, D. J. (1990). An investigation of some English primary school teachers' understanding of the concepts force and gravity. *British Educational Research Journal*, 16, 383–397. <https://doi.org/10.1080/0141192900160406>
- Laine, E., Veermans, M., Lahti, A., & Veermans, K. (2017). Generation of student interest in an inquiry-based mobile learning environment. *Frontline Learning Research*, 5, 42–60. <https://doi.org/10.14786/flr.v5i4.306>
- Land, S. M., & Zembal-Saul, C. (2003). Scaffolding reflection and articulation of scientific explanations in a data-rich, project-based learning environment: An investigation of progress portfolio. *Educational Technology Research and Development*, 51, 65–84. <https://doi.org/10.1007/Bf02504544>
- Lazonder, A. W., Hagemans, M. G., & de Jong, T. (2010). Offering and discovering domain information in simulation-based inquiry learning. *Learning and Instruction*, 20, 511–520. <https://doi.org/10.1016/j.learninstruc.2009.08.001>
- Lazonder, A. W., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. *Review of Educational Research*, 86, 681–718. <https://doi.org/10.3102/0034654315627366>
- Lazonder, A. W., Wilhelm, P., & van Lieburg, E. (2009). Unraveling the influence of domain knowledge during simulation-based inquiry learning. *Instructional Science*, 37, 437–451. <https://doi.org/10.1007/s11251-008-9055-8>
- Lee, V. R., & Wilkerson, M. H. (2018). Data use by middle and secondary students in the digital age: A status report and future prospects. Commissioned Paper for the National Academies of Sciences, Engineering, and Medicine, Board on Science Education, Committee on Science Investigations and Engineering Design for Grades 6–12. Washington, D.C.
- Lin, H., Cheng, H., & Lawrenz, F. (2000). The assessment of students and teachers' understanding of gas laws. *Journal of Chemical Education*, 77, 235–238. <https://doi.org/10.1021/ed077p235>
- Lin, X., Hmelo, C. E., & Kinzer, C. K. (1999). Designing technology to support reflection. *Educational Technology Research and Development*, 47, 23–40. <https://doi.org/10.1007/Bf02299633>
- Linn, M. C., Chang, H., Chiu, J., Zhang, H., & McElhaney, K. (2010). Can desirable difficulties overcome deceptive clarity in scientific visualizations. In A. S. Benjamin (Ed.), *Successful remembering and successful forgetting: A festschrift in honor of Robert A. Bjork* (pp. 239–262). New York: Psychology press.
- Liu, O. L., Rios, J. A., Heilman, M., Gerard, L., & Linn, M. C. (2016). Validation of automated scoring of science assessments. *Journal of Research in Science Teaching*, 53, 215–233. <https://doi.org/10.1002/tea.21299>
- Luik, P. (2007). Characteristics of drills related to development of skills. *Journal of Computer Assisted Learning*, 23, 56–68. <https://doi.org/10.1111/j.1365-2729.2007.00201.x>
- MacIsaac, D. (2015). Frank McCulley's simulated environments at The Physics Aviary. *The Physics Teacher*, 53, 509–509. <https://doi.org/10.1119/1.4933164>
- Makransky, G., Thisgaard, M. W., & Gadegaard, H. (2016). Virtual simulations as preparation for lab exercises: Assessing learning of key laboratory skills in microbiology and improvement of essential non-cognitive skills. *PLoS One*, 11, e0155895. <https://doi.org/10.1371/journal.pone.0155895>
- Manlove, S., Lazonder, A. W., & de Jong, T. (2007). Software scaffolds to promote regulation during scientific inquiry learning. *Metacognition & Learning*, 2, 141–155. <https://doi.org/10.1007/s11409-007-9012-y>
- Mayer, R. E. (2004). Should there be a three-strikes rule against pure discovery learning? *American Psychologist*, 59, 14–19. <https://doi.org/10.1037/0003-066X.59.1.14>
- McDermott, L. C. (1984). Research on conceptual understanding in mechanics. *Physics Today*, 37, 24–32.
- Minner, D. D., Levy, A. J., & Century, J. (2010). Inquiry-based science instruction—What is it and does it matter? Results from a research synthesis years 1984 to 2002. *Journal of Research in Science Teaching*, 47, 474–496. <https://doi.org/10.1002/tea.20347>
- Moore, E. B., & Perkins, K. K. (2018). Advances in PhET interactive simulations: Interoperable and accessible. In A. K. M. Azad, M. Auer, A. Edwards, & T. de Jong (Eds.), *Cyber-physical laboratories in engineering and science education* (pp. 141–163). Cham (Switzerland): Springer.
- Nakhleh, M. B. (1992). Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education*, 69, 191. <https://doi.org/10.1021/ed069p191>
- National Academies of Sciences Engineering Medicine (2018). *How people learn II: Learners, contexts, and cultures*. Washington, DC: The National Academies Press.
- National Science Foundation (2000). An introduction to inquiry. In *Foundations. Inquiry: Thoughts, views and strategies for the K-5 classroom* (ed., Vol. 2) (pp. 1–5). Arlington, VA.
- Nedungadi, P., Malini, P., & Raman, R. (2015). Inquiry based learning pedagogy for chemistry practical experiments using OLabs. In E.-S. M. El-Alfy, S. M. Thampi, H. Takagi, S. Piramuthu, & T. Hanne (Eds.), *Advances in intelligent informatics. Advances in intelligent systems and computing* (ed., Vol. 320) (pp. 633–642). Cham: Springer International Publishing.

- Nedungadi, P., Ramesh, M. V., Pradeep, P., & Raman, R. (2018). Providing pedagogical support for collaborative development of virtual and remote labs: Amrita VILCAP. In A. K. M. Azad, M. Auer, A. Edwards, & T. de Jong (Eds.), *Cyber-physical laboratories in engineering and science education* (pp. 219–241). Cham (Switzerland): Springer.
- OECD (2016). *PISA 2015 results (volume II): Policies and practices for successful schools*. Paris (France): PISA, OECD Publishing.
- Ortiz, L. G., Heron, P. R. L., & Shaffer, P. S. (2005). Student understanding of static equilibrium: Predicting and accounting for balancing. *American Journal of Physics*, 73, 545–553. <https://doi.org/10.1119/1.1862640>
- Osborne, J. (2010). Arguing to learn in Science: The role of collaborative, critical discourse. *Science*, 328, 463–466. <https://doi.org/10.1126/science.1183944>
- Pedaste, M., Mäeots, M., Siiman, L. A., de Jong, T., van Riesen, S. A. N., Kamp, E. T., ... Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and inquiry cycle. *Educational Research Review*, 14, 47–61. <https://doi.org/10.1016/j.edurev.2015.02.003>
- Peffer, M. E., Beckler, M. L., Schunn, C., Renken, M., & Revak, A. (2015). Science classroom inquiry (SCI) simulations: A novel method to scaffold science learning. *PLoS One*, 10, e0120638. <https://doi.org/10.1371/journal.pone.0120638>
- Perez, S., Massey-Allard, J., Butler, D., Ives, J., Bonn, D., Yee, N., & Roll, I. (2017). Identifying productive inquiry in virtual labs using sequence mining. In E. André, R. Baker, X. Hu, M. M. T. Rodrigo, & B. du Boulay (Eds.), *Artificial intelligence in Education: 18th international conference, AIED 2017, Wuhan, China, June 28 - July 1, 2017, proceedings* (pp. 287–298). Cham: Springer International Publishing.
- Pines, A. L., & West, L. H. T. (1986). Conceptual understanding and science learning: An interpretation of research within a sources-of-knowledge framework. *Science Education*, 70, 583–604. <https://doi.org/10.1002/sce.3730700510>
- Plass, J. L., Milne, C., Homer, B. D., Schwartz, R. N., Hayward, E. O., Jordan, T., ... Barrientos, J. (2012). Investigating the effectiveness of computer simulations for chemistry learning. *Journal of Research in Science Teaching*, 49, 394–419. <https://doi.org/10.1002/tea.21008>
- Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education*, 94, 223–231. <https://doi.org/10.1002/j.2168-9830.2004.tb00809.x>
- Protopsaltis, A., Hetzner, S., Seitlinger, P., Bedek, M., Rusman, S. E., Firssova, O., ... Scott, P. (2013). *weSPOT project, Deliverable D2.1: State of the art analysis*. Heerlen (the Netherlands): Open University.
- Renken, M. D., & Nunez, N. (2013). Computer simulations and clear observations do not guarantee conceptual understanding. *Learning and Instruction*, 23, 10–23. <https://doi.org/10.1016/j.learninstruc.2012.08.006>
- Resnick, M., Maloney, J., Monroy-Hernandez, A., Rusk, N., Eastmond, E., Brennan, K., ... Kafai, Y. (2009). Scratch: Programming for all. *Communications of the ACM*, 52, 60–67. <https://doi.org/10.1145/1592761.1592779>
- Rodríguez-Triana, M. J., Martínez-Monés, A., Asensio-Pérez, J. I., & Dimitriadis, Y. (2015). Scripting and monitoring meet each other: Aligning learning analytics and learning design to support teachers in orchestrating CSCL situations. *British Journal of Educational Technology*, 46, 330–343. <https://doi.org/10.1111/bjet.12198>
- Rodríguez-Triana, M. J., Prieto, L. P., Vozniuk, A., Boroujeni, M. S., Schwendimann, B. A., Holzer, A., & Gillet, D. (2017). Monitoring, awareness and reflection in blended technology enhanced learning: A systematic review. *International Journal of Technology Enhanced Learning*, 9, 126–150. <https://doi.org/10.1504/ijtel.2017.084489>
- Roll, I., Butler, D., Yee, N., Welsh, A., Perez, S., Briseno, A., ... Bonn, D. (2018). Understanding the impact of guiding inquiry: The relationship between directive support, student attributes, and transfer of knowledge, attitudes, and behaviours in inquiry learning. *Instructional Science*, 46, 77–104. <https://doi.org/10.1007/s11251-017-9437-x>
- Roschelle, J., Martin, W., Ahn, J., & Schank, P. (2017). *Cyberlearning community report: The state of cyberlearning and the future of learning with technology*. Menlo Park CA: SRI International.
- Rosenthal, R. (1979). The file drawer problem and tolerance for null results. *Psychological Bulletin*, 86, 638. <https://doi.org/10.1037/0033-2909.86.3.638>
- Rutten, N., van Joolingen, W. R., & van der Veen, J. T. (2012). The learning effects of computer simulations in science education. *Computers & Education*, 58, 136–153. <https://doi.org/10.1016/j.compedu.2011.07.017>
- Ryoo, K., & Linn, M. C. (2016). Designing automated guidance for concept diagrams in inquiry instruction. *Journal of Research in Science Teaching*, 53, 1003–1035. <https://doi.org/10.1002/tea.21321>
- Sansone, N., Ligorio, M. B., & Buglass, S. L. (2018). Peer e-tutoring: Effects on students' participation and interaction style in online courses. *Innovations in Education and Teaching International*, 55, 13–22. <https://doi.org/10.1080/14703297.2016.1190296>
- Sao Pedro, M. A., Baker, R. S. J., Gobert, J. D., Montalvo, O., & Nakama, A. (2013). Leveraging machine-learned detectors of systematic inquiry behavior to estimate and predict transfer of inquiry skill. *User Modeling and User-Adapted Interaction*, 23, 1–39. <https://doi.org/10.1007/s11257-011-9101-0>
- Sarikaya, A., Correll, M., Bartram, L., Tory, M., & Fisher, D. (in press). What do we talk about when we talk about dashboards? *IEEE Transactions on Visualization and Computer Graphics*, 29.
- Schneider, M., & Preckel, F. (2017). Variables associated with achievement in higher education: A systematic review of meta-analyses. *Psychological Bulletin*, 143, 565–600. <https://doi.org/10.1037/bul0000098>
- Schön, D. A. (1987). *Educating the reflective practitioner*. San Francisco: Jossey Bass.
- Schroeder, C. M., Scott, T. P., Tolson, H., Huang, T. Y., & Lee, Y. (2007). A meta-analysis of national research: Effects of teaching strategies on student achievement in science in the United States. *Journal of Research in Science Teaching*, 44, 1436–1460. <https://doi.org/10.1002/tea.20212>
- Schuster, D., Cobern, W. W., Adams, B. A. J., Undreiu, A., & Pleasants, B. (2018). Learning of core disciplinary ideas: Efficacy comparison of two contrasting modes of science instruction. *Research in Science Education*, 48, 389–435. <https://doi.org/10.1007/s11165-016-9573-3>
- Schwab, J. J., & Brandwein, P. F. (1962). The teaching of science as enquiry. In J. J. Schwab, & P. F. Brandwein (Eds.), *The teaching of science* (pp. 3–103). Cambridge, MA: Harvard University Press.
- Schwartz, D. L. (1995). The emergence of abstract representations in dyad problem solving. *Journal of the Learning Sciences*, 4, 321–354. https://doi.org/10.1207/s15327809jls0403_3
- Schwendimann, B. A., Rodríguez-Triana, M. J., Vozniuk, A., Prieto, L. P., Boroujeni, M. S., Holzer, A., ... Dillenbourg, P. (2017). Perceiving learning at a glance: A systematic literature review of learning dashboard research. *IEEE Transactions on Learning Technologies*, 10, 30–41. <https://doi.org/10.1109/TLT.2016.2599522>
- Shymansky, J. A., Hedges, L. V., & Woodworth, G. (1990). A reassessment of the effects of inquiry-based science curricula of the 60's on student performance. *Journal of Research in Science Teaching*, 27, 127–144. <https://doi.org/10.1002/tea.3660270205>
- Slotta, J. D., & Linn, M. C. (2009). *WISE science: Web-based inquiry in the classroom*. New York: Teachers College Press.
- Smetana, L. K., & Bell, R. L. (2012). Computer simulations to support Science instruction and learning: A critical review of the literature. *International Journal of Science Education*, 34, 1337–1370. <https://doi.org/10.1080/09500693.2011.605182>
- Smith, K. J., & Metz, P. A. (1996). Evaluating student understanding of solution chemistry through microscopic representations. *Journal of Chemical Education*, 73, 233–235. <https://doi.org/10.1021/ed073p233>
- Specht, M., Bedek, M., Duval, E., Held, P., Okada, A., Stevanov, K., ... Strahovnik, V. (2012). weSPOT: Inquiry based learning meets learning

- analytics. Paper presented at the 3rd International Conference on e-Learning.
- Stockard, J., Wood, T. W., Coughlin, C., & Khoury, C. R. (2018). The effectiveness of direct instruction curricula: A meta-analysis of a half century of research. *Review of Educational Research*, 88, 479–507. <https://doi.org/10.3102/0034654317751919>
- Sullivan, S., Gnesdilow, D., Puntambekar, S., & Kim, J.-S. (2017). Middle school students' learning of mechanics concepts through engagement in different sequences of physical and virtual experiments. *International Journal of Science Education*, 39, 1573–1600. <https://doi.org/10.1080/09500693.2017.1341668>
- Sun, D., Looi, C. K., & Xie, W. (2017). Learning with collaborative inquiry: A science learning environment for secondary students. *Technology, Pedagogy and Education*, 26, 241–263. <https://doi.org/10.1080/1475939X.2016.1205509>
- Tafoya, E., Sunal, D. W., & Knecht, P. (1980). Assessing inquiry potential: A tool for curriculum decision makers. *School Science and Mathematics*, 80, 43–48.
- Tansomboon, C., Gerard, L. F., Vitale, J. M., & Linn, M. C. (2017). Designing automated guidance to promote productive revision of Science explanations. *International Journal of Artificial Intelligence in Education*, 27, 729–757. <https://doi.org/10.1007/s40593-017-0145-0>
- Teig, N., Scherer, R., & Nilsen, T. (2018). More isn't always better: The curvilinear relationship between inquiry-based teaching and student achievement in science. *Learning and Instruction*, 56, 20–29. <https://doi.org/10.1016/j.learninstruc.2018.02.006>
- Toth, E. E., Ludvico, L. R., & Morrow, B. L. (2014). Blended inquiry with hands-on and virtual laboratories: The role of perceptual features during knowledge construction. *Interactive Learning Environments*, 22, 614–630. <https://doi.org/10.1080/10494820.2012.693102>
- Trouille, L. E., Coble, K., Cochran, G. L., Bailey, J. M., Camarillo, C. T., Nickerson, M. D., & Cominsky, L. R. (2013). Investigating student ideas about cosmology III: Big bang theory, expansion, age, and history of the universe. *Astronomy Education Review*, 12, 010110. <https://doi.org/10.3847/AER2013016>
- Trout, L., Lee, C. L., Moog, R., & Rickey, D. (2008). Inquiry learning: What is it? How do you do it? In S. L. Bretz (Ed.), *Chemistry in the National Science Education Standards: Models for meaningful learning in the high school chemistry classroom* (2nd ed.) (pp. 29–43). Washington, D.C: American Chemical Society, Education Division.
- Trowbridge, D. E., & McDermott, L. C. (1980). Investigation of student understanding of the concept of velocity in one dimension. *American Journal of Physics*, 48, 1020–1028. <https://doi.org/10.1119/1.12298>
- van Dijk, A. M., Eysink, T. H. S., & de Jong, T. (2016). Ability-related differences in performance of an inquiry task: The added value of prompts. *Learning and Individual Differences*, 47, 145–155. <https://doi.org/10.1016/j.lindif.2016.01.008>
- van Dijk, A. M., Eysink, T. H. S., & de Jong, T. (submitted). Comparing the ability-adjusted jigsaw method to individual learning.
- van Joolingen, W., & de Jong, T. (1993). Exploring a domain with a computer simulation: Traversing variable and relation space with the help of a hypothesis scratchpad. In D. Towner, T. de Jong, & H. Spada (Eds.), *Simulation-based experiential learning* (pp. 191–206). Berlin: Springer.
- van Riesen, S. A. N., Gijlers, H., Anjewierden, A., & de Jong, T. (2018a). The influence of prior knowledge on the effectiveness of guided experiment design. *International Journal of Science Education*, 11, 1327–1344.
- van Riesen, S. A. N., Gijlers, H., Anjewierden, A., & de Jong, T. (2018b). Supporting learners' experiment design. *Educational Technology Research & Development*, 66, 475–491.
- Verbert, K., Duval, E., Klerkx, J., Govaerts, S., & Santos, J. L. (2013). Learning analytics dashboard applications. *American Behavioral Scientist*, 57, 1500–1509. <https://doi.org/10.1177/0002764213479363>
- Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. *European Journal of Science Education*, 1, 205–221. <https://doi.org/10.1080/0140528790010209>
- Viennot, L. (2008). Learning and conceptual understanding: Beyond simplistic ideas, what have we learned. *International Commission on Physics Education*.
- Wagh, A., Cook-Whitt, K., & Wilensky, U. (2017). Bridging inquiry-based science and constructionism: Exploring the alignment between students tinkering with code of computational models and goals of inquiry. *Journal of Research in Science Teaching*, 54, 615–641. <https://doi.org/10.1002/tea.21379>
- Waldrop, M. M. (2015). Why we are teaching science wrong, and how to make it right. *Nature*, 523, 272–274. <https://doi.org/10.1038/523272a>
- Walker, E., Rummel, N., & Koedinger, K. R. (2011). Designing automated adaptive support to improve student helping behaviors in a peer tutoring activity. *International Journal of Computer-Supported Collaborative Learning*, 6, 279–306. <https://doi.org/10.1007/s11412-011-9111-2>
- Weaver, J. P., Chastain, R. J., DeCaro, D. A., & DeCaro, M. S. (2018). Reverse the routine: Problem solving before instruction improves conceptual knowledge in undergraduate physics. *Contemporary Educational Psychology*, 52, 36–47. <https://doi.org/10.1016/j.cedpsych.2017.12.003>
- Wecker, C., Rachel, A., Heran-Dörr, E., Waltner, C., Wiesner, H., & Fischer, F. (2013). Presenting theoretical ideas prior to inquiry activities fosters theory-level knowledge. *Journal of Research in Science Teaching*, 50, 1180–1206. <https://doi.org/10.1002/tea.21106>
- Wieman, C. E., Adams, W. K., & Perkins, K. K. (2008). PhET: Simulations that enhance learning. *Science*, 322, 682–683. <https://doi.org/10.1126/science.1161948>
- Woolley, J. S., Deal, A. M., Green, J., Hathenbruck, F., Kurtz, S. A., Park, T. K. H., ... Jensen, J. L. (2018). Undergraduate students demonstrate common false scientific reasoning strategies. *Thinking Skills and Creativity*, 27, 101–113. <https://doi.org/10.1016/j.tsc.2017.12.004>
- Xie, C., Tinker, R., Tinker, B., Pallant, A., Damelin, D., & Berenfeld, B. (2011). Computational experiments for science education. *Science*, 332, 1516–1517. <https://doi.org/10.1126/science.1197314>
- Yaron, D., Karabinos, M., Lange, D., Greeno, J. G., & Leinhardt, G. (2010). The ChemCollective—Virtual labs for introductory chemistry courses. *Science*, 328, 584–585. <https://doi.org/10.1126/science.1182435>
- Zacharia, Z. C., & de Jong, T. (2014). The effects on students' conceptual understanding of electric circuits of introducing virtual manipulatives within a physical manipulatives-oriented curriculum. *Cognition and Instruction*, 32, 101–158. <https://doi.org/10.1080/07370008.2014.887083>
- Zacharia, Z. C., Manoli, C., Xenofontos, N., de Jong, T., Pedaste, M., van Riesen, S. A. N., ... Tsourlidaki, E. (2015). Identifying potential types of guidance for supporting student inquiry in using virtual and remote labs: A literature review. *Educational Technology Research & Development*, 63, 257–302. <https://doi.org/10.1007/s11423-015-9370-0>
- Zhu, M., Lee, H., Wang, T., Liu, O. L., Belur, V., & Pallant, A. (2017). Investigating the impact of automated feedback on students' scientific argumentation. *International Journal of Science Education*, 39, 1648–1668. <https://doi.org/10.1080/09500693.2017.1347303>

How to cite this article: de Jong T. Moving towards engaged learning in STEM domains; there is no simple answer, but clearly a road ahead. *J Comput Assist Learn*. 2019;35:153–167. <https://doi.org/10.1111/jcal.12337>