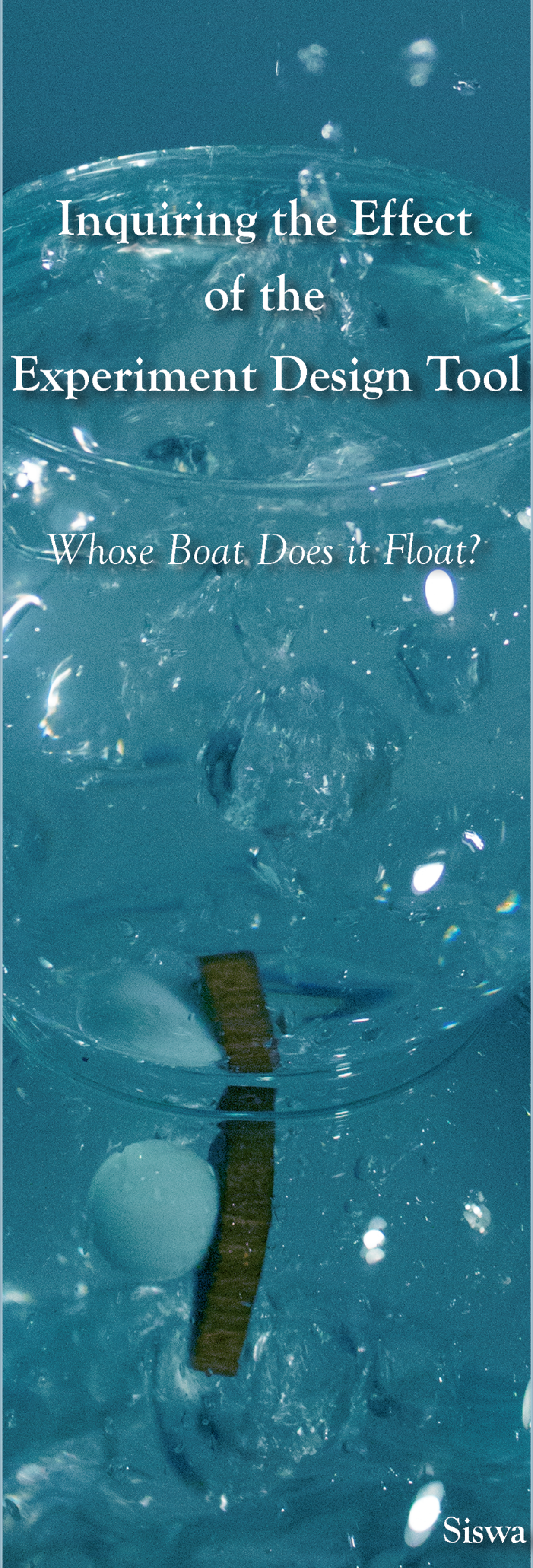

Inquiring the Effect of the Experiment Design Tool

Whose Boat Does it Float?

Siswa A. N. van Riesen

Inquiring the Effect of the Experiment Design Tool

Whose Boat Does it Float?

Siswa A. N. van Riesen

INQUIRING THE EFFECT OF THE EXPERIMENT DESIGN TOOL:

WHOSE BOAT DOES IT FLOAT?

DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
prof. dr. T. T. M. Palstra,
on account of the decision of the Doctorate Board,
to be publicly defended
on Friday the 26th of October 2018 at 12.45 hrs

by

Siswa Anakanda Njawa van Riesen

born on the 18th of April 1987
in Amersfoort, the Netherlands

This dissertation has been approved by:

Supervisor:

prof. dr. A. J. M. de Jong

Co-supervisor:

dr. A. H. Gijlers

Cover design: Siswa A. N. van Riesen

Printed: De Ipskamp, Enschede, The Netherlands

Lay-out: Siswa A. N. van Riesen

DSI Ph. D. thesis series No. 18-016

ISBN: 978-90-365-4632-4

DOI: 10.3990/1.9789036546324

ISSN: 2589-7721

GRADUATION COMMITTEE:

Chairman:	prof. dr. T. A. J. Toonen
Supervisor:	prof. dr. A. J. M. de Jong
Co-supervisor:	dr. A. H. Gijlers
Members:	prof. dr. A. W. Lazonder
	prof. dr. P. C. J. Segers
	prof. dr. M. Specht
	prof. dr. Z. C. Zacharia
	dr. H. van der Meij

Acknowledgement

This document is partially funded by the European Union in the context of the Go-Lab project (Grant Agreement no. 317601) under the Information and Communication Technologies (ICT) theme of the 7th Framework Programme for R&D (FP7). This document does not represent the opinion of the European Union, and the European Union is not responsible for any use that might be made of its content.

It was conducted in the context of the Interuniversity Center for Educational Science (research school ICO) and the Digital Society Institute (DSI), and is part of both the ICO and DSI dissertation series.

Word of Thanks

As nearly anyone who has completed, or tried to complete, their dissertation probably agrees upon, there are many highs and lows during the process of doing a PhD. My PhD started as a great high and ended as a high as well, with lots of great moments along the way. Many of those moments were accomplishments, but I think that at least as many of those were because of the great people I was surrounded with during my PhD; people who have inspired me, motivated me, made me laugh, made me think, people who made me a better scientist, and people who pushed and/or encouraged me or who just let me be me. It were also those persons who were there to help me overcome the lows that I experienced, which have ultimately made me a stronger person.

I want to start by thanking Ton de Jong, who was not only my promotor but whom I was fortunate enough to also have as a tutor for my Master's thesis. He opened up so many opportunities for me that enriched both my career and my personal life that it's hard to select the ones that affected me most. Ton, thank you for letting me experience a diversity of cultures, both geographical and educational ones, for making me part of a great international project that involved many skilled and interesting colleagues whom I got to know and work with, for encouraging me to take on many tasks of entirely different natures, for involving me in the front- and back-end of a project with the magnitude of Go-Lab, for helping me become a better and independent scientist, and for all the other things I neglected to mention here.

I'd also like to thank Hannie Gijlers and Anjo Anjewierden, who have been my supervisor(s) and so much more. Thanks for all the academic support, the brainstorming sessions, the collaboration, programming the EDT, the emotional support, and the friendship. I really appreciate all that you taught me and the encouraging conversations.

Special thanks also go out to Ellen Wassink-Kamp, who was my Go-Lab colleague, whom I have shared an office with, and who has become my friend. Thank you for the collaboration during which we truly complemented each other, for the open and honest conversations, for being there whenever I needed you, for the friendship that we built; for everything you have done as a colleague and as a friend that made you the obvious choice as my paranymph.

All my former colleagues at the department IST, thank you for having been there and making my time at the office a pleasant and interesting time. Your unique trades, qualities, and expertise positively contributed to my experience at the office. It was a delight to get to know and work with each and every one of you. I truly valued your diverse and unique characters, and the interactions with you allowed me to develop myself as a more all-round person.

Furthermore, I'd like to thank my Go-Lab colleagues without whom my journey would have been a lot less interesting and from whom I've learned so much regarding the academic world, diverse educational cultures, and international collaboration, and with whom I've had many conversations and shared many memorable moments. Thank you all for everything you have meant to me during, and even after, the project.

A lot of thanks also go out to the teachers, students, and educational- and usability experts who participated in the studies, or who contributed to my PhD in any other way. It was a pleasure to work with you and you taught me a lot about the Dutch educational system. Thank you for being so cooperative, and for giving me the freedom, time, and effort to conduct my studies the way I designed them.

I also want to thank my friends and family for being there for me and for all the moments we shared. Special thanks go out to my incredible parents, who have always encouraged me to be the best version of myself. Thank you for all your support, encouragements, the academic (and other) opportunities you gave me, and for making me become the person I am today. Dear dad, I am proud to have you as my paranymph.

Special thanks go out to my amazing husband Daniël Heikoop, who has been there for me every step of the way and in any way you can possibly imagine. Thank you for (still) letting me be who I am, for encouraging me or slowing me down when I need it, for all the emotional support, for being the person I can discuss and share everything from academic work to personal matters with, and for so much more. Basically, thank you for being the one I can always count on in every aspect.

Last, I want to thank our "kleine gup", our little boy who we are expecting to meet between Saint Nicholas Day and Christmas this year. You gave me the final push and motivation to finish my dissertation before starting a new chapter in my life.

Thank you all so much!

TABLE OF CONTENTS

1

General Introduction

This dissertation focusses on guidance for designing and conducting experiments within online inquiry learning environments. In all reported studies the effect of several types and levels of guidance for designing and conducting experiments on students' knowledge gain about buoyancy and Archimedes' principle was analysed. Specific attention was paid to the influence of prior knowledge on the effectiveness of the guidance. In this chapter the literature that served as the foundation for the reported studies is addressed.

Inquiry Learning

Education is continuously adapting to the demands of society and the focus has shifted from recalling information to active learning. In modern society, information about anything can be found at any time, making it increasingly important for students to have skills with which they can make sense of the incoming information and apply newly gained knowledge to familiar and new situations (Larson & Miller, 2011). Education should equip students with skills to successfully participate in society, and prepare them for their future careers (Jang, 2016). An educational learning method that anticipates on this is inquiry learning. Inquiry learning has received a considerable amount of attention in educational science studies and its value has been recognised by teaching programs and teachers, resulting in its integration in many educational science programs worldwide (e.g., Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Furtak, Seidel, Iverson, & Briggs, 2012; Lazonder & Harmsen, 2016; Minner, Levy, & Century, 2010). In inquiry learning, students take on the role of scientists and engage in inquiry processes like setting up and conducting experiments (de Jong, 2006; Keselman, 2003; Pedaste et al., 2015; White & Frederiksen, 1998). The effectiveness of inquiry learning has been demonstrated in many studies, provided that students are guided in their inquiry processes (e.g., Alfieri et al., 2011; Furtak et al., 2012; Lazonder & Harmsen, 2016; Minner et al., 2010).

Models of Inquiry Learning

Inquiry learning consists of several inquiry phases, often presented in the form of an inquiry cycle. Different scholars have developed an inquiry cycle incorporating inquiry phases they consider to be essential, resulting in a multitude of models that share certain concepts and underlying principles, but that also differ in certain aspects (e.g., Bybee et al., 2006; White & Frederiksen, 1998). For example, one of the most well-known inquiry cycles is the BSCS 5E Instructional Model, consisting of five inquiry phases: engagement, exploration, explanation, elaboration, and evaluation (BSCS, 1989, in Bybee et al., 2006). In this cycle, students first get engaged in the activity and activate their prior knowledge, second they design and conduct experiments, third they explain their results, fourth they elaborate on this and perform new activities to make learning deeper and more meaningful, and finally they evaluate their learning. Another example that shows many similarities with the 5E Model is the Inquiry Cycle of White and Frederiksen (1998). In this cycle, which is also comprised of five phases, students 1) formulate a research question, 2) make predictions or hypotheses regarding the question, 3) plan and carry out experiments, 4) analyse their data and summarise their findings, and 5) apply their new insights to various situations. During these activities, students can reflect upon the processes they engaged in and on the newly learned material. Reflecting upon one's inquiry has found students to produce better products (Davis, 2000), to lead to deeper learning, and students have been found to gain more complex knowledge (Kori, Mäeots, & Pedaste, 2014). Reflection helps students to integrate knowledge they obtained from their experiments with their prior knowledge, and thereby helps them build a coherent understanding of the learning material (Linn, Eylon, Rafferty, & Vitale, 2015), which can then be used to design new experiments and adapt more effective experimentation strategies (Davis, 2000; Linn et al., 2015; Pedaste et al., 2015).

In order to unify the already existing inquiry models, Pedaste et al. (2015) conducted a systematic review study about commonalities and differences between inquiry cycles that had been created up until that moment, and created a new inquiry cycle, which is the one that is adopted in this dissertation. Pedaste and colleagues analysed the inquiry activities scholars had described, and grouped those based on the descriptions. They found that distinct inquiry cycles often incorporated similar activities, but that these activities were referred to by various terms, demonstrating a lack of clear terminology across the field. The inquiry cycle of Pedaste et al. (2015) that was created based on their literature review is depicted in Figure 1.

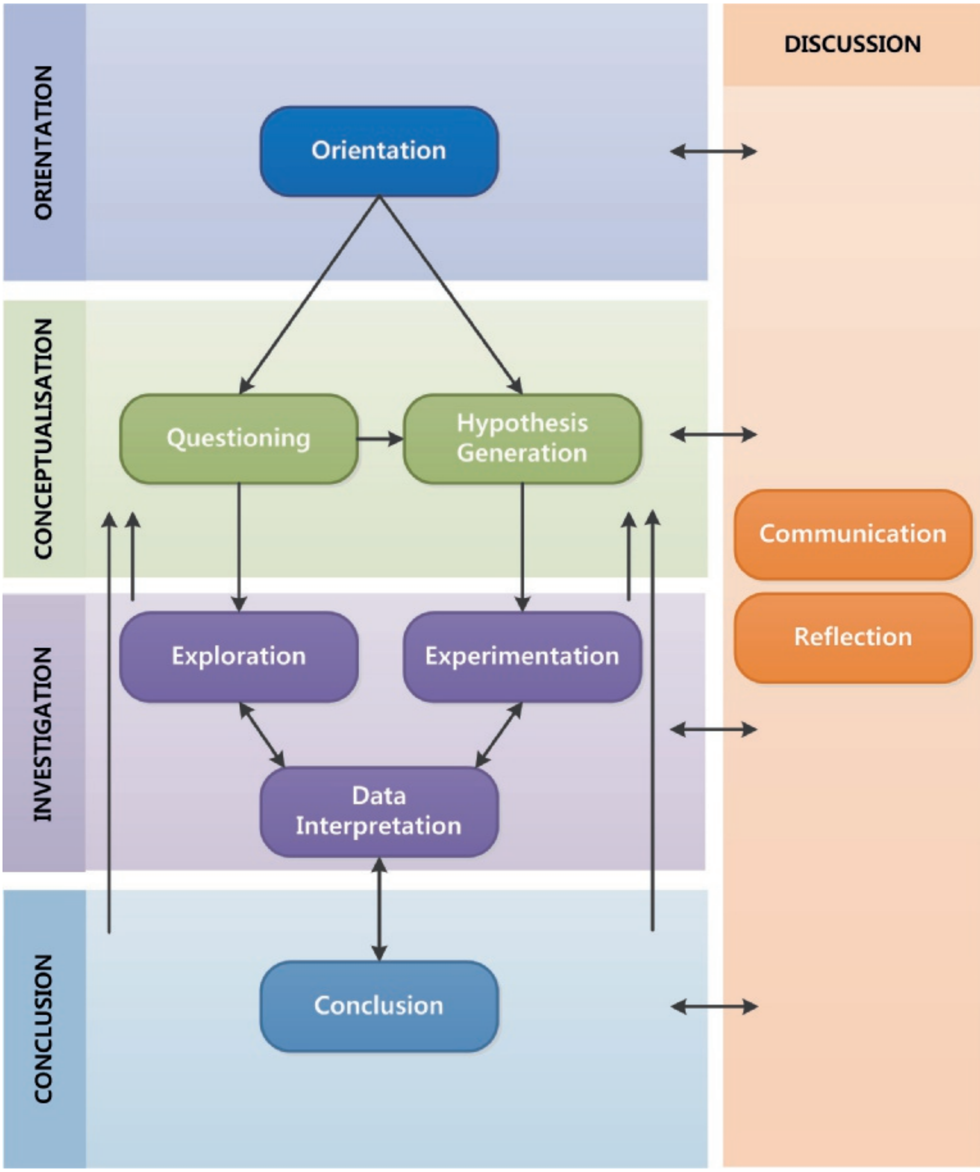

Figure 1. Inquiry-Based Learning Framework of Pedaste et al. (2015).

Pedaste et al. (2015) distinguished five main phases in their inquiry cycle: orientation, conceptualisation, investigation, conclusion and discussion. During the *orientation phase* students familiarise themselves with the topic of investigation and reactivate their prior knowledge. In the *conceptualisation phase* students formulate a research question and/or hypothesis; both of them should be based on theories about the topic of investigation, they should demonstrate the purpose of the investigation by incorporating independent and dependent variables, and they should be investigable. A research question differs from a hypothesis in the aspect that a formulated research question does not contain an expected outcome, whereas a hypothesis demonstrates an expected outcome that should be falsifiable by conducting an investigation. In the *investigation phase* students set up and conduct experiments to answer their research question and/or test their hypothesis, and they explore, observe and analyse the results. When students have conducted a sufficient amount of quality experiments they can move to the next phase to draw a conclusion. In the *conclusion phase* students draw conclusions from their data to answer the research question or test the hypothesis. The last inquiry phase Pedaste et al. (2015) distinguish is the *discussion phase*, which they treat slightly different from the other four phases. This phase entails students' communication about their findings and conclusions to others from whom they receive feedback, and students reflect upon their inquiry. The discussion phase can occur at the end of a single inquiry phase, or after students have completed the entire inquiry cycle.

Advantages and Disadvantages of Inquiry Learning

Inquiry learning requires students to actively work with the learning matter (Fosnot & Perry, 2005; Keselman, 2003; Minner et al., 2010). Students who learn actively have been found to be more cognitively engaged than students who passively receive information, and as a result develop deeper understandings (Cakir, 2008; Chi, 2009; Chi & Wylie, 2014; Fosnot & Perry, 2005). More specifically, guided inquiry learning motivates students to add new learning material to their existing knowledge, reorganise existing cognitive structures, and apply the newly gained knowledge to novel situations (Cakir, 2008; Edelson, Gordin, & Pea, 1999; Fosnot & Perry, 2005). It also fosters critical thinking and high-level processing (Carnesi & DiGiorgio, 2009), and it promotes a positive attitude towards learning (Hwang, Sung, & Chang, 2011; Laine, Veermans, Lahti, & Veermans, 2017).

Despite the positive effects of inquiry learning that were found in many studies, the method has also been critiqued (Cairns & Areepattamannil, 2017; Kirschner, Sweller, & Clark, 2006). For example, Kirschner et al. (2006) argue that no real evidence has been provided in favour of pure inquiry learning. Inquiry learning, when students are not properly guided, has indeed caused students to become frustrated (Brown & Campione, 1994), and has found to be less effective than direct instruction (Klahr & Nigam, 2004). However, even Brown and Campione (1994), who acknowledge that unguided inquiry learning can be ineffective for learning, advocate in favour of *guided* inquiry learning based on results of several years of study. In one of their studies, Brown and Campione (1994) compared three groups of students over a period of three semesters: 1) the 'research group' participated in inquiry learning during all semesters, 2) the 'partial control group' participated in inquiry learning during the first semester but was taught in the traditional way for the second and third semester, and 3) the 'read-only control group' only read the learning material but did not investigate anything themselves. Results clearly showed that the research group outperformed the read-only control group on all post-tests at the end of each semester, and they outperformed the partial control group in the second and third semester.

These results are exemplary for many studies, including review studies comparing teaching methods. For example, a review study by Alfieri et al. (2011) showed that unguided or minimally guided inquiry learning is less effective than direct instruction, but students who are properly guided during their inquiry learning processes outperformed students who received the same information via direct instruction or unguided inquiry learning. In a more recent review study that included 72 empirical studies, Lazonder and Harmsen (2016) also concluded that guidance is crucial for effective inquiry learning.

Experiment Design

At the core of inquiry learning is the investigation phase, during which students design and conduct the actual experiment, usually with the goal to test a hypothesis or answer a research question (Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003; van Riesen, Gijlers, Anjewierden, & de Jong, 2018). A well-designed experiment bridges the conceptualisation phase to the conclusion phase, and yields results to bring the student closer to form a conclusion to the hypothesis or research question (Arnold, Kremer, & Mayer, 2014; de Jong & van Joolingen, 1998; Pedaste et al., 2015).

Designing an experiment involves several activities, including selecting the variables to include in the experiment, specifying the roles of the selected variables, and assigning values to the variables that are being manipulated or controlled for. When selecting variables to include in the experiment, students should identify the variables that are associated with answering the research question or testing the hypothesis. They have to carefully think about what they want to investigate and how they can operationalise that, and accordingly determine what to measure or observe (dependent variable), what to manipulate (independent variable), and what to control for (control variable) (Arnold et al., 2014; Chinn & Malhotra, 2002; Klahr & Dunbar, 1988). It is important for students to understand that the outcome of an experiment can be influenced by each variable that is not controlled for, and thus for them to realise that only independent variables should be varied and other variables should be controlled for or observed as much as possible. An experiment normally consists of several trials in which only the independent variable is manipulated. The student then assigns a unique value to each independent variable across experimental trials, and one value to each control variable that is included in an experiment. Designing experiments entails several processes and it is essential for students to have some understanding of inquiry and to possess inquiry skills (de Jong & van Joolingen, 1998). Students of all ages experience difficulties in designing a useful experiment (de Jong, 2006). Transforming a research question into a practical experimental setup has been found to be very difficult for students, who frequently lack the skills and experience to do this (de Jong, 2006; Lawson, 2002). This is especially true for designing experiments for research questions or hypotheses that are more theoretical and that do not directly offer the manipulatable or measurable variable on a silver platter, causing students to fail converting abstract or theoretical variables into variables they can use in their experiment design (Lawson, 2002). Students' experiment designs often also include irrelevant variables that have no relation to the research question, and/or neglect variables that are relevant to the research question (de Jong & van Joolingen, 1998; Lawson, 2002; van Joolingen & de Jong, 1991). Including irrelevant information in their experiment design adds noise to the results and impedes the sense making process, whereas leaving out relevant variables will not provide students with correct and sufficient information that can lead to a conclusion. Students also tend to vary too many variables at the same time, which causes them to struggle to make sense of the data because too many factors could have caused the effect (de Jong, 2006; Glaser, Schauble, Raghavan, & Zeitz, 1992; Klahr & Nigam, 2004). Moreover, students are often not familiar with fruitful strategies of assigning values to the variables, like using extreme values to explore the domain or using smaller increments between experimental trials around changes in experiment outcomes in order to pinpoint when an effect occurs (Veermans, van Joolingen, & de Jong, 2006).

Guidance

In order to help students overcome these difficulties, they should be provided with guidance. Guided inquiry learning has been found to be effective for learning and even superior to other instructional methods, provided that students are properly guided (Hmelo-Silver, Duncan, & Chinn, 2007).

Computer-supported inquiry learning environments often incorporate tools to help students design their experiments (Zacharia et al., 2015). Tools help students perform a task they cannot yet perform on their own. They support the learning process by simplifying or taking over part of the task, and they allow students to gain higher-order skills (de Jong, 2006; de Jong & Lazonder, 2014; Reiser, 2004; Simons & Klein, 2007). The hypothesis scratchpad is an example of a tool that supports students in the form of a template with elements (i.e., conditionals, relations, and variables) that students can include to formulate their hypothesis (van Joolingen & de Jong, 1993). This tool provides students with structure and limits their search space, helping them not to become distracted by irrelevant factors. Another example, focusing on supporting the investigation phase, is the monitoring tool that automatically stores experimental trials that students have designed, in terms of included variables and their assigned values or outcomes (Veermans, de Jong, & van Joolingen, 2000). Students can rerun all experimental trials that are stored in the tool, and arrange them in ascending or descending order making it easier to compare results. The rationale behind this tool is that students can focus on discovering relationships between variables, because the monitoring tool takes over parts of the task, reducing the difficulty and at the same time automating repetitive and thereby redundant actions students had to perform themselves if they were not guided by the tool.

Guidance for experiment design often incorporates heuristics, which are expert guidelines or principles about how to perform certain actions, frequently in the form of hints or suggestions (Zacharia et al., 2015). They can also be embedded in a tool, for example, by allowing students to perform only those actions that comply with the heuristic(s). Heuristics help students become familiar with, and successfully apply, effective strategies for experiment design, which is especially beneficial for novice students who still need to learn about best practices of setting up a fruitful experiment (Veermans et al., 2006; Zacharia et al., 2015). Several strategies can be applied to design an experiment that allows drawing a conclusion based on the results of the experiment. The most popular, and often effective, strategy for experiment design is the Control of Variables Strategy (CVS), in which all variables are controlled for except the variable of interest (Klahr & Nigam, 2004; Zacharia et al., 2015). By varying only one variable at a time and control for all other factors, results of an experiment can be ascribed to the variable of interest, based on which a valid conclusion can be drawn (Klahr & Nigam, 2004; Schunn & Anderson, 1999; Tschirgi, 1980). This strategy is also known as the heuristic 'Vary One Thing At a Time (VOTAT)' (Tschirgi, 1980). In addition to knowledge about how to single out an effect, students also benefit from having a repertoire of strategies on assigning values to the variables they included in their designs. For example, for students who are new to the domain, an informative first experiment may include an independent variable to which students 'assign extremely low and extremely high values', because trials with extreme values can mark the boundaries of the domain (Schunn & Anderson, 1999; Veermans et al., 2006). Another strategy for assigning values to variables is to keep 'equal increments between trials', which can provide the student with valuable information about how strongly the dependent variable is affected by the independent variable (Schunn & Anderson, 1999; Veermans et al., 2006). A more general heuristic that is also very useful in designing experiments, is to 'keep records of what you are doing' (Klahr & Dunbar, 1988; Veermans et al., 2006). This reduces the chance that experimental trials are unnecessarily reproduced, and it allows students to inspect their results.

Scaffolding Design Framework

The effectiveness of tools for inquiry learning, is dependent on several factors. Quintana et al. (2004) developed a Scaffolding Design Framework with guidelines for designing effective tools for students' inquiry learning. The guidelines of this framework were applied to create the Experiment Design Tool, as described in Chapter 2. The framework was based on literature about the scientific processes students are engaged in, difficulties students experience in this, and ways in which tools can provide guidance to students. Seven main guidelines are distinguished in the framework. First, tools should be adapted to students' prior knowledge and use language that they understand. Tools that are responsive to students' existing level of expertise help them focus on concepts and structures related to the learning matter instead of irrelevant distractions. Moreover, this encourages students to integrate newly required information with their existing knowledge (Linn, Bell, & Davis, 2004; Quintana et al., 2004). Second, tools should guide students in acquiring knowledge and skills about the discipline and its semantics. Strategies that students can apply within the discipline should be made explicit to students, encouraging them to practice applying those strategies within their limits and allowing them to build strategic knowledge (Quintana et al., 2004). Third, tools should provide students with representations they can inspect in different ways. Allowing students to directly manipulate a representation and get immediate feedback, can help them give more meaning to abstract concepts (Linn et al., 2004; Quintana et al., 2004). Fourth, tools should provide students with a clear structure of the task to help them learn about relevant steps they can or need to take in order to accomplish the task. Students lack strategic knowledge about how to handle complex tasks and can become overwhelmed by the numerous inquiry processes they should manage (Bransford, Brown, & Cocking, 2000). Providing students with a clear structure that allows them to practice the inquiry skill step-by-step, reduces the complexity of the task and allows students to gradually help students master the skill (Linn et al., 2004; Quintana et al., 2004). Fifth, tools should embed expert guidance to help them understand and employ useful strategies. Experts often have a repertoire of strategies that have been proven to be fruitful in inquiry tasks, whereas students show less sophisticated experimentation behaviour. Providing them with expert knowledge helps them understand and execute effective strategies (Quintana et al., 2004). Sixth, tools should automatically handle routine tasks that may distract them from learning. Complex learning tasks require students' focus on meaningful aspects of the task, which can be enhanced by minimising extraneous efforts and repetition of simple tasks (Quintana et al., 2004). Seventh, tools should encourage students to articulate and reflect upon their learning. Students who make their findings explicit by communicating about and reflecting on them, have been found to better integrate existing knowledge in new knowledge and create deeper understandings (Kori et al., 2014; Linn et al., 2015).

Prior Knowledge

Prior knowledge about the domain highly influences students' conceptual knowledge gains, their ability to design useful experiments, and the effectiveness of guidance (Alexander & Judy, 1988; Hailikari, Katajavuori, & Lindblom-Ylanne, 2008; Kalyuga, 2007; Lazonder, Wilhelm, & Hagemans, 2008). Low prior knowledge students have been found to use less refined strategies than their more knowledgeable peers, and often conduct unsystematic experiments (Alexander & Judy, 1988; Hmelo, Nagarajan, & Day, 2000; Schauble, Glaser, Raghavan, & Reiner, 1991). As a result, they need to design and conduct more experimental trials before they can draw a conclusion, or they are unable to draw a conclusion at all (Alexander & Judy, 1988; Schauble et al., 1991).

Guidance that is effective for low prior knowledge students, may be ineffective for high prior knowledge students, and vice versa. It is generally acknowledged that low prior knowledge students produce better learning results with more guidance, and that high prior knowledge students benefit from less guidance (Alexander & Judy, 1988; Kalyuga & Renkl, 2009; Lazonder et al., 2008; Raes, Schellens, de Wever, & van der Hoven, 2012; Tuovinen & Sweller, 1999). Low prior knowledge students are not yet familiar with important concepts and relations within a domain, leading to difficulties with the selection of relevant variables and the assignment of values that make sense (Schauble et al., 1991). Additional guidance can help students identify relevant variables to include in their experiment design, and/or take over part of the task to eliminate the difficulty of the skill students need to master in order to accomplish the task (Tuovinen & Sweller, 1999). However, it is important to note that even though low prior knowledge students often benefit from higher levels of guidance, guidance can become too complex. Guidance should be understandable and not place heavy demands on students' cognition, because that can result in the opposite effect of hindering low prior knowledge students instead of guiding them (Roll, Baker, Aleven, & Koedinger, 2014; Roll et al., 2018; Roll, Yee, & Cervantes, 2014; van Dijk, Eysink, & de Jong, 2016).

High prior knowledge students already possess knowledge about important concepts and relationships within the domain, and their understanding of the material helps them design well-structured experiments with less, or even without, additional guidance (Alexander & Judy, 1988; Hmelo et al., 2000; Schauble et al., 1991). Guidance can even become redundant and disruptive of their learning processes, resulting in a negative effect on motivation and learning (Kalyuga, 2007; van Dijk et al., 2016). This phenomenon is referred to as the "expertise reversal effect" (Kalyuga, 2007). However, it is also important to realise that high prior knowledge students have little room left to increase their knowledge.

Laboratories

Experiments can be conducted in different types of laboratories, each with their own advantages and disadvantages. The main types of laboratories are hands-on laboratories and online laboratories. Traditionally, experiments were conducted in hands-on laboratories, which are described as physical laboratories in which students need to be present to set up and conduct the experiment (Reuter, 2009). It involves gathering and preparing all materials, and students should make sure that the variables of interest can be manipulated with the materials that are available to them. Depending on the subject matter, hands-on laboratories can involve certain risks, both for students and the utilised equipment (Corter, Esche, Chassapis, Ma, & Nickerson, 2011). An example is that certain materials can be toxic or they can explode if the lab is not operated correctly. These risks can be reduced or entirely eliminated by conducting experiments in online laboratories. Online laboratories are operated through a medium like a computer and are usually developed and maintained by a consortium consisting of, amongst others, course developers, subject matter experts, and software developers. The consortium prepares the laboratory by setting up the experiment and making sure it can be operated by students, which is a one-time procedure making it cost- and time effective (Almarshoud, 2011; Corter et al., 2011). Students can design and perform experiments within the space provided by the consortium, and if permitted by the laboratory developers, they can choose which variables to manipulate and which values to assign to them. This builds in some limitations for students because they are unable to explore everything, but it also provides them with (visual) constrains that can lead them in the correct direction to build knowledge (Toth, Ludvico, & Morrow, 2014). One of the main advantages of online labs is that they can be used from anywhere in the world, as long as the student is permitted access to the lab and is connected to the Internet. Two kinds of online labs can be distinguished, remote and virtual labs. Remote laboratories are physical laboratories operated through a medium (Almarshoud, 2011). Students can connect to the laboratory and do not have to prepare the materials and equipment necessary to conduct experiments, which saves time and money. Remote laboratories can be shared by many students and safety mechanisms can be built in, providing students with the opportunity to work with (advanced) equipment they would be prohibited to use otherwise (Cooper, 2005; Gomes & Bogosyan, 2009). Experiments can be conducted with the available materials and equipment and students can observe the results. A limitation of remote labs is that students have to work with a given set of materials and a set-up that was prepared by the consortium, providing them with little flexibility. Virtual labs are also operated through a medium, but are software simulation programs in which students carry out experiments (de Jong, Sotiriou, & Gillet, 2014; Sancristobal et al., 2012). These laboratories have the advantage that variables can take on many values; they are also accurate, time- and cost-effective, and experiments can be repeated easily, which provides students with excellent opportunities to gain theoretical understandings (Almarshoud, 2011; Balamuralithara & Woods, 2009; de Jong, Linn, & Zacharia, 2013; Gomes & Bogosyan, 2009; Schiffhauer et al., 2012, April). Virtual laboratories thus are very suitable to explore theoretical foundations of a domain by means of online inquiry learning, which is why participants in the studies in this dissertation worked with virtual labs.

Problem Statement and Dissertation Outline

One of the major issues of inquiry learning, is that its effectiveness has mainly been established when students are 'properly guided'. The question remains what constitutes proper guidance. Research has shown that what is considered to be proper guidance varies from one student to another, and that many factors influence the effectiveness of guidance on students' learning. One of the most important factors, as reported above, to influence this, is prior knowledge. In general, low prior knowledge students benefit from higher levels of guidance than high prior knowledge students. One of the main objectives of the studies reported in this dissertation, was to gain more insight in elements of guidance for experiment design that work for specific types of prior knowledge students. More specifically, for the three reported studies an Experiment Design Tool (EDT) was created and further developed into different versions with distinct features, in order to study their effects on learning gain of different prior knowledge students in two different domains. Another main objective was to develop one experiment design tool that can effectively guide students with distinct levels of prior knowledge in their experiment design processes.

The Experiment Design Tool (EDT)

The Experiment Design Tool that was based on the Scaffolding Design Framework (Quintana et al., 2004) and especially developed and refined for the studies reported in this dissertation, guides students in the design of their experiments. Students can select variables they want to include in their experiment design, determine the role (i.e., control, independent, or dependent variable), and assign values to the variables. Depending on the configuration of the EDT, students 1) can receive feedback based on their actions, 2) be required to apply CVS, 3) be required to plan a minimum amount of experimental trials, or 4) be required to reflect upon their experiment design. Chapters 2 – 4 each report one study in which the specific functionalities of the EDT are described in more detail.

Participants

All students who participated in one of the studies in this dissertation were Dutch third year pre-university students (approximate age: 15 years). In the Dutch educational system students receive secondary education on one level that matches their ability and that prepares them for the corresponding type of higher education. Students in the pre-university track follow six years of secondary education preparing them for university, of which students within a school all take the same courses during the first three years, but select a specialisation for the final three years.

Pre-university students were selected because they should master the skill of designing experiments, as it is one of their learning goals in the Dutch curriculum. Within the pre-university track, third year students were selected because these students have not yet selected their specialisation and, regardless of their mark, all follow the same courses, which was expected to result in diverse levels of prior knowledge.

Domains: Buoyancy and Archimedes' Principle

Participants reported in this dissertation all had to design and conduct experiments to learn about buoyancy and Archimedes' principle. In science education buoyancy plays an important role, and in daily life everyone encounters buoyant forces. In the Netherlands children are taught how to swim at very young ages and grow up experiencing buoyant forces. Moreover, buoyancy is part of the Dutch curriculum for third-year pre-university students, and buoyancy is a prerequisite for Archimedes' principle, which is sometimes taught as additional material. Learning about buoyancy through inquiry learning prior to Archimedes' principle addresses students' intuitive ideas and misconceptions, allowing them to start their experimentation in the Archimedes' principle domain with correct prior knowledge about buoyancy (Heron, Loverude, Shaffer, & McDermott, 2003).

For the buoyancy domain, students had to design experiments with which they could determine the factors that caused an object to float, suspend, or sink in a fluid-filled container. In order to understand buoyancy, it is important for students to have a conceptual understanding of density, which can be calculated by dividing the mass (in grams) of an object or fluid by the volume (in cm^3). If an object has a lower density than the fluid then the object will float, if the densities are equal then the object will suspend, and if the object's density is higher than the fluid's density then the object will sink (Hardy, Jonen, Möller, & Stern, 2006).

To learn about Archimedes' principle, students designed experiments to discover the relationships between objects, fluids and fluid displacement. Eventually, they were expected to understand Archimedes' principle and conclude that "an object fully or partially immersed in a fluid is buoyed up by a force equal to the weight of the fluid that the object displaces" (Halliday, Resnick, & Walker, 1997, in Hughes, 2005). By conducting experiments, they could gradually unravel the domain and find that 1) in case of a floating or suspended object, the mass of the object equals the mass of the fluid, and 2) in case of a suspended or sunken object, the volume of the object equals the volume of the fluid (Hughes, 2005).

The Studies

All studies in this dissertation are in-class experiments in which students had to work individually in an online inquiry learning environment. In all studies, the effects of three learning environments on knowledge gain were compared. The differences between the learning environments of each study are shown in Table 1.1.

Table 1.1

Differences between learning environments (LE) in each study

Study & Chapter	LE1	LE2	LE3
Study 1, Chapter 2	Contained the EDT and additional research questions	Only contained additional research questions	Did not contain the EDT or additional research questions
Study 2, Chapter 3	Contained an EDT that required students to design at least three experimental trials at once and to apply CVS	Contained an EDT that did not require students to design at least three experimental trials or to apply CVS	Did not contain an EDT
Study 3, Chapter 4	Contained the EDT of Study 2 of LE2 and required students to reflect upon their experiment design	Only contained the EDT of Study 2 of LE2	Contained a simplified version of the EDT

The first version of the EDT, based on the Scaffolding Design Framework (Quintana et al., 2004), was created for the first study discussed in this dissertation. The goal of the EDT was to guide students' design of their experiments. It was the most structured version of the EDT that was tested in this dissertation, it contained the most restrictions, and it was the only version to provide students with feedback on their experiment designs, provided in the form of pop-up screens. For the study reported in Chapter 2, this first version was embedded in an online inquiry learning environment that also included additional research questions, and it was compared to two control conditions without an EDT; one control condition also contained the additional research questions, while the other control condition did not. The additional questions were included because guiding research questions often positively influence learning. During the study, informal observations were also made, and they showed that some students became frustrated with some of the features of the EDT. Students showed annoyance with the pop-up screens containing the feedback, the step-by-step restrictions that were built in the EDT, and the additional research questions they had to answer.

For the second study, the EDT was redesigned to the extent that the basic structure of the EDT was kept, but the features that caused frustration were changed. Also, the EDT was made configurable and two configurations (Constrained and Open EDT) with different levels of support were compared to study their effects on learning gain of different prior knowledge students. The configurability was built in to ultimately have one tool for experiment design that can easily be adapted (by teachers) in order to be effective for students from all levels of prior knowledge.

Students in all conditions of the study reported in Chapter 4 worked in learning environments that only differed from each other in terms of the version of the embedded EDT. With the ultimate goal of having one experiment design tool that aids students of all levels of prior knowledge, the effect of two new versions on learning gain was studied. The Open EDT was used again in one condition, and in a second condition the Open EDT was combined with an experiment design Reflection Tool. The Reflection Tool was added because reflection can cause deeper learning and improve learning results (Kori et al., 2014). Students in the third condition had to work with a minimalistic EDT. This configuration of the EDT was less restrictive in nature than the other configurations, and thus gave students more freedom in their experiment designs. It was expected that this would especially benefit students with higher prior knowledge.

Go-Lab

The EDT and learning environments were created within the Go-Lab project. Go-Lab is a European project that offers a range of free to use online inquiry learning environments, online laboratories and data sets, and tools to guide students' inquiry processes or to help teachers monitor students' progressions (de Jong et al., 2014). Since the start of Go-Lab in 2012, hundreds of learning environments, laboratories, and tools have been added to the Go-Lab sharing platform (www.golabz.eu) in different languages and for several age groups and domains. All materials are free for use, and many materials can be adapted to fit the need of the student. Learning environments, that are called Inquiry Learning Spaces or ILSs in the Go-Lab context, can also be created from scratch, providing teachers with total freedom to develop their own lessons. Go-Lab continues to be maintained and further developed within the follow-up project Next-Lab.

References

Alexander, P. A., & Judy, J. E. (1988). The interaction of domain-specific and strategic knowledge in academic performance. *Review of Educational Research, 58*, 375-404. doi:10.3102/00346543058004375

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. doi:10.1037/A0021017

Almarshoud, A. F. (2011). The advancement in using remote laboratories in electrical engineering education: A review. *European Journal of Engineering Education, 36*, 425-433. doi:10.1080/03043797.2011.604125

Arnold, J. C., Kremer, K., & Mayer, J. (2014). Understanding students' experiments: What kind of support do they need in inquiry tasks? *International Journal of Science Education, 36*, 2719-2749. doi:10.1080/09500693.2014.930209

Balamuralithara, B., & Woods, P. C. (2009). Virtual laboratories in engineering education: The simulation lab and remote lab. *Computer Applications in Engineering Education, 17*, 108-118. doi:10.1002/cae.20186

Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How people learn: Brain, mind, experience, and school (expanded ed.)*. Washington, DC: National Academy Press.

Brown, A. L., & Campione, J. C. (1994). Guided discovery in a community of learners. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 229-270). Cambridge, MA: MIT Press.

Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A., & Landes, N. (2006). *The BSCS 5E Instructional Model: Origins and effectiveness*. Retrieved from https://uteach.wiki.uml.edu/file/view/UTeach_5Es.pdf/355111234/UTeach_5Es.pdf

Cairns, D., & Areepattamannil, S. (2017). Exploring the relations of inquiry-based teaching to science achievement and dispositions in 54 countries. *Research in Science Education*. doi:10.1007/s11165-017-9639-x

Cakir, M. (2008). Constructivist approaches to learning in science and their implications for science pedagogy: A literature review. *International Journal of Environmental & Science Education, 3*, 193-206.

Carnesi, S., & DiGiorgio, K. (2009). Teaching the inquiry process to 21st century learners. *Library Media Connection, 27*, 32-36.

Chi, M. T. H. (2009). Active-constructive-interactive: A conceptual framework for differentiating learning activities. *Topics in Cognitive Science, 1*, 73-105. doi:10.1111/j.1756-8765.2008.01005.x

Chi, M. T. H., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist, 49*, 219-243. doi:10.1080/00461520.2014.965823

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86*, 175-218. doi:10.1002/sce.10001

Cooper, M. (2005). Remote laboratories in teaching and learning: Issues impinging on widespread adoption in science and engineering education. *International Journal of Online Engineering (iJOE), 1*.

Corter, J. E., Esche, S. K., Chassapis, C., Ma, J., & Nickerson, J. V. (2011). Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories. *Computers & Education, 57*, 2054-2067. doi:10.1016/j.compedu.2011.04.009

Davis, E. A. (2000). Scaffolding students' knowledge integration: prompts for reflection in KIE. *International Journal of Science Education, 22*, 819-837. doi:10.1080/095006900412293

de Jong, T. (2006). Computer simulations: Technological advances in inquiry learning. *Science, 312*, 532-533. doi:10.1126/science.1127750

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* (2nd ed., pp. 371-390). Cambridge: Cambridge University Press.

de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science, 340*, 305-308. doi: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. doi: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*, 179-201. doi:10.2307/1170753

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences, 8*, 391-450. doi:10.1207/s15327809jls0803&4_3

Fosnot, C. T., & Perry, R. S. (2005). Constructivism: A psychological theory of learning. In C. T. Fosnot (Ed.), *Constructivism: Theory, perspectives, and practice* (2nd ed., pp. 8-38). New York and London: Teachers College Press, Columbia University.

Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. *Review of Educational Research, 82*, 300-329. doi:10.3102/0034654312457206

Glaser, R., Schauble, L., Raghavan, K., & Zeitz, C. (1992). Scientific reasoning across different domains. In E. de Corte, M. C. Linn, H. Mandl, & L. Verschaffel (Eds.), *Computer-based learning environments and problem solving* (pp. 345-371). Berlin, Heidelberg: Springer Berlin Heidelberg.

Gomes, L., & Bogosyan, S. (2009). Current trends in remote laboratories. *IEEE Transactions on Industrial Electronics, 56*, 4744-4756. doi:10.1109/TIE.2009.2033293

Hailikari, T., Katajavuori, N., & Lindblom-Ylanne, S. (2008). The relevance of prior knowledge in learning and instructional design. *American Journal of Pharmaceutical Education, 72*, Article 113. doi:10.5688/aj7205113

Hardy, I., Jonen, A., Möller, K., & Stern, E. (2006). Effects of instructional support within constructivist learning environments for elementary school students' understanding of "floating and sinking". *Journal of Educational Psychology, 98*, 307-326. doi:10.1037/0022-0663.98.2.307

Heron, P. R. L., Loverude, M. E., Shaffer, P. S., & McDermott, L. C. (2003). Helping students develop an understanding of Archimedes' principle. II. Development of research-based instructional materials. *American Journal of Physics, 71*, 1188. doi:10.1119/1.1607337

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist, 42*, 99-107. doi:10.1080/00461520701263368

Hmelo, C. E., Nagarajan, A., & Day, R. S. (2000). Effects of high and low prior knowledge on construction of a joint problem space. *Journal of Experimental Education, 69*, 36-56. doi:10.1080/00220970009600648

Hughes, S. W. (2005). Archimedes revisited: A faster, better, cheaper method of accurately measuring the volume of small objects. *Physics Education, 40*, 468-474.

Hwang, G., Sung, H., & Chang, H. (2011). *The effect of integrating STS strategy to online inquiry-based learning on students' learning performance*. Paper presented at the IEEE International Conferences on Internet of Things, and Cyber, Physical and Social Computing.

Jang, H. (2016). Identifying 21st century STEM competencies using workplace data. *Journal of Science Education and Technology, 25*, 284-301. doi:10.1007/s10956-015-9593-1

Kalyuga, S. (2007). Expertise reversal effect and its implications for learner-tailored instruction. *Educational Psychology Review, 19*, 509-539. doi:10.1007/s10648-007-9054-3

Kalyuga, S., & Renkl, A. (2009). Expertise reversal effect and its instructional implications: Introduction to the special issue. *Instructional Science, 38*, 209-215. doi:10.1007/s11251-009-9102-0

Keselman, A. (2003). Supporting inquiry learning by promoting normative understanding of multivariable causality. *Journal of Research in Science Teaching, 40*, 898-921. doi:10.1002/Tea.10115

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist, 41*, 75-86. doi:10.1207/s15326985ep4102_1

Klahr, D., & Dunbar, K. (1988). Dual space search during scientific reasoning. *Cognitive Science, 12*, 1-48. doi:10.1207/s15516709cog1201_1

Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction: Effect of direct instruction and discovery learning. *Psychological Science, 15*, 661-667. doi:10.1111/j.0956-7976.2004.00737.x

Kori, K., Mäeots, M., & Pedaste, M. (2014). Guided reflection to support quality of reflection and inquiry in web-based learning. *Procedia - Social and Behavioral Sciences, 112*, 242-251. doi:10.1016/j.sbspro.2014.01.1161

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. doi:10.14786/flr.v5i4.306

Larson, L. C., & Miller, T. N. (2011). 21st century skills: Prepare students for the future. *Kappa Delta Pi Record, 47*, 121-123. doi:10.1080/00228958.2011.10516575

Lawson, A. E. (2002). Sound and faulty arguments generated by preservice biology teachers when testing hypotheses involving unobservable entities. *Journal of Research in Science Teaching, 39*, 237-252. doi:10.1002/Tea.10019

Lazonder, A. W., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. *Review of Educational Research*. doi:10.3102/0034654315627366

Lazonder, A. W., Wilhelm, P., & Hagemans, M. G. (2008). The influence of domain knowledge on strategy use during simulation-based inquiry learning. *Learning and Instruction, 18*, 580-592. doi:10.1016/j.learninstruc.2007.12.001

Linn, M. C., Bell, P., & Davis, E. A. (2004). Specific design principles: Elaborating the scaffolded knowledge integration framework. In M. C. Linn, E. A. Davis, & P. Bell (Eds.), *Internet environments for science education* (pp. 315-339). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Linn, M. C., Eylon, B. S., Rafferty, A., & Vitale, J. M. (2015). Designing instruction to improve lifelong inquiry learning. *Eurasia Journal of Mathematics, Science & Technology Education, 11*, 217-225. doi:10.12973/eurasia.2015.1317a

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. doi:10.1002/Tea.20347

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*, 692-720. doi:10.1002/Tea.10105

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 the inquiry cycle. *Educational Research Review, 14*, 47-61. doi:10.1016/j.edurev.2015.02.003

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., . . . Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences, 13*, 337-386. doi:10.1207/s15327809jls1303_4

Raes, A., Schellens, T., de Wever, B., & van der Hoven, E. (2012). Scaffolding information problem solving in web-based collaborative inquiry learning. *Computers & Education, 59*, 82-94. doi:10.1016/j.compedu.2011.11.010

Reiser, B. J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. *Journal of the Learning Sciences, 13*, 273-304. doi:10.1207/s15327809jls1303_2

Reuter, R. (2009). Online versus in the classroom: Student success in a hands-on lab class. *American Journal of Distance Education, 23*, 151-162. doi:10.1080/08923640903080620

Roll, I., Baker, R. S. J. d., Aleven, V., & Koedinger, K. R. (2014). On the benefits of seeking (and avoiding) help in online problem solving environment. *Journal of the Learning Sciences, 23*, 537–560. doi:10.1080/10508406.2014.883977

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. doi:10.1007/s11251-017-9437-x

Roll, I., Yee, N., & Cervantes, A. (2014). Not a magic bullet: The effect of scaffolding on knowledge and attitudes in online simulations. *International Conference of the Learning Sciences Proceedings*. doi:879-886

Sancristobal, E., Martín, S., Gil, R., Orduña, P., Tawfik, M., Pesquera, A., . . . Castro, M. (2012). *State of art, initiatives and new challenges for virtual and remote labs.* Paper presented at the 12th IEEE International Conference on Advanced Learning Technologies, Rome, Italy.

Schauble, L., Glaser, R., Raghavan, K., & Reiner, M. (1991). Causal models and experimentation strategies in scientific reasoning. *Journal of the Learning Sciences, 1*, 201-238. doi:10.1207/s15327809jls0102_3

Schiffhauer, S., Gößling, J., Wirth, J., Bergs, M., Walpuski, M., & Sumfleth, E. (2012, April). *Fostering experimental skills by a combination of hands-on and computer-based learning-environments*. Paper presented at the Annual Meeting of the American Educational Research Association (AERA), Vancouver, BC, Canada.

Schunn, C. D., & Anderson, J. R. (1999). The generality/specificity of expertise in scientific reasoning. *Cognitive Science, 23*, 337-370. doi:10.1207/s15516709cog2303_3

Simons, K. D., & Klein, J. D. (2007). The impact of scaffolding and student achievement levels in a problem-based learning environment. *Instructional Science, 35*, 41-72. doi:10.1007/s11251-006-9002-5

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. doi:10.1080/10494820.2012.693102

Tschirgi, J. E. (1980). Sensible reasoning: A hypothesis about hypotheses. *Child Development, 51*, 1-10. doi:10.2307/1129583

Tuovinen, J. E., & Sweller, J. (1999). A comparison of cognitive load associated with discovery learning and worked examples. *Journal of Educational Psychology, 91*, 334-341. doi:10.1037/0022-0663.91.2.334

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. doi:10.1016/j.lindif.2016.01.008

van Joolingen, W., & de Jong, T. (1991). An hypothesis scratchpad as a supportive instrument in simulation learning environments.

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. Towne, T. de Jong, & H. Spada (Eds.), *Simulation-based experiential learning* (pp. 191-206). Berlin: Springer.

van Riesen, S. A. N., Gijlers, H., Anjewierden, A. A., & de Jong, T. (2018). Supporting learners' experiment design. *Educational Technology Research and Development, 66*, 475-491. doi:10.1007/s11423-017-9568-4

Veermans, K., de Jong, T., & van Joolingen, W. R. (2000). Promoting self-directed learning in simulation-based discovery learning environments through intelligent support. *Interactive Learning Environments, 8*, 229-255. doi:10.1076/1049-4820(200012)8:3;1-D;FT229

Veermans, K., van Joolingen, W. R., & de Jong, T. (2006). Use of heuristics to facilitate scientific discovery learning in a simulation learning environment in a physics domain. *International Journal of Science Education, 28*, 341-361. doi:10.1080/09500690500277615

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction, 16*, 3-118. doi:10.1207/s1532690xci1601_2

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 when using virtual and remote labs in science: A literature review. *Educational Technology Research and Development, 63*, 257-302. doi:10.1007/s11423-015-9370-0

2

Supporting Learners' Experiment Design

Study 1

This chapter is based on:

van Riesen, S. A. N., Gijlers, H., Anjewierden, A. A., & de Jong, T. (2018). Supporting learners' experiment design. *Educational Technology Research and Development, 66*, 475-491. doi:10.1007/s11423-017-9568-4

Abstract

Inquiry learning is an educational approach in which learners actively construct knowledge and in which performing investigations and conducting experiments is central. To support learners in designing informative experiments we created a tool, the Experiment Design Tool (EDT), that provided learners with a step-by-step structure to select variables and to assign values to these variables, together with offering built-in heuristics for experiment design. To further structure the students' approach, the EDT was offered within a set of detailed research questions which again were grouped under a set of broader research questions. Learning results for learners who worked with the EDT were compared to results for learners in two control conditions. In the first control condition, learners received only the detailed research questions and not the EDT; in the second control condition, learners received only the limited set of general research questions. In all conditions, learners conducted their experiments in an online learning environment about the physics topic of Archimedes' principle. Conceptual knowledge was measured before and after the intervention using parallel forms of a knowledge test. Overall results showed significant learning gains in all three conditions, but no significant differences between conditions. However, learners who started with low prior knowledge showed a significantly higher learning gain in the EDT condition than in the two control conditions. This result indicates that the effect of providing learners with tools does not follow a "one-size-fits-all" principle, but may depend on specific learner characteristics, such as prior knowledge.

Introduction

Inquiry learning, a constructivist approach, is now widely recognised as a valuable instructional approach in science education (e.g., Minner, Levy, & Century, 2010). Central to constructivist approaches is that learners actively construct knowledge (Fosnot & Perry, 2005; Keselman, 2003; Minner et al., 2010). Active thinking and working with new material adds to and (re)organises existing cognitive structures and thereby fosters deeper understandings than passively receiving information (Cakir, 2008; Fosnot & Perry, 2005). Different levels of active cognitive engagement have been described in the ICAP-framework that provides a clear taxonomy of four different categories of learning engagement (Interactive, Constructive, Active, and Passive) that each elicits different knowledge gains or learning processes (Chi, 2009; Chi & Wylie, 2014). The main idea of the framework is that as learners become more cognitively engaged with the learning materials and show learning behaviours corresponding to the level of engagement, their learning will increase. The framework is supported by a large body of research (Chi & Wylie, 2014). In inquiry learning, learners actively construct knowledge by engaging in multiple phases of inquiry and familiarising themselves with the topic of interest, formulating research questions or hypotheses, planning and conducting experiments, drawing conclusions, reflecting upon these inquiry processes and results, and communicating their findings to others (de Jong, 2006; Pedaste et al., 2015; White & Frederiksen, 1998). The effectiveness of inquiry learning has been demonstrated in many studies, provided that learners are guided in their inquiry processes (e.g., Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Furtak, Seidel, Iverson, & Briggs, 2012; Lazonder & Harmsen, 2016; Minner et al., 2010).

One of the core elements in the multifaceted task of inquiry learning is the actual investigation during which learners design and conduct experiments (Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). Designing experiments involves a number of distinct elements. Learners first need to identify the variables associated with answering their research question or testing their hypothesis. More specifically, they need to specify the dependent, independent and control variables; they need to determine what variable(s) to measure or observe, what variable to manipulate, and what variable(s) to control (Arnold, Kremer, & Mayer, 2014). The second step in designing experiments is to determine values for the independent and control variables. Different values are assigned to the independent variable across experimental trials, allowing the learners to investigate the effects on the dependent variable. Variables that are not manipulated, control variables, have the same value across experimental trials, creating similar background conditions that allow the learners to compare results (Schunn & Anderson, 1999; Tschirgi, 1980). Well-designed experiments serve as a bridge between the research question or hypothesis and the data analysis (Arnold et al., 2014), and provide the learner with adequate information to answer research questions or test hypotheses (de Jong & van Joolingen, 1998).

However, learners find it difficult to set up well-designed experiments. They often design experiments that do not align with their research question or test their hypothesis by manipulating variables that have no relation with the research question or hypothesis, or they fail to identify the manipulatable and observable variables within their research question or hypothesis (de Jong & van Joolingen, 1998; Lawson, 2002). If the research question or hypothesis does not include a directly manipulatable variable, learners are often unable to convert abstract or theoretical variables into variables they can measure or observe (Lawson, 2002). Another difficulty is that learners sometimes vary too many variables, making it challenging to draw conclusions. When too many variables are varied, one cannot tell which variable is responsible for an observed effect (Glaser, Schauble, Raghavan, & Zeitz, 1992).

To overcome these difficulties and help learners with the processes of inquiry learning, learners should be guided (Hmelo-Silver, Duncan, & Chinn, 2007). Effective forms of guidance for designing fruitful experiments include providing learners with heuristics and giving them tools. Heuristics are rules of thumb in the form of hints and suggestions about how to carry out certain actions (Zacharia et al., 2015). Examples of heuristics for designing experiments are 'vary one thing at a time', 'assign simple values to the independent variable', and 'keep records of what you are doing' (Klahr & Dunbar, 1988; Veermans, van Joolingen, & de Jong, 2006). In the 'vary one thing at a time' heuristic, also known as the control of variables strategy (CVS), learners vary only the variable of interest and keep all other variables constant (Klahr & Nigam, 2004). CVS allows the learner to conclude that any effect on the dependent variable can be attributed to the one variable that was varied. In their overview of inquiry support, Zacharia et al. (2015) show that CVS is the most popular heuristic used to support experimentation.

Tools support learners in performing a task that they cannot perform on their own. Tools support a learning process by providing structure and/or taking over part of the task from the learners (de Jong & Lazonder, 2014; Reiser, 2004; Simons & Klein, 2007). In the current study, we designed such a tool to support learners in the process of designing experiments. This tool, the Experiment Design Tool (EDT), gave learners a structure for experiment design, provided them with concrete variables to manipulate and measure, prompted them to assign values to variables across experimental trials, and included specific experimentation heuristics. The final design of the EDT was primarily based on the Scaffolding Design Framework (Quintana et al., 2004), as further explained in the Method section. The EDT was integrated into an online learning environment containing a virtual laboratory. Virtual laboratories are software simulation programs in which learners carry out experiments using a computer (de Jong, Sotiriou, & Gillet, 2014). These laboratories have the advantage that variables can be assigned many values; they are also accurate, time- and cost-effective, and experiments can be repeated easily (Balamuralithara & Woods, 2009; de Jong, Linn, & Zacharia, 2013; Gomes & Bogosyan, 2009; Schiffhauer et al., 2012, April). The virtual laboratory used in the current study covered the physics topics of buoyancy and Archimedes' principle.

There are indications that the type of guidance that is effective for learning differs between learners with different levels of prior knowledge (Raes, Schellens, de Wever, & van der Hoven, 2012). Research has shown that unguided learners with low prior knowledge apply less sophisticated strategies and demonstrate more undirected behaviour in inquiry learning than more knowledgeable learners, who are using better strategies and require fewer trials to reach conclusions (Alexander & Judy, 1988; Klahr & Dunbar, 1988). There is general agreement that learners with low prior knowledge benefit from higher levels of guidance (e.g., Alexander & Judy, 1988; Hmelo, Nagarajan, & Day, 2000; Tuovinen & Sweller, 1999). More knowledgeable learners are less likely to need additional guidance because they already possess enough knowledge to support the construction of mental representations. For these learners, guidance can become redundant and even have a negative effect on learning, which is referred to as the ''expertise reversal effect'' (Kalyuga, 2007).

The objective of this study was to evaluate the effectiveness of a specific tool for experiment design and to investigate whether this tool had a positive effect on learners' gain of conceptual knowledge. In doing so, we were specifically interested in whether it was indeed the lower prior knowledge students who would profit most from working with the EDT.

Method

In the current study, we compared learners' gain in domain knowledge between a condition in which students worked with the EDT, and two control conditions. Learners in all conditions worked in an online learning environment where they received research questions and then had to design and conduct experiments in a virtual laboratory, called ''Splash'', on buoyancy and Archimedes' principle. In the EDT condition, learners received a set of thirteen specific research questions that were organised under a series of five broader research questions that matched the sub-laboratories in Splash. For each of the thirteen detailed research questions, learners could design an experiment by using the EDT. These thirteen research questions were provided to give all students the same starting points for designing their experiments, and the five main categories were used to organise the work for the learners. To evaluate the effect of the EDT, two control conditions were developed. In the 'control specific' (CS) condition, learners worked with the same learning environment as the learners in the EDT condition, but without the EDT itself, which means they received the thirteen specific questions grouped under the five broader questions. In the 'control main' (CM) condition, learners again worked with the same learning environment, but received only the five main research questions. In this way, we could single out the effect of the EDT per se from a possible effect of the related research questions. We expected that learners who worked with the EDT would show higher conceptual knowledge gains than learners who did not work with the EDT. Moreover, we expected that low prior knowledge learners in particular would be more likely to benefit from the EDT than learners with high prior knowledge.

Participants

A total of 120 third-year students (14–15 years old) from four pre-university track classes at two secondary schools in the Netherlands participated in this study. In the Netherlands, there are several levels of education. Students in the pre-university track receive the highest level of secondary education in order to prepare them for university studies. We chose to include pre-university track students because the complexity and properties of the learning task fit well with this educational level. Within their own class, learners were randomly assigned to one of the three conditions.

After eliminating learners who missed a session or who conducted fewer than four experimental trials about Archimedes' principle (as indication of too little learning activity), the data from a total of 86 learners were taken into account in the analyses.

Domain: Archimedes' Principle

The domain involved in the present study was Archimedes' principle, which states that ''an object fully or partially immersed in a fluid is buoyed up by a force equal to the weight of the fluid that the object displaces'' (Halliday, Resnick, & Walker, 1997, in Hughes, 2005). This principle therefore entails that the mass of fluid displaced by a floating or suspended object is equal to the mass of the object, and the volume of fluid displaced by a sunken or suspended object is equal to the volume of the object (Hughes, 2005).

Understanding of buoyancy is a prerequisite for learning about Archimedes' principle, and Heron, Loverude, Shaffer, and McDermott (2003) found that it was helpful to provide learners with laboratory experience in buoyancy prior to introducing Archimedes' principle, in order to address intuitive ideas and misconceptions. The learners who participated in our study had already been taught about buoyancy by their teacher in regular classes before they participated in our study, but to ensure that all of them understood buoyancy and to familiarise them with the structure of the learning environment, including the laboratory and the EDT, we chose to present a set of inquiries about buoyancy prior to introducing Archimedes' principle. Post-test scores revealed very high scores on buoyancy, indicating that they indeed possessed the required prior knowledge about buoyancy.

In the Netherlands, Archimedes' principle is not part of the official examination program, but it is sometimes taught as additional material. However, none of the schools that participated in our study had taught students about Archimedes' principle, which made it a suitable topic for them to learn about in the learning environments.

Materials

Virtual Laboratory: Splash

Splash is a virtual laboratory (Figure 2.1) on the domains of buoyancy and Archimedes' principle. The laboratory that was used in the current study covered five topics. The first three topics fell within the domain of buoyancy; in this study they served to activate learners' knowledge about buoyancy and to familiarise them with the learning environment. The final two topics were about Archimedes' principle.

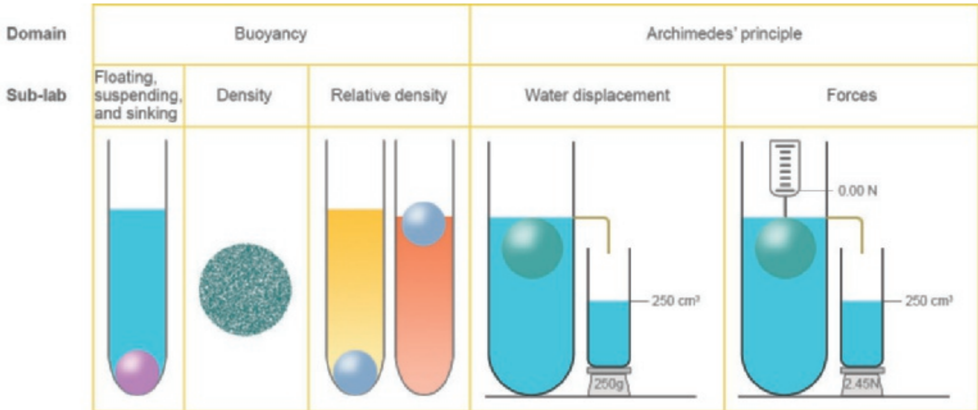

Figure 2.1. Examples of topics in the Splash laboratory.

The laboratory displays water-filled containers in which learners can place balls. Learners can choose the properties of the balls (mass, volume and density). The designed balls can be dropped in the containers and learners can observe whether the balls sink fully, are suspended, or float in water. Moreover, for Archimedes' principle, the displaced water will flow into empty containers that display the mass and volume of the displaced water, or forces.

Learning Environment

Learners in all conditions worked in an online learning environment, which had a similar structure in each condition. Learners first received instructions stating that they had to answer a set of research questions, which meant that they had to plan experiments and conduct these experiments in the Splash laboratory. The learning environment incorporated three main elements: a research question (Figure 2.2A), the laboratory in which experiments could be conducted (Figure 2.2B), and a text field in which conclusions from the experiments could be entered (Figure 2.2C). After learners entered their conclusion for the research question, they received a new research question to investigate.

Learners in the EDT condition had to use the EDT (Figure 2.2D) to plan experiments and note down the results they obtained for thirteen more specific research questions in order to answer the five main research questions. An example of a more specific question is: "Conduct a series of experiments with objects that all have the same mass, but differ in volume. What is the volume and mass of the displaced water? First, do this for objects that sink, then objects that suspend, and then objects that float". An example of a main question is: "How do properties of objects placed in water influence the amount of water displacement caused by these objects?". Learners in the CS condition worked in essentially the same learning environment, but without the EDT. Learners in the CM condition worked with the same learning environment as the CS group, but they were provided with just the five main research questions, one for each of the five topics in Splash. A more detailed description of the EDT is given in the next section.

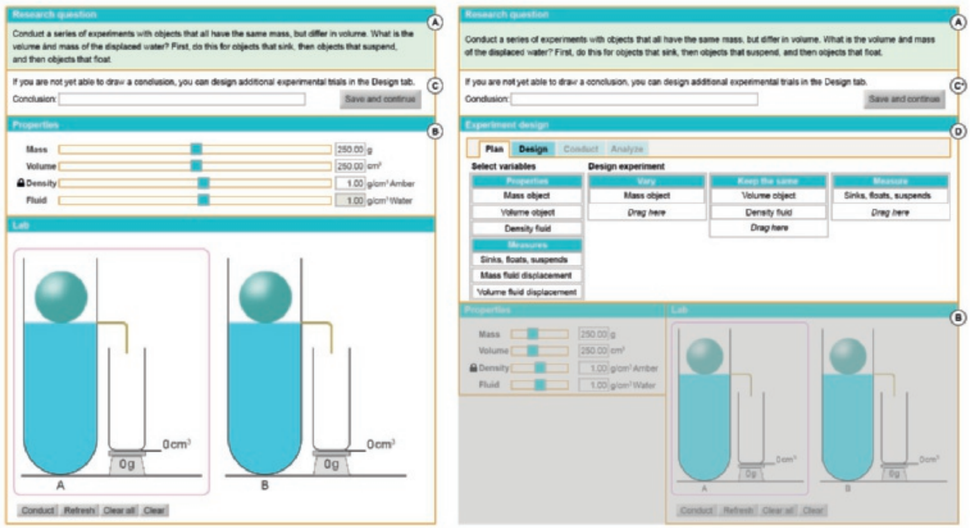

Figure 2.2. The learning environments. On the left is the interface for the CS condition, and on the right the interface for the EDT condition is depicted. In the EDT interface, the conclusion box only becomes visible when learners have reached the analysis tab in the EDT.

The Experiment Design Tool

The EDT (Figure 2.3) provides learners with structure by breaking down the process of designing and conducting an experiment into several steps: (1) choosing the variables and assigning the chosen variables as independent, control, and dependent variables; (2) assigning values to the variables; (3) conducting the experiment; and (4) analysing the results. It also helps learners to design experiments that follow the CVS, to work with simple values (e.g., 100, 150, etc.), and it helps them to keep records of what they are doing.

Step 1. First, learners are given a list of predefined variables. For each variable, they decide whether they want to vary it across experimental trials (independent variable), keep it the same (control variable) or measure/observe it (dependent variable) by dragging the variable to the chosen category. They receive feedback on their actions by means of a pop-up screen. For example, if they indicate that they want to vary a variable, they receive feedback that this means that they want to study the effect of the chosen variable on the variable they want to measure or observe.

Step 2. Second, learners specify the number of experimental trials that together will make up one experiment and they choose the values of the control and independent variables. They assign one value per experimental trial to the selected independent variable (e.g., in the first trial they experiment with a mass of 300 g and in the second trial they use a mass of 400 g), and a value to each control variable that remains the same over all experimental trials within an experiment (e.g., volume = 200 cm^3 in every trial for that experiment).

Step 3. Third, learners run their experiment. The trials they design in the EDT are automatically transferred to Splash. After observing the results in Splash, they document their observation or measurement of the dependent variable in the tool.

Step 4. Fourth, learners analyse their results. They can sort their data in ascending or descending order per variable. This makes it easier to compare results and to decide if they can draw conclusions based on their data, or if they need to plan and conduct more trials or even more experiments.

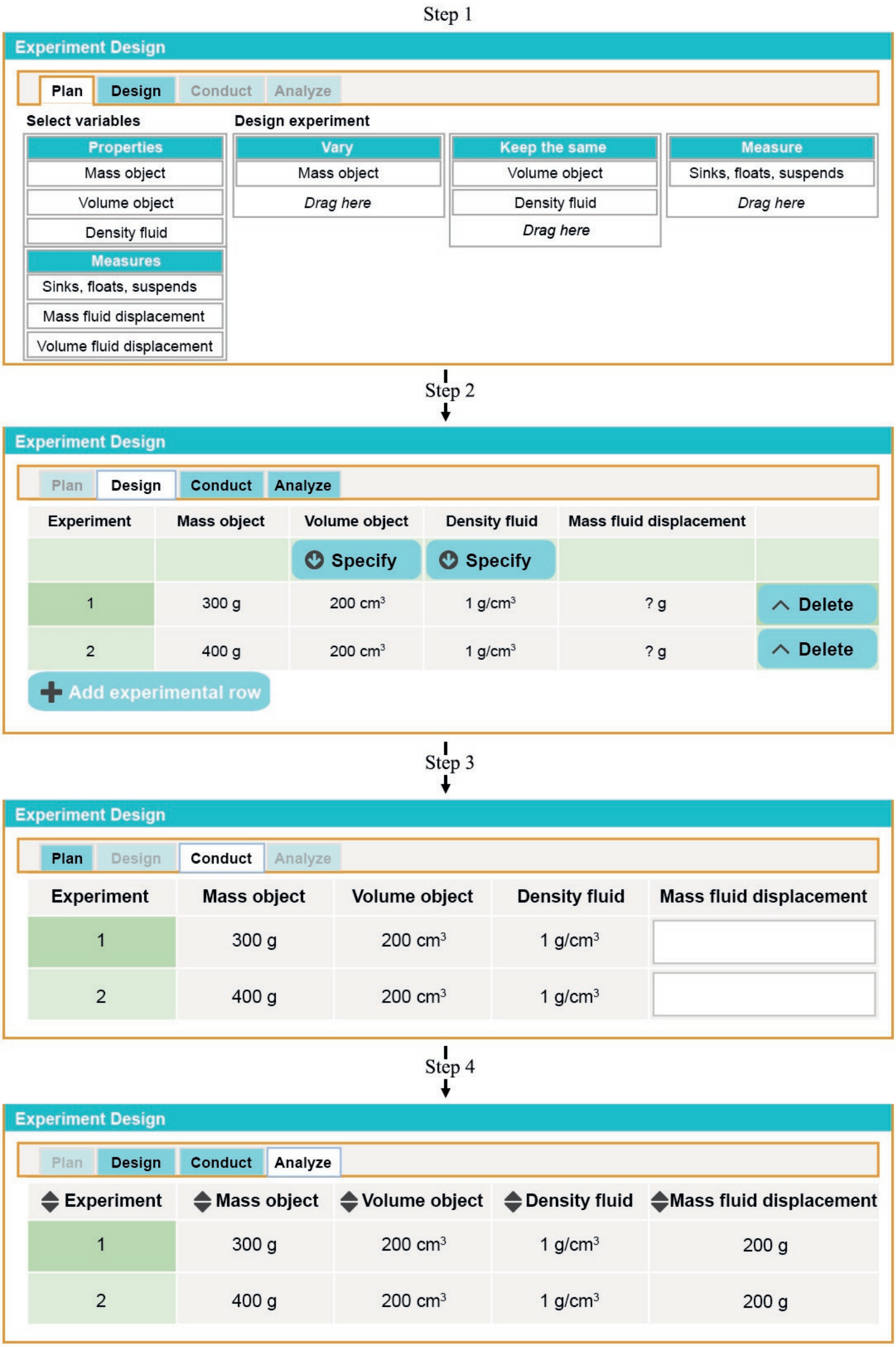

Figure 2.3. The Experiment Design Tool.

The main framework that was used for the design of the EDT is the Scaffolding Design Framework by Quintana et al. (2004) that gives guidelines for the design of tools:

Guideline 1. ''Use representations and language that bridge learners' understanding''. Pre-university track learners have begun learning how to design experiments, but they are not familiar with scientific terms such as independent, control, and dependent variables. In the EDT, these terms are replaced by language that is used in the classroom. For example, ''independent'' is replaced by ''vary'' and ''dependent'' is replaced by ''measure''.

Guideline 2. ''Organise tools and artefacts around the semantics of the discipline''. In experiment design, learners have to be aware that different types of variables exist, each with their own functionality. The EDT distinguishes between independent or control variables that can be varied or kept the same within an experiment and dependent variables that can be measured.

Guideline 3. ''Use representations that learners can inspect in different ways to reveal important properties of underlying data''. The EDT offers learners the possibility of recording their experimental design, observations, and/or measures. The recorded design and measures are presented in the form of a table. Each variable can be sorted in ascending or descending order, which helps to reveal important properties of the underlying data.

Guideline 4. ''Provide structure for complex tasks and functionality''. In experiment design, learners have to decide which variables to use, specify their roles within the experiment, and decide which values they want to assign to the variables. The EDT offers structure in several ways. The EDT consists of four tabs that break down the process of experiment design into smaller steps as explained previously. Additional structure is provided within the distinct tabs. The first tab contains a table with three columns to explicitly distinguish between the different types of variables. Moreover, learners are given a set of (relevant) variables they can include in the design of their experiment by dragging these variables to one of the columns and thereby specifying the roles of these variables. In the second tab, learners can specify the values of the control and independent variables. The EDT offers a range of possible values they can choose from in order to restrict their choices. They can design a maximum of six experimental trials at once. In the third tab learners can record their observation or measure, and the fourth tab contains a table that allows learners to sort variables in ascending or descending order.

Guideline 5. ''Embed expert guidance about scientific practices''. Expert guidance is incorporated in the EDT in several ways. First, several heuristics regarding experiment design that are often applied by successful scientists are implicitly present in the EDT. For example, 'vary one thing at a time' is built in by restricting the number of varied variables to just one, and 'assign simple values to the independent variable' is implemented by means of sliders that only allow learners to select simple values. Second, the EDT provides learners with feedback on their actions by means of a pop-up screen.

Guideline 6. ''Automatically handle non-salient, routine tasks''. All control variables only have to be assigned a value once. The EDT automatically assigns the chosen value to all trials within the experiment.

Guideline 7. ''Facilitate ongoing articulation and reflection during the investigation''. The EDT provides learners with feedback about their actions. Learners are encouraged to think about their experimental design: the EDT explains what learners' actions entail and asks them if they intended to perform those actions or if they want to reconsider.

Assessment

Learners' conceptual knowledge was assessed both before and after the intervention with parallel forms of a pencil-and-paper knowledge test that was designed specifically for this study. The pre- and post-test included the same questions, but the values within questions, as well as the order of questions, were different. The tests each consisted of two parts that addressed what learners encountered in a session with the learning environment in the current study –buoyancy and Archimedes' principle– and used open-ended questions for which learners could obtain a maximum of 35 points. The first part of each test (25 points) concerned buoyancy. The second part of each test (10 points) concerned Archimedes' principle. After learners' tests were scored, one item related to Archimedes' principle was removed from the analysis because learners interpreted that question very differently than was intended, which left a total of nine possible points for the second part of the test.

In the test, learners were asked to write down definitions of the key concepts, and they had to apply this knowledge by providing the masses, volumes, and densities of balls in different situations, the amount of displaced water, and/or forces that act upon the ball or the displaced water. Learners received one point for each correct answer. An example of an Archimedes' principle question was: ''A ball is being placed in a tube filled with water. This causes the water to be displaced. The displaced water is caught in a measuring cup. Below you can see the set-up before the ball is released. Provide the amount of displaced water and the values displayed on the spring balance and the scale after the ball was released in the tube''. The set-up that was shown to them was a figure taken from Splash. In the figure, a ball is hanging on a spring balance placed above a water-filled tube, with a measuring cup on a scale next to it to catch the displaced water. In this example, learners could receive one point for the correct amount of displaced water, one point for the correct value displayed on the spring balance, and one point for the correct value displayed on the scale.

Because the test consisted of open questions that were scored using a coding scheme, a second researcher used the coding scheme to score the post-tests from one of the four classes (n = 30). Agreement between the two researchers reached Kappa = 0.943. To determine the reliability of the tests, separate Cronbach's alpha's for both parts of the pre-test and the post-test were determined, based on the participants whose data were taken into account for this study (n = 86). The first part of the pre-test (about buoyancy) had a Cronbach's alpha of .92 and the second part of the pre-test (about Archimedes' principle) a Cronbach's alpha of .84. The post-test had a Cronbach's alpha of .91 for the buoyancy part and a Cronbach's alpha of .88 for the Archimedes' principle part.

Procedure

The study took place in the classroom during four sessions of 50-60 min each, over a period of two and a half weeks. During the first session, learners' prior conceptual knowledge was measured using the pre-test. Learners could use the entire session to complete the test, but all learners finished within half an hour. The intervention began in the second session, where learners worked with the learning environment that matched their condition. The topic of investigation in this session was buoyancy, in order to familiarise them with the learning environment and to activate their knowledge. Learners were told that they were to do experiments about floating, sinking and suspended objects, and density by individually designing and conducting experiments on the computer to answer the provided research questions. All the information learners needed in order to be able to successfully complete the tasks were presented to them in the learning environment, there was no teacher intervention. Learners in all conditions also received a booklet consisting of lined paper and all the research questions so that they could take notes whenever they wanted. Learners in the control conditions were encouraged to write down their experiments, including the results, in the booklet. They could use the entire second session to learn about buoyancy by means of inquiry learning. In the third session learners worked in the same learning environment as in the second session, but now they learned about Archimedes' principle, more specifically about water displacement and forces, instead of buoyancy. During the fourth session, learners' conceptual knowledge was measured with the post-test, for which they could again use the entire session.

Results

In the current study, the EDT condition was compared with two control conditions to study the effect of the EDT on learners' gain of conceptual knowledge about Archimedes' principle. Because the data were not normally distributed, an independent samples Kruskal-Wallis test was conducted to check for a priori differences between conditions. No significant differences were found between the conditions regarding physics grade, $H(2) = 1.97$, $p = .374$; math grade, $H(2) = 2.24$, $p = .327$; and pre-test scores for both buoyancy, $H(2) = 1.26$, $p = .534$ and Archimedes' principle, $H(2) = 1.70$, $p = .428$, indicating that the groups were comparable. Moreover, there was no significant difference on learners' post-test scores for buoyancy; in all conditions learners, on average, answered 88% of the questions on buoyancy correctly.

Our first analysis concerned learners' knowledge gains about Archimedes' principle and whether learners who worked with the EDT gained more knowledge than learners who did not work with the EDT. First, we explored whether learners gained knowledge about Archimedes' principle independent of their condition. A Wilcoxon signed-rank test showed a significant increase in score from pre- to post-test ($Z = 6.126$, $p < .001$, $d_{Cohen} = 0.99$), demonstrating a significant learning effect.

Separate analyses per condition were also performed to explore learners' learning gain per condition. Learners' scores significantly increased from pre- to post-test in all conditions (EDT condition: $Z = 4.133$, $p < .001$, $d_{Cohen} = 1.33$; CS condition: $Z = 3.576$, $p < .001$, $d_{Cohen} = 0.83$; CM condition: $Z = 3.044$, $p = .002$, $d_{Cohen} = 0.92$), showing a large learning effect in all conditions. Table 2.1 shows the means and SDs of the pre- and post-test scores for all conditions, as well as the difference scores between pre- and post-test.

Table 2.1

Test scores for Archimedes' principle (max score = 9)

	EDT (n = 26)		CS (n = 32)		CM (n = 28)		Total (n = 86)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Pre-test	2.31	2.72	1.59	1.78	1.43	2.06	1.76	2.20
Post-test	5.66	2.30	3.72	3.12	3.89	3.18	4.36	3.01
Difference score	3.35	2.58	2.13	2.66	2.46	3.61	2.60	2.99

To determine whether learners who worked with the EDT gained more conceptual knowledge than learners in the control conditions, an independent samples Kruskal-Wallis test was performed. No significant differences were found between the conditions, $H(2) = 2.96$, $p = .228$.

Secondly, we were specifically interested in differences in the effects of guidance on low prior knowledge learners and high prior knowledge learners. Learners were classified as low prior knowledge learners if they had a maximum of two out of nine correct answers (the lower quartile of the maximum score) on the part of the pre-test that covered Archimedes' principle. Based on this criterion, 63 out of 86 learners were classified as low prior knowledge learners. Since a solid majority of our learners had low prior knowledge about Archimedes' principle, leaving very few high prior knowledge learners, we only analysed the results for low prior knowledge learners. An independent samples Kruskal-Wallis test showed a significant difference between the conditions, $H(2) = 6.54$, $p = .038$. Follow-up Mann–Whitney analyses showed significantly higher learning gains for low prior knowledge learners in the EDT condition compared to low prior knowledge learners in the CS condition, $U = 115.50$, $z = 2.438$, $p = .015$, $r = .16$. Table 2.2 presents the means and SDs of the pre- and post-test scores of low prior knowledge learners, per condition. These findings demonstrate that low prior knowledge learners benefited from additional support in the form of the Experiment Design Tool.

Table 2.2

Test scores for lower prior knowledge learners for Archimedes' principle (max score = 9)

	EDT (*n* = 18)		CS (*n* = 23)		CM (*n* = 22)		Total (*n* = 63)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Pre-test	0.72	0.89	0.70	0.93	0.50	0.86	0.63	0.89
Post-test	5.17	2.33	2.74	3.08	3.64	3.20	3.75	3.05
Difference score	4.44	2.23	2.04	2.99	3.14	3.27	3.11	3.02

Conclusion and Discussion

For the current study, we designed an EDT based on the Scaffolding Design Framework by Quintana et al. (2004), and studied its effect on conceptual learning results for secondary school students. The EDT was specifically created to allow learners to design informative experiments and gain conceptual knowledge. The effectiveness of the EDT was studied by comparing an experimental condition, in which learners designed and conducted experiments using the EDT, with two control conditions, in which learners worked in a similar learning environment but without the EDT. We were interested in the effects of the EDT on learners' conceptual knowledge gains, specifically for low prior knowledge learners. Our results showed that low prior knowledge learners who were guided by the EDT gained significantly more conceptual knowledge than those in the CS condition, and descriptive statistics showed –not significant– higher learning gains for learners in the EDT condition than those in the CM condition. This effect was not found when learners with all levels of prior knowledge were taken into account, which is in conjunction with previous findings that low prior knowledge learners benefit more from guidance than their more knowledgeable peers (Alexander & Judy, 1988). An important difference between different levels of learners is seen in the strategies they apply to work towards a solution of a problem (Hmelo et al., 2000; Schauble, Glaser, Raghavan, & Reiner, 1991). Low prior knowledge learners lack internal information about concepts and meaningful relationships between concepts, and they show less sophisticated strategies than high prior knowledge learners (Alexander & Judy, 1988; Schauble et al., 1991). As a result, in inquiry learning low prior knowledge learners often conduct unsystematic experiments in which learners fail to vary the appropriate variable and in which there is a mismatch between the research question and the conducted experimental trials, whereas high prior knowledge learners show goal-oriented inquiry behaviour and conduct well-structured experiments (Hmelo et al., 2000; McElhaney & Linn, 2011). In other words, high prior knowledge learners are better equipped to structure a task themselves than low prior knowledge learners, which could explain why we found significantly higher learning gains in favour of the EDT for low prior knowledge learners only. One of the main features of the EDT is that it provides learners with structure and heuristics to help them design systematic experiments, and it provides them with a useful strategy for gaining domain knowledge; learners automatically apply the Control of Variables Strategy, allowing them to discover the effect of one independent variable on the dependent variable at a time.

Another difference between learners with different levels of prior knowledge and experience is that novices have the tendency to immediately start working towards a solution to the problem without thinking it through, whereas experts first try to understand the problem (Getzels & Csikszentmihalyi, 1976; Paige & Simon, 1966). This tendency may be especially problematic when learners try to make inferences about research questions within domains in which experimental results are influenced by interacting variables, as in Archimedes' principle, rather than by a single variable. Dealing with interacting variables has been found to be especially difficult for learners when they must design and conduct experiments in computer-supported learning environments, and it is greatly affected by learners' inadequate application of the Control of Variables Strategy (Beishuizen, Wilhelm, & Schimmel, 2004). Grasping the concept of Archimedes' principle requires learners to understand that the density (mass divided by volume) of the object compared to the density of the fluid determines if the object floats, suspends, or sinks in the fluid. Additionally, learners must understand that different relationships exist between the object's properties and the amount of displaced fluid for objects that float and objects that sink (i.e., for floating objects the mass of the object equals the mass of the displaced fluid, and the volume of the object is greater than the volume of the displaced fluid, whereas for sinking objects the volume of the object equals the volume of the displaced fluid, and the mass of the object is greater than the mass of the displaced fluid). If learners immediately start working towards answering research questions regarding Archimedes' principle by conducting random experiments, and thereby fail to consider relative density and interactions between floatability, object properties and fluid displacement, they will end up with experimentation outcomes from which it is extremely difficult to extract relationships between the independent and dependent variables. The EDT prevents learners from immediately working towards a solution, but instead encourages them to think about their experimental designs and it provides them with feedback that prompt them to reflect upon their experimental designs.

Another result that deserves some attention is that low prior knowledge learners who worked with the EDT only outperformed those in the CS condition significantly and not those in the CM condition. The thirteen specific questions that were provided to learners in the EDT and the CS condition organised the main research questions and were meant to aid the students, but descriptive statistics showed higher learning gains for learners in the CM condition than for learners in the CS condition, who in fact had very little learning gain. This may be explained by the added task demands of additional research questions that was posed on learners in the CS condition who were not equipped with sufficient prior knowledge, capability and/or tools –either cognitive through prior knowledge and experiences or external by means of tools such as the EDT. Even though the additional questions aimed to provide a sense of direction for designing experiments, they also take time to answer and add to the task, which may have caused learners who were not provided with additional inquiry support in the form of the EDT to struggle with successfully completing the task within the given time. The additional questions and the time they took to answer may have been beyond learners' zone of proximal development, and in order for learning to occur the activities and guidance should match their zone of proximal development. In a recent study by Perez et al. (2017) in which they identified productive inquiry in virtual labs by means of sequence mining, they also found that novice learners who conducted simpler experiments matching their level of expertise achieved higher learning outcomes than novices who focused more on complex circuit configurations. Most studies in which the effectiveness of tools have been tested present results that do not take conditions related to the functioning of tools into account (Zacharia et al., 2015). Our results show that there's no one-size-fits-all approach that applies to learners' guidance regarding experiment design, and that prior knowledge should be evaluated when introducing tools. The effect of support is very much influenced by the context and can be different per situation. The Scaffolding Design Framework should be adapted to stress the importance of context, and show that the relationship between learner characteristics, domain characteristics, and the place in the curriculum are of high importance to take into account in the design of tools. Future studies should also include qualitative data regarding learner decisions to understand their rationales behind their experiment designs and qualitative data about learner actions in designing experiments to provide us with richer insights in the processes underlying the results. Furthermore, it should be investigated whether we are generally in need of more sensitive and sophisticated models of scaffolding in order for tools to remain one step ahead of the learner and thereby be able to support the advancing learner.

References

Alexander, P. A., & Judy, J. E. (1988). The interaction of domain-specific and strategic knowledge in academic performance. *Review of Educational Research, 58*, 375-404. doi:10.3102/00346543058004375

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. doi:10.1037/A0021017

Arnold, J. C., Kremer, K., & Mayer, J. (2014). Understanding students' experiments: What kind of support do they need in inquiry tasks? *International Journal of Science Education, 36*, 2719-2749. doi:10.1080/09500693.2014.930209

Balamuralithara, B., & Woods, P. C. (2009). Virtual laboratories in engineering education: The simulation lab and remote lab. *Computer Applications in Engineering Education, 17*, 108-118. doi:10.1002/cae.20186

Beishuizen, J., Wilhelm, P., & Schimmel, M. (2004). Computer-supported Inquiry Learning: Effects of training and practice. *Computers and Education, 42*, 389-402. doi:10.1016/j.compedu.2003.10.003

Cakir, M. (2008). Constructivist approaches to learning in science and their implications for science pedagogy: A literature review. *International Journal of Environmental & Science Education, 3*, 193-206.

Chi, M. T. H. (2009). Active-constructive-interactive: A conceptual framework for differentiating learning activities. *Topics in Cognitive Science, 1*, 73-105. doi:10.1111/j.1756-8765.2008.01005.x

Chi, M. T. H., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist, 49*, 219-243. doi:10.1080/00461520.2014.965823

de Jong, T. (2006). Computer simulations: Technological advances in inquiry learning. *Science, 312*, 532-533. doi:10.1126/science.1127750

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* (2nd ed., pp. 371-390). Cambridge: Cambridge University Press.

de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science, 340*, 305-308. doi: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. doi: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*, 179-201. doi:10.2307/1170753

Fosnot, C. T., & Perry, R. S. (2005). Constructivism: A psychological theory of learning. In C. T. Fosnot (Ed.), *Constructivism: Theory, perspectives, and practice* (2nd ed., pp. 8-38). New York and London: Teachers College Press, Columbia University.

Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. *Review of Educational Research, 82*, 300-329. doi:10.3102/0034654312457206

Getzels, J. W., & Csikszentmihalyi, M. (1976). *The creative vision: A longitudinal study of problem finding in art*. New York: Wiley.

Glaser, R., Schauble, L., Raghavan, K., & Zeitz, C. (1992). Scientific reasoning across different domains. In E. de Corte, M. C. Linn, H. Mandl, & L. Verschaffel (Eds.), *Computer-based learning environments and problem solving* (pp. 345-371). Berlin, Heidelberg: Springer Berlin Heidelberg.

Gomes, L., & Bogosyan, S. (2009). Current trends in remote laboratories. *IEEE Transactions on Industrial Electronics, 56*, 4744-4756. doi:10.1109/TIE.2009.2033293

Heron, P. R. L., Loverude, M. E., Shaffer, P. S., & McDermott, L. C. (2003). Helping students develop an understanding of Archimedes' principle. II. Development of research-based instructional materials. *American Journal of Physics, 71*, 1188. doi:10.1119/1.1607337

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist, 42*, 99-107. doi:10.1080/00461520701263368

Hmelo, C. E., Nagarajan, A., & Day, R. S. (2000). Effects of high and low prior knowledge on construction of a joint problem space. *Journal of Experimental Education, 69*, 36-56. doi:10.1080/00220970009600648

Hughes, S. W. (2005). Archimedes revisited: A faster, better, cheaper method of accurately measuring the volume of small objects. *Physics Education, 40*, 468-474.

Kalyuga, S. (2007). Expertise reversal effect and its implications for learner-tailored instruction. *Educational Psychology Review, 19*, 509-539. doi:10.1007/s10648-007-9054-3

Keselman, A. (2003). Supporting inquiry learning by promoting normative understanding of multivariable causality. *Journal of Research in Science Teaching, 40*, 898-921. doi:10.1002/Tea.10115

Klahr, D., & Dunbar, K. (1988). Dual space search during scientific reasoning. *Cognitive Science, 12*, 1-48. doi:10.1207/s15516709cog1201_1

Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction: Effect of direct instruction and discovery learning. *Psychological Science, 15*, 661-667. doi:10.1111/j.0956-7976.2004.00737.x

Lawson, A. E. (2002). Sound and faulty arguments generated by preservice biology teachers when testing hypotheses involving unobservable entities. *Journal of Research in Science Teaching, 39*, 237-252. doi:10.1002/Tea.10019

Lazonder, A. W., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. *Review of Educational Research*. doi:10.3102/0034654315627366

McElhaney, K. W., & Linn, M. C. (2011). Investigations of a complex, realistic task: Intentional, unsystematic, and exhaustive experimenters. *Journal of Research in Science Teaching, 48*, 745-770. doi:10.1002/tea.20423

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. doi:10.1002/Tea.20347

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*, 692-720. doi:10.1002/Tea.10105

Paige, J. M., & Simon, H. A. (1966). Cognitive processes in solving algebra word problems. In B. Kleinmutz (Ed.), *Problem Solving*. New York: John Wiley & Sons, Inc.

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 the inquiry cycle. *Educational Research Review, 14*, 47-61. doi:10.1016/j.edurev.2015.02.003

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, Wuhan, China, June 28 - July 1, 2017, proceedings* (pp. 287-298): Cham: Springer International Publishing.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., . . . Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences, 13*, 337-386. doi:10.1207/s15327809jls1303_4

Raes, A., Schellens, T., de Wever, B., & van der Hoven, E. (2012). Scaffolding information problem solving in web-based collaborative inquiry learning. *Computers & Education, 59*, 82-94. doi:10.1016/j.compedu.2011.11.010

Reiser, B. J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. *Journal of the Learning Sciences, 13*, 273-304. doi:10.1207/s15327809jls1303_2

Schauble, L., Glaser, R., Raghavan, K., & Reiner, M. (1991). Causal models and experimentation strategies in scientific reasoning. *Journal of the Learning Sciences, 1*, 201-238. doi:10.1207/s15327809jls0102_3

Schiffhauer, S., Gößling, J., Wirth, J., Bergs, M., Walpuski, M., & Sumfleth, E. (2012, April). *Fostering experimental skills by a combination of hands-on and computer-based learning-environments*. Paper presented at the Annual Meeting of the American Educational Research Association (AERA), Vancouver, BC, Canada.

Schunn, C. D., & Anderson, J. R. (1999). The generality/specificity of expertise in scientific reasoning. *Cognitive Science, 23*, 337-370. doi:10.1207/s15516709cog2303_3

Simons, K. D., & Klein, J. D. (2007). The impact of scaffolding and student achievement levels in a problem-based learning environment. *Instructional Science, 35*, 41-72. doi:10.1007/s11251-006-9002-5

Tschirgi, J. E. (1980). Sensible reasoning: A hypothesis about hypotheses. *Child Development, 51*, 1-10. doi:10.2307/1129583

Tuovinen, J. E., & Sweller, J. (1999). A comparison of cognitive load associated with discovery learning and worked examples. *Journal of Educational Psychology, 91*, 334-341. doi:10.1037/0022-0663.91.2.334

Veermans, K., van Joolingen, W. R., & de Jong, T. (2006). Use of heuristics to facilitate scientific discovery learning in a simulation learning environment in a physics domain. *International Journal of Science Education, 28*, 341-361. doi:10.1080/09500690500277615

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction, 16*, 3-118. doi:10.1207/s1532690xci1601_2

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 when using virtual and remote labs in science: A literature review. *Educational Technology Research and Development, 63*, 257-302. doi:10.1007/s11423-015-9370-0

3

The Influence of Prior Knowledge on the Effectiveness of Guided Experiment Design

Study 2

This chapter is based on:

van Riesen, S. A. N., Gijlers, H., Anjewierden, A. A., & de Jong, T. (2018). *The influence of prior knowledge on the effectiveness of guided experiment design*. Manuscript submitted for publication.

Abstract

Inquiry learning is an effective learning approach if learners are properly guided. Its effectiveness depends on learners' prior knowledge, the domain, and their relationship. In a previous study we developed an Experiment Design Tool (EDT) guiding learners in designing experiments. The EDT significantly benefited low prior knowledge learners. For the current study the EDT was refined in order to also serve higher prior knowledge learners. Two versions were created; the 'Constrained EDT' required learners to design minimally three experimental trials and to apply CVS before they could conduct their experiment, and the 'Open EDT' allowed learners to design as many trials as they wanted, and to vary more than one variable between trials. Three conditions were compared in terms of learning gain for learners having distinct levels of prior knowledge. Participants designed and conducted experiments within an online learning environment that 1) did not include an EDT, 2) included the Constrained EDT, or 3) included the Open EDT. Results indicated low prior knowledge learners to benefit most from the Constrained EDT, low-intermediate prior knowledge learners from the Open EDT, and high-intermediate prior knowledge learners from no EDT. We advocate guidance to be configurable to serve learners with varying levels of prior knowledge.

Introduction

Educational objectives are shifting in our current society, where learners increasingly must learn actively and independently because this has been acknowledged to yield better learning results (SLO Nationaal Expertisecentrum Leerplanontwikkeling, 2016). An educational approach that anticipates this trend is inquiry learning, which has found to be effective for learning as long as learners are guided in the processes involved (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011). The essence of this approach is that learners construct knowledge by carrying out inquiries; learners practice (a subset of) inquiry processes such as becoming oriented to the topic of investigation, formulating hypotheses and/or research questions, setting up and conducting experiments, drawing conclusions, and reflecting upon their inquiries (Pedaste et al., 2015). Inquiry learning stimulates learners to acquire, integrate, and apply new knowledge (Edelson, Gordin, & Pea, 1999), which can lead to deeper processing of knowledge and higher-order understanding (Carnesi & DiGiorgio, 2009).

A Core Inquiry Process: Designing Experiments

Designing experiments is one of the core activities of inquiry learning, situated in the middle of the inquiry cycle as the linchpin between the more theoretical phases of hypothesis generation and drawing conclusions (Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003; van Riesen, Gijlers, Anjewierden, & de Jong, 2018). Learners must design experiments with which they can obtain results that are relevant for drawing conclusions regarding their hypothesis or research question. Experiment design thus builds a bridge between the hypothesis or research question, and data analysis and conclusion drawing (Arnold, Kremer, & Mayer, 2014).

Designing useful experiments requires understanding of inquiry and possession of inquiry skills, and it entails several aspects and processes that have found to be difficult for learners of all ages (de Jong & van Joolingen, 1998). One of the inquiry processes that has been found to predict conceptual knowledge gains is planning, which includes setting goals, selecting and implementing relevant strategies to meet those goals, and activating prior knowledge (de Jong & Njoo, 1992; Schraw, Crippen, & Hartley, 2006; Schunk, 1996). In experiment design, the goal is usually to further explore a domain by testing a hypothesis or answering a research question. Depending on someone's prior knowledge of the domain and on the specific purpose of the experiment, certain experimentation strategies such as the Control of Variables Strategy described in the following paragraph, can be selected and implemented in order to work towards that goal. However, learners typically start working on tasks without engaging in spontaneous or serious planning; if they do engage in planning, they are often unsystematic about it, causing them to struggle with the task (de Jong & van Joolingen, 1998; Manlove, Lazonder, & de Jong, 2006; Veenman, Elshout, & Meijer, 1997).

A well-designed experiment typically serves the goal of answering a research question or testing a hypothesis. In their experiment design, learners should design multiple trials in which they include variables that are relevant and required to answer the research question or test the hypothesis. However, they often select variables that have nothing to do with the question or hypothesis and/or neglect important variables that do (de Jong & van Joolingen, 1998; van Joolingen & de Jong, 1991), especially when they have little or no knowledge of the domain. Learners should also specify the roles of the selected variables by choosing what they want to measure (dependent variable), vary (independent variable) and control for (control variable), and they must decide upon values of the independent and control variables for the experimental trials they will conduct. A strategy that successful researchers often apply is the Control of Variables Strategy (CVS), in which, over a set of trials, all variables are kept constant except the variable for which they want to study its effect on the dependent variable, allowing them to draw conclusions from unconfounded experiments (Klahr & Nigam, 2004). Any effect on the dependent variable that occurs can then be ascribed to the independent variable of interest. Learners, on the other hand, often do not apply CVS, but instead vary too many variables (Klahr & Nigam, 2004), which impedes the process of drawing conclusions because any effect found may be due to a variety of influences (Glaser, Schauble, Raghavan, & Zeitz, 1992).

When learners have selected the variables they want to include in their experiment, they should design multiple experimental trials in which they choose different values for the independent variables. Two strategies for choosing those values are to use extreme values, or have equal increments between trials (Veermans, van Joolingen, & de Jong, 2006). In order to explore the boundaries of a domain, learners can start an experiment by using extremely low or high values. Using equal increments between trials provides information about whether or not an effect is present, when an effect occurs, the strength of an effect, and the trajectory of the effect (e.g., linear, exponential, etc.).

Guidance

Guiding learners in designing and conducting experiments helps them to conduct useful and systematic experiments from which they can derive knowledge (Zacharia et al., 2015). One of the most frequently applied forms of guidance in online learning environments is heuristics, which are hints or suggestions on how to complete assignments. Novice learners who have yet to learn about effective strategies for setting up experiments benefit especially from heuristics (Veermans et al., 2006; Zacharia et al., 2015). Examples of heuristics are to 'vary one thing at a time', and to 'control all other variables by using the same value across experimental trials' (Veermans et al., 2006), which both refer to the Control of Variables Strategy (Klahr & Nigam, 2004). Heuristics can be explicitly stated for the learner, or they can be used implicitly, for example, by embedding them in a tool that only allows learners to perform actions that comply with the heuristic(s). Tools are another form of guidance; they transform or take over part of a task and thereby help learners to accomplish tasks they would not have been able to do on their own (de Jong, 2006; Reiser, 2004; Simons & Klein, 2007). One example is a monitoring tool in which experiments – described as a set of values assigned to input and output variables – are stored (Veermans, de Jong, & van Joolingen, 2000). The rationale behind this tool is that it allows learners to focus on important relationships within the domain of interest, because the tool takes over part of the task by providing learners with some sort of external memory in which the experimental trials they conduct are automatically stored. Learners can replay the saved trials, and rearrange them in ascending or descending order to be better able to compare results. The monitoring tool eliminates the difficulty of remembering the experimental trials that have been conducted and interpreting the results, while simultaneously thinking of appropriate follow-up trials to conduct. Another example is the SCY Experimental Design Tool in which learners can write and evaluate their experiment design by means of a checklist (Lazonder, 2014). The tool incorporates an overview and explanations of experimental processes, including the research question, hypothesis, principle of manipulation, materials, and data treatment. Moreover, learners receive instructions on how to perform the task.

The Experiment Design Tool (EDT)

Based on heuristics and the Scaffolding Design Framework (Quintana et al., 2004), an Experiment Design Tool (EDT) was developed by van Riesen et al. (2018) to help learners design and conduct experiments in an online inquiry learning environment. The EDT supports learners in the complex and possibly overwhelming task of designing experiments by breaking down the process of designing and conducting an experiment into smaller steps, and by taking over parts of these smaller steps for the learner, for example, by automatically assigning the same value to each control variable within an experiment. First, the EDT provides learners with a predefined list of variables that learners can select and include in their experiment as independent, control, or dependent variable. Second, the EDT allows learners to design multiple experimental trials at once and determine values for each variable per trial (within predefined ranges). Third, the learners conduct the prepared experimental trials in a lab and document the results in the EDT. Finally, they analyse results and draw conclusions, which they write down in a conclusion text box. The EDT is meant to provide a structured and constrained learning environment within which learners can design their experiment, thereby allowing learners to design informative experiments.

Results from a recent study with the EDT showed that low prior knowledge learners, that is, learners whose conceptual knowledge about the domain did not exceed 25% of a conceptual knowledge test before working with the learning environment, significantly benefited from the EDT (van Riesen et al., 2018). The results of that study showed that guidance should fit with learners' prior knowledge, and the relationship between learners and the domain. For the current study, the EDT was further adapted (see Method section for more details) based on observations and findings from the above-mentioned study. In order to make the EDT suitable for more diverse groups of learners, domains, and curricula, we investigated the effect of two configurations of the EDT on the learning gains of learners with different levels of prior knowledge of the domain.

One configuration, the Constrained EDT, was created to offer learners a set structure in which the application of CVS was required, namely, only one variable could be varied at a time, and in which at least three experimental trials had to be designed at once. It was expected that this configuration of the EDT with a high level of guidance would be especially beneficial for low prior knowledge learners. It is generally acknowledged that low prior knowledge learners benefit most from additional guidance (Alexander & Judy, 1988). Few low prior knowledge learners engage in planning when they are not guided, despite the fact that planning has found to be very important for learning (Hagemans, van der Meij, & de Jong, 2013; Manlove et al., 2006; Zimmerman, 2002). Dalgarno, Kennedy, and Bennett (2014) also found that low prior knowledge learners applied CVS noticeably less than learners with higher prior knowledge when they analysed learners' experimentation strategies, and that learners who applied CVS performed better on a conceptual knowledge post-test than learners who did not apply CVS.

The second configuration, the Open EDT, had a more exploratory nature. The basics of the Open EDT were identical to the Constrained EDT, but learners were free to conduct their designed trials whenever they wanted without having to first design at least three trials, and they were not obliged to apply CVS but could vary more than one variable if desired. It was expected that the Open EDT would be best for low-intermediate prior knowledge learners, because they already possess basic knowledge about the domain, but still need to explore relationships between variables. A review study by Pedaste et al. (2015) revealed that an exploratory approach to the domain is beneficial for learners lacking specific knowledge about the domain.

Virtual Lab

Learners in the current study conducted their designed experiments in a virtual lab. A virtual lab is a type of online lab that is operated through a medium such as the computer, and is described as a simulation of reality (de Jong, Linn, & Zacharia, 2013; Sancristobal et al., 2012). An important advantage of virtual labs over physical labs is that they allow variables to take on many values, and learners can conduct an unlimited number of experiments that consume less time than experiments conducted in other types of labs, which provides them with excellent opportunities to gain theoretical understandings (Almarshoud, 2011). In a study by Toth, Ludvico, and Morrow (2014) in which virtual labs and hands-on labs about DNA gel-electrophoresis were compared, it was found that virtual labs had significant advantages for gaining conceptual knowledge, and learning was deeper and more purposeful than learning with hands-on labs.

Domains: Buoyancy and Archimedes' Principle

The virtual lab that was used in the study was about the domains of buoyancy and Archimedes' principle. Buoyancy plays an important role in science education and everyday life, it can be challenging for learners of all ages, and its understanding is a prerequisite for understanding Archimedes' principle (van Riesen et al., 2018). It requires a conceptual understanding of density (mass divided by volume), and floating and sinking; objects placed in a fluid float when the density of the object is lower than the density of the fluid, and they sink when the density of the object is higher than the density of the fluid (Hardy, Jonen, Möller, & Stern, 2006). Learners of all ages experience challenges in understanding the relationship between density and floating or sinking; they often think that the floatability of an object is determined by its weight without considering volume as well, they fail to recognise the relationship between mass and volume, or they focus on specific features of objects such as holes in an object that may cause it to float (Driver, Squires, Rushworth, & Wood-Robinson, 1994, in Loverude, 2009; McKinnon & Renner, 1971, in Loverude, Kautz, & Heron, 2003).

Archimedes' principle is related to buoyancy, and is often used as additional subject-matter in Dutch education. Archimedes' principle can be explained in terms of water displacement or forces (van Riesen et al., 2018). Floating objects have the same mass as the fluid they displace, sinking objects have the same volume as the displaced fluid, and suspended objects have the same mass and volume as the fluid they displace (Hughes, 2005). When explained in terms of forces, Archimedes' principle states that "an object fully or partially immersed in a fluid is buoyed up by a force equal to the weight of the fluid that the object displaces" (Halliday, Resnick, & Walker, 1997, in Hughes, 2005, p. 469).

In the current study, which is quasi-experimental, students designed and conducted experiments in an online learning environment to answer research questions about buoyancy and Archimedes' Principle that were provided to them in that environment. Three learning environments with different supports for designing and conducting experiments were compared. Additional support in the form of one of the two configurations of the EDT was provided in the two experimental conditions. Students in the control condition performed their experiments without using any form of the EDT.

Method

Participants

Three secondary schools in the Netherlands participated in the current study, with a total of 160 pre-university students from six third year classes (approximately 15 years old). After eliminating four outliers based on their difference scores regarding buoyancy, two outliers based on their difference scores regarding Archimedes' principle, one student who was observed not to take the study seriously, and 44 students who missed a session, the data from a total of 109 students remained for analyses.

Learning Environments

Upon entering the environment, learners saw instructions on the screen telling them about their task of designing and conducting experiments in a virtual lab, called Splash, in order to answer research questions provided to them in the learning environment. After students had read the instructions they could continue to the investigation space (Figure 3.1), which included a research question, a conclusion text box, a mechanism to prepare experiments with, Splash (a virtual lab about buoyancy and Archimedes' principle), and a help button to retrieve domain information upon request. The three learning environments each contained the same set of fourteen research questions. Students were presented with one research question at a time, in order, and they could only continue with the next research question after they had designed and conducted their experiments, and had entered their conclusion in the conclusion text box.

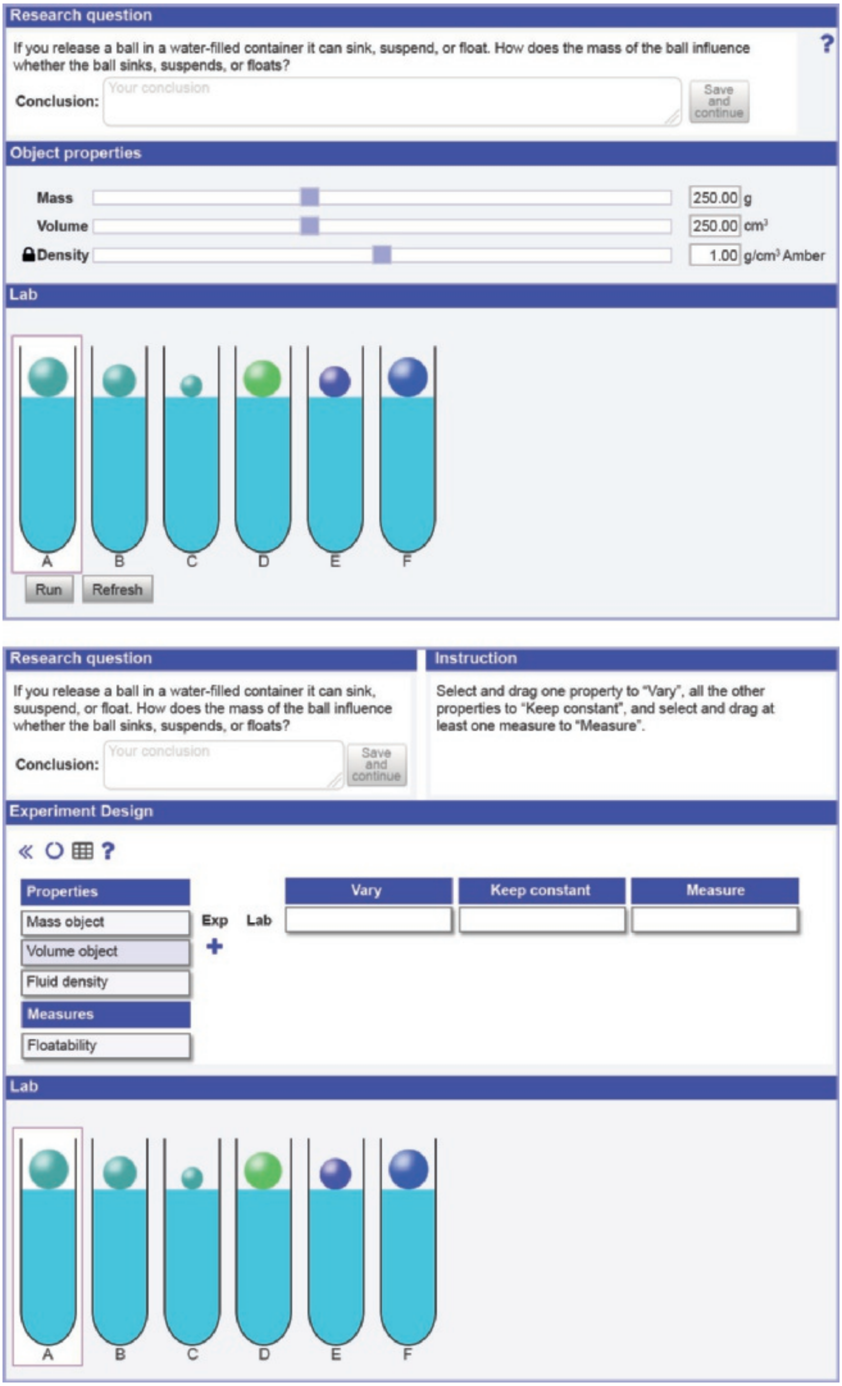

Figure 3.1. The learning environments, with the learning environment for the control group at the top and the learning environment for students in the EDT conditions at the bottom.

Online Virtual Lab: Splash

Students worked with an online virtual lab called Splash (the Lab in Figure 3.1). In Splash, several fluid-filled tubes are displayed; the fluids can be water or fluids with a different density. Students must determine the mass, volume and density of the balls that are provided, which they can then place in the fluid-filled tubes. They can observe whether the balls sink, float, or suspend in the fluid, how much fluid is displaced by the ball, and how the domain-related forces, such as buoyant force and gravity, act upon each other.

Support

The learning environments were similarly structured for each of the conditions and only differed in the support offered to students for the processes of designing and conducting experiments (Figure 3.1). Learners in the control condition had to use sliders in the Object properties box to adjust the settings for their experiments, whereas learners in the experimental conditions used one of the configurations of the EDT, as is described in more detail in the following sections.

Control Condition

The learning environment that was used by students in the control condition offered the least amount of support. Students could prepare their experiments and conduct them directly in Splash by means of sliders that assigned values to the variables in their experiments. They could take notes in their provided booklet and write down everything they considered to be relevant to answer the research question, including their experimental trials and observed results. This learning environment did not include the EDT to help students design their experiments.

EDT Conditions: Constrained EDT and Open EDT

Students in the two experimental conditions worked with a learning environment that included one of the two configurations of the Experiment Design Tool (EDT) to support students in the processes of designing and conducting experiments (Figure 3.2). The basic functionality of the two configurations was the same. The EDT was developed to address elements that are central in experimentation; it revolved around the independent, control, and dependent variables. The tool presented students with a list of pre-selected variables to use in their experiment design. For each variable, students had to decide if they wanted to vary it across experimental trials, control it, or measure it, by dragging it to one of the boxes 'vary', 'keep constant', or 'measure'. Students could plan multiple experimental trials by adding them to the design, and assigned values to the independent and control variables for each trial by means of a slider that allowed them to choose from a range of values. Different values across trials could be assigned to variables in the 'vary' box while only one value was provided for each variable in the 'keep constant' box, because that value was automatically copied by the EDT to all other experimental trials within the experiment. At all times, students could read instructions at the top of their screen on how to use the EDT. The instructions were presented just-in-time and were based on students' actions. For example, when they started designing their experiment they received instructions to drag and drop all property variables to the 'vary' and 'keep constant' boxes, and to drag at least one variable they wanted to measure to 'measure'.

When the experiment design was ready, students could select the trials they wanted to conduct in Splash. The selected trials were automatically transferred from the EDT to Splash so students did not have to enter the chosen values twice. In Splash they could observe what happened, and write down the results in the EDT. Students could enter their results for the dependent variables after they had conducted the trials. The completed trials for which they had entered results were all automatically saved in a history table that they could view at all times. Moreover, the history table allowed them to sort variable values in ascending or descending order, which made it easier to reach conclusions or decide whether more trials or even experiments were required to answer the research question. In case students wanted to conduct more trials or experiments to answer the research question, they could add more trials, adjust their design, or design an entirely new experiment. Any of those options still allowed them to view the history table with all of their completed trials for the research question they were trying to answer.

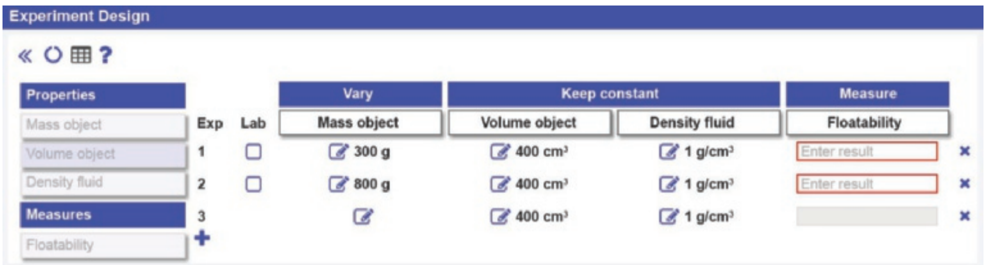

Figure 3.2. The Open Experiment Design Tool (EDT).

The two configurations of the tool differed in two aspects, as shown in Figure 3.3. One configuration had a more exploratory character and the other configuration offered more structure to the students. The first way the two configurations differed was in the number of trials students had to design before they could conduct them in the lab. The second way the two configurations differed was in the application of experiment design strategies.

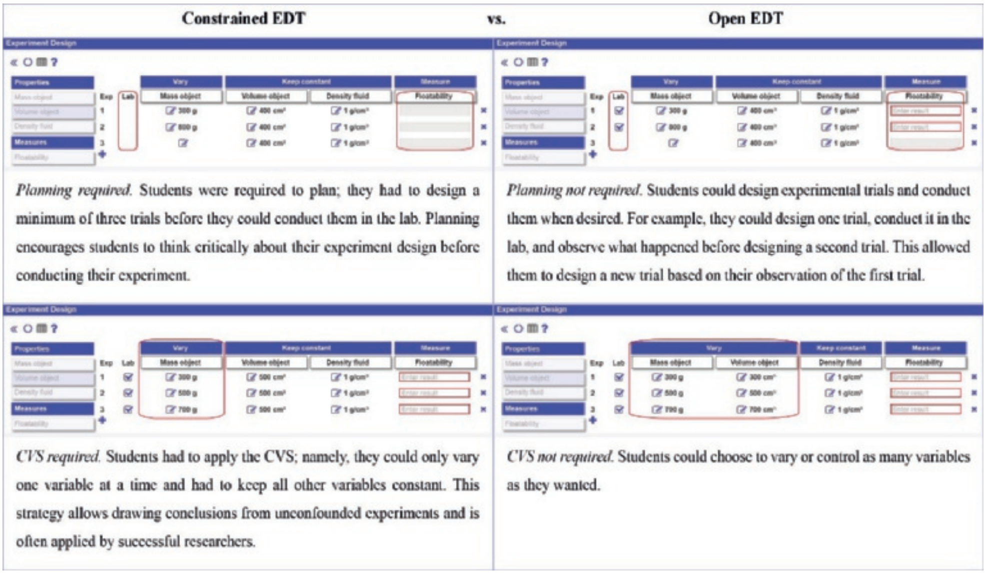

Figure 3.3. Differences between the Constrained EDT and the Open EDT.

Assessment

Students' knowledge of buoyancy and Archimedes' Principle, the topics in Splash, was assessed both before and after the intervention with parallel pencil-and-paper pre- and post-tests that were based on tests created by van Riesen et al. (2018). The pre-test contained the same questions as the post-test, but differed in the values provided within questions and in the order of the questions. The tests that we used in our current study consisted of 58 open-ended questions that measured students' understanding of the key concepts and principles of the topics in Splash, with 25 points available for buoyancy and 33 for Archimedes' principle. Students had to write down definitions and apply their knowledge by providing the mass, volume, and density of balls and fluids in different situations, the amount of water that was displaced by the ball, and/or forces that were present in the provided situations. Students were given thirty minutes to complete the test, and were allowed to use a calculator and a pen. To determine the reliability of the tests, separate Cronbach alpha's for both parts (buoyancy and Archimedes' principle) of the pre- and the post-tests were determined based on the 109 participants that were taken into account in the analyses. The first part of the pre-test (about buoyancy) showed a Cronbach's alpha of .936 (25 items), and the second part of the pre-test (about Archimedes' principle) a Cronbach's alpha of .886 (33 items). Cronbach's alpha's of .921 were found for the buoyancy part of the post-test (25 items) and of .907 for the Archimedes' principle part of the post-test (33 items), all of which demonstrate high reliabilities.

Procedure

The study was carried out during four sessions of 50-60 minutes each, over a period of two and a half weeks, in the computer lab at their school during their regular physics lessons. At the beginning of the first session students were told what they were going to do in the four sessions making up the study. Thereafter, they had half an hour to complete the pre-test, which was enough time for all students to finish. Finally, they were assigned to one of the three conditions based on their physics marks that we retrieved from their teacher to create similar background conditions between conditions, and within their condition they were given instructions and a demonstration on how to perform the tasks for the upcoming lessons within the learning environment. They could ask any questions they (still) had. During the second session students received a booklet matching the condition they were assigned to. All booklets contained instructions about the tasks they were going to perform, and the research questions they had to answer during the lesson in order for them to see which questions were still coming and to take notes for specific questions if they wanted to. In addition, the booklets given to students in the control group provided specific spaces where they could write down anything they thought might help them answer the research question, such as their experiment design and observed results. All students worked individually with the learning environment at a computer. Instructions had already been provided to them during the first session, but were also present in the learning environment and on paper, so they could immediately start designing and conducting experiments to learn about buoyancy during the second session. The third session was similar to the second session; students also worked with the learning environment, but the topic of investigation was Archimedes' principle instead of buoyancy.

During the fourth session students took the post-test, which they again had half an hour to complete, and they all finished within the allotted time again.

Results

In the current study three conditions were compared, which differed in the support provided for designing and conducting experiments in an online learning environment. First, we explored whether students in all conditions gained knowledge about buoyancy and Archimedes' principle. Paired samples *t*-tests were conducted for each condition and showed significant increases in score from pre- to post-test for buoyancy (control condition: $t(35) = -3.941$, $p < .001$, $d = 0.66$; Constrained EDT condition: $t(35) = -3.088$, $p = .004$, $d = 0.51$; Open EDT condition: $t(36) = -3.709$, $p = .001$, $d = 0.61$) and for Archimedes' principle (control condition: $t(35) = -4.378$, $p < .001$, $d = 0.73$; Constrained EDT condition: $t(35) = -2.711$, $p = .010$, $d = 0.45$; Open EDT condition: $t(36) = -3.630$, $p = .001$, $d = 0.60$) in all three conditions. Table 3.1 shows the means and SDs of the pre- and post-test scores for all conditions, as well as the difference scores.

Table 3.1

Test scores per condition for all students

	Control (*n* = 36)		Constr. EDT (*n* = 36)		Open EDT (*n* = 37)		Total (*n* = 109)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
	Buoyancy (Max = 25)							
Pre-test	14.89	8.25	15.44	6.30	15.70	7.54	15.35	7.35
Post-test	18.83	6.02	18.39	5.84	19.78	6.44	19.01	6.08
Difference score	3.94	6.00	2.94	5.72	4.08	6.69	3.66	6.12
	Archimedes' principle (Max = 33)							
Pre-test	4.69	4.45	4.89	4.00	4.24	4.26	4.61	4.21
Post-test	8.97	7.98	6.86	3.86	7.14	4.61	7.65	5.78
Difference score	4.28	5.86	1.97	4.37	2.89	4.85	3.05	5.10

Our first principal interest was whether mean conceptual learning gains differed between students who received different guidance for designing experiments. One-way ANOVA's showed no a-priori differences between conditions regarding prior knowledge about buoyancy, $F(2, 106) = 0.115$, $p = 0.892$, and about Archimedes' principle, $F(2, 106) = 0.223$, $p = 0.800$. Univariate analyses showed no significant differences between conditions for buoyancy, $F(2, 106) = 0.37$, $p = 0.693$, $\eta_p^2 = .007$, and for Archimedes' principle, $F(2, 106) = 1.89$, $p = 0.156$, $\eta_p^2 = .034$.

Different Prior Knowledge Groups

Our second principal interest was in differences between conditions for students with distinct levels of prior knowledge. Here we were only concerned with buoyancy and not Archimedes' principle, because 93% of all students had low prior knowledge about Archimedes' principle, preventing us from performing any useful analyses about that topic. Based on their pre-test scores about buoyancy, students were classified as 1) low prior knowledge, when they scored 0-25% on the pre-test, 2) low-intermediate prior knowledge, when they scored 26-50% on the pre-test, 3) high-intermediate prior knowledge, when they scored 51-75% on the pre-test, or 4) high prior knowledge students, when they scored 76-100% on the pre-test.

Because of the low number of students per group, an independent-samples Kruskal-Wallis test was conducted, which showed a significant difference between conditions only for low-intermediate prior knowledge students learning about buoyancy, $H(2) = 9.14$, $p = .010$. Follow-up Mann-Whitney analyses showed that low-intermediate prior knowledge students in the control condition and in the Open EDT condition gained significantly more knowledge than low-intermediate prior knowledge students in the Constrained EDT condition, (control vs Constrained EDT: $U = 3.5$, $p = .047$, $r = 0.60$; Constrained EDT vs Open EDT: $U = 0.0$, $p = .010$, $r = 0.81$), and a non-significant effect that approached significance was found in favour of the Open EDT condition compared to the control condition ($U = 8.0$, $p = .062$, $r = 0.52$). Table 3.2 shows the means and SDs of the pre- and post-test scores for buoyancy for low-intermediate prior knowledge students in all conditions, as well as the difference scores.

Table 3.2

Test scores for buoyancy (max = 25) per condition for low-intermediate prior knowledge students

	Control (n = 7)		Constr. EDT (n = 4)		Open EDT (n = 6)		Total (n = 17)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Pre-test	9.43	1.40	9.00	2.00	8.67	2.07	9.06	1.71
Post-test	17.00	6.08	9.25	3.40	22.83	3.13	17.24	6.84
Difference score	7.57	6.29	0.25	4.03	14.17	4.17	8.18	7.26

The results for the other groups of students with different levels of prior knowledge are non-significant, but they should not be ignored. Descriptive statistics regarding difference scores between the pre- and post-test, as presented in Table 3.3, show that the groups of students with different levels of prior knowledge each gained most knowledge in a different condition; low prior knowledge students gained most when they worked with the Constrained EDT, low-intermediate prior knowledge students when they worked with the Open EDT, and high-intermediate prior knowledge students when they were not guided by the EDT. High prior knowledge students did not gain knowledge, but they already had an average pre-test score for buoyancy of 22.30, and therefore had little room to gain any knowledge.

Table 3.3

Difference scores for buoyancy (max = 25) per condition for each prior knowledge group

Prior	Control			Constr. EDT			Open EDT			Total		
knowledge	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*
Low	8.88	6.42	8	10.83	4.83	6	5.57	8.26	7	8.33	6.74	21
Low-interm.	7.57	6.29	7	0.25	4.03	4	14.17	4.17	6	8.18	7.26	17
High-interm.	4.80	2.28	5	3.36	4.27	14	3.83	4.54	6	3.76	3.92	25
High	-0.38	2.90	16	-0.58	4.14	12	0.22	2.65	18	-0.20	3.12	46

Conclusion and Discussion

In the current study we investigated the effect of two versions of the EDT in terms of conceptual learning gain, and compared the results to a control condition. One EDT (Constrained EDT) required learners to plan and apply CVS. The other EDT (Open EDT) was more exploratory, and provided learners with the same opportunities as learners who worked with the Constrained EDT (i.e., they could design several trials at once, and they could apply CVS just as easily as in the Constrained EDT), but without requiring them to perform the mandatory steps in the Constrained EDT. The two versions of the EDT were based on an earlier version of the EDT (van Riesen et al., 2018) that was designed according to the Scaffolding Framework of Quintana et al. (2004) along with the theoretical background that supports that framework.

When we took all learners into account when comparing conditions, no significant differences were found regarding knowledge gains. However, as expected, when we distinguished between groups of learners based on their prior knowledge on buoyancy, a significant effect was found for low-intermediate learners, insofar as this group performed significantly better with the Open EDT compared to the Constrained EDT on buoyancy. Moreover, descriptive statistics for all prior knowledge groups showed promising trends that point in the direction of even more specific prior knowledge-related differences. Our results showed that each of the three conditions resulted in distinctly (albeit not significantly) higher scores for one specific group of prior knowledge learners on buoyancy; the Constrained EDT resulted in greatest knowledge gain for low prior knowledge learners compared to other conditions (non-significant), the Open EDT had significantly better performance for low-intermediate prior knowledge learners compared to the Constrained EDT, and the control condition had the best learning gains for high-intermediate prior knowledge learners (non-significant). These (directional) results suggest a coherence between prior knowledge and the type and level of support that is effective for designing experiments, and support the widely acknowledged consensus that prior knowledge has a prominent role in new learning (Alexander & Judy, 1988; Hmelo, Nagarajan, & Day, 2000; Tuovinen & Sweller, 1999).

Thus, our current study showed that the match between learners' prior knowledge and the type of support they require should be handled very delicately. The effects of the interventions within the conditions in our study on learners with distinct levels of prior knowledge may be explained by the characteristics of the conditions, and how they foster or limit the application of certain search methods that learners can apply in their experimentation processes (Klahr & Simon, 1999).

To elaborate, low prior knowledge learners on buoyancy performed best when they were guided by the Constrained EDT (non-significantly). In the current study, learners could assign a wide range of masses and volumes to objects. The array of different possible masses and volumes the learner could select in the current study, combined with the interaction between the mass, volume and density of the object and the fluid in which it is placed, can lead to many experimental trials. This is especially the case when learners apply unsystematic experimentation behaviour and fail to document their experimental trials and results. When learners are not properly guided, they often apply weak search methods such as "generate and test", as defined by Klahr and Simon (1999), in which learners try something, and observe whether it leads to the desired outcome without pursuing a structured plan. This strategy can consume a lot of time and can be like trying to find a specific ring in a big box filled with rings, and tossing the ring back every time it is not the correct one. The Constrained EDT provided learners with the clearest structure for designing experiments, and required learners to plan at least three experimental trials at once, in which they also had to keep all variables constant except for the independent variable. Since low prior knowledge learners still need to figure out the effect each causal variable has on the dependent variables, a clear experimental structure requiring them to vary exactly one variable could help them gain insight into the effect of these variables on the dependent variable, allowing them to work through the learning material step by step (Quintana et al., 2004). Moreover, the Constrained EDT automatically saved all the experimental trials and allowed learners to organise the results for inspection by allowing them to sort each variable in ascending or descending order.

Interestingly, in contrast with the low prior knowledge learners, low-intermediate prior knowledge learners performed significantly better when they worked with the Open EDT compared to the Constrained EDT. The Open EDT offered learners the same structure for experimental design as the Constrained EDT (i.e., learners could see variables they could keep constant, vary or measure, and the EDT automatically assigned identical values to control variables in different experimental trials), but it differed in that experimental trials could also be conducted when learners had not prepared at least three experimental trials, and it allowed them to vary more than one variable at a time.

Learners who have no specific idea about the domain benefit from applying an exploratory approach to the domain, in which they try to find relationships between variables in a systematic way (Pedaste et al., 2015). The Open EDT allows broader exploration than the Constrained EDT because learners who work with the Open EDT can conduct single trials and are not required to apply CVS, giving them the freedom to design and conduct one trial, observe what happens, and design a new trial accordingly. As with the Constrained EDT, all completed trials for which learners have entered the results are automatically documented and learners record their observation for each trial themselves, which then provides them with the opportunity to review their observations at any point. The characteristics of the Open EDT make it very suitable for learners to apply the exploratory search method known as "hill climbing" (Klahr & Simon, 1999), in which they first design several experimental trials that do not necessarily need to be heading in the same direction, then observe what happens, and then design new trials based on the results from the trials that show greatest promise for answering the research question (Klahr & Simon, 1999). Our results suggest that the Open EDT is more suitable for learners who already have at least some knowledge about the domain of investigation, but who still have a considerable amount to learn, which fits well with other literature (e.g., Lim, 2004; Pedaste et al., 2015).

Furthermore, high-intermediate prior knowledge learners in the current study gained most knowledge when they were not working with the EDT at all (non-significant). A strand of research supports the finding that more knowledgeable learners require less guidance and apply more sophisticated strategies than their peers who have little prior knowledge (e.g., Alexander & Judy, 1988; Hmelo et al., 2000; Tuovinen & Sweller, 1999). Klahr and Simon (1999) found that more knowledgeable learners often use strong methods that allow them to find solutions with little or no search, for example, by applying known formulas or physics rules. When learners are familiar with the formula for density: $\rho = m / V$, and when they also know the relationship between object density, fluid density, and floatability, they can simply apply those rules to know whether an object sinks, submerges, or floats in a certain fluid. They only need to conduct a few experimental trials in order to check the correctness of their prior knowledge or extend their knowledge, which they can do more easily by setting up an experimental trial directly in the lab, observing what happens, and continuing with another experimental trial until they feel confident about their answer to the research question. Guidance in the form of the EDT would therefore be unnecessary to aid their learning and might even slow down their learning compared to when no additional support is provided, which seemed to have been the case in our current study.

Lastly, high prior knowledge learners did not gain knowledge of the topic of buoyancy, but it should be noted that they had already scored very high on the pre-test. Despite their very high pre-test scores, high prior knowledge learners who worked with the Constrained EDT even showed a negative learning effect of more than half a point. Similar findings were obtained by Kalyuga (2007), who also found that guidance can have a negative effect on high prior knowledge learners, which he referred to as the "expertise reversal effect". The redundant additional support may distract learners and prevent them from performing the task as well as they could have with less support.

It is important to stress that we have discussed our results based on literature that we mapped to our study, with which we have attempted to explain relationships between learner and learning environment characteristics, and learning gains. A limitation of our study is that we focused only on learning gains measured with a pre- and post-test. Our study could have benefited from additional forms of data collection and analysis, such as log file analyses, which might have shown us whether or not learners actually performed the actions that we have suggested could have been encouraged by the type of EDT they worked with. Multiple methods could thus have provided us with richer insights in students' learning processes and learning outcomes.

Nevertheless, the results from our study suggest that prior knowledge influences the degree to which learners benefit from different types and levels of support, and that the match between effective guidance for inquiry learning in an online environment and prior knowledge is a very delicate matter that should be treated carefully. Designers of guidance should not just consider low or high prior knowledge learners, but should focus more on a continuum of levels of prior knowledge. This can be achieved by designing guidance in such a way that it automatically adapts to learners' prior knowledge levels, or by allowing manual configuration so that teachers can adjust guidance based on learners' prior knowledge and behaviours. We studied the effectiveness of two configurations of the

EDT. The configurability of the EDT allows teachers to provide learners with the level of guidance they require in order for them to learn most effectively; ideally, teachers should regularly monitor learners' knowledge and adapt the guidance accordingly.

Future research should investigate the distinction between different levels of prior knowledge with respect to their optimal type and level of support from our EDT with a larger sample size to analyse whether the results still hold. More in-depth methods should also be used in order to get a better understanding of the processes learners go through and the rationales behind their choice of experimentation strategies.

References

Alexander, P. A., & Judy, J. E. (1988). The interaction of domain-specific and strategic knowledge in academic performance. *Review of Educational Research, 58*, 375-404. doi:10.3102/00346543058004375

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. doi:10.1037/A0021017

Almarshoud, A. F. (2011). The advancement in using remote laboratories in electrical engineering education: A review. *European Journal of Engineering Education, 36*, 425-433. doi:10.1080/03043797.2011.604125

Arnold, J. C., Kremer, K., & Mayer, J. (2014). Understanding students' experiments: What kind of support do they need in inquiry tasks? *International Journal of Science Education, 36*, 2719-2749. doi:10.1080/09500693.2014.930209

Carnesi, S., & DiGiorgio, K. (2009). Teaching the inquiry process to 21st century learners. *Library Media Connection, 27*, 32-36.

Dalgarno, B., Kennedy, G., & Bennett, S. (2014). The impact of students' exploration strategies on discovery learning using computer-based simulations. *Educational Media International, 51*, 310-329. doi:10.1080/09523987.2014.977009

de Jong, T. (2006). Computer simulations: Technological advances in inquiry learning. *Science, 312*, 532-533. doi:10.1126/science.1127750

de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science, 340*, 305-308. doi:10.1126/science.1230579

de Jong, T., & Njoo, M. (1992). Learning and instruction with computer simulations: Learning processes involved. In E. de Corte, M. Linn, H. Mandl, & L. Verschaffel (Eds.), *Computer-based learning environments and problem solving* (pp. 411-429). Berlin, Germany: Springer-Verlag.

de Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research, 68*, 179-201. doi:10.2307/1170753

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences, 8*, 391-450. doi:10.1207/s15327809jls0803&4_3

Glaser, R., Schauble, L., Raghavan, K., & Zeitz, C. (1992). Scientific reasoning across different domains. In E. de Corte, M. C. Linn, H. Mandl, & L. Verschaffel (Eds.), *Computer-based learning environments and problem solving* (pp. 345-371). Berlin, Heidelberg: Springer Berlin Heidelberg.

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. doi:10.1037/a0029433

Hardy, I., Jonen, A., Möller, K., & Stern, E. (2006). Effects of instructional support within constructivist learning environments for elementary school students' understanding of "floating and sinking". *Journal of Educational Psychology, 98*, 307-326. doi:10.1037/0022-0663.98.2.307

Hmelo, C. E., Nagarajan, A., & Day, R. S. (2000). Effects of high and low prior knowledge on construction of a joint problem space. *The Journal of Experimental Education, 69*, 36-56. doi:10.1080/00220970009600648

Hughes, S. W. (2005). Archimedes revisited: A faster, better, cheaper method of accurately measuring the volume of small objects. *Physics Education, 40*, 468-474.

Kalyuga, S. (2007). Expertise reversal effect and its implications for learner-tailored instruction. *Educational Psychology Review, 19*, 509-539. doi:10.1007/s10648-007-9054-3

Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction: Effect of direct instruction and discovery learning. *Psychological Science, 15*, 661-667. doi:10.1111/j.0956-7976.2004.00737.x

Klahr, D., & Simon, H. A. (1999). Studies of scientific discovery: Complementary approaches and convergent findings. *Psychological Bulletin, 125*, 524-543. doi:10.1037/0033-2909.125.5.524

Lazonder, A. W. (2014). Inquiry learning. In J. M. Spector, M. D. Merrill, J. Elen, & M. J. Bishop (Eds.), *Handbook of research on educational communications and technology* (pp. 453-464). New York: Springer Science + Business Media.

Lim, B. (2004). Challenges and issues in designing inquiry on the Web. *British Journal of Educational Technology, 35*(5), 627-643. doi:10.1111/j.0007-1013.2004.00419.x

Loverude, M. E. (2009). A research-based interactive lecture demonstration on sinking and floating. *American Journal of Physics, 77*, 897-901. doi:10.1119/1.3191688

Loverude, M. E., Kautz, C. H., & Heron, P. R. L. (2003). Helping students develop an understanding of Archimedes' principle. I. Research on student understanding. *American Journal of Physics, 71*, 1178-1187. doi:10.1119/1.1607335

Manlove, S., Lazonder, A. W., & de Jong, T. (2006). Regulative support for collaborative scientific inquiry learning. *Journal of Computer Assisted Learning, 22*, 87-98. doi:10.1111/j.1365-2729.2006.00162.x

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*, 692-720. doi:10.1002/Tea.10105

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 the inquiry cycle. *Educational Research Review, 14*, 47-61. doi:10.1016/j.edurev.2015.02.003

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., . . . Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences, 13*, 337-386. doi:10.1207/s15327809jls1303_4

Reiser, B. J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. *Journal of the Learning Sciences, 13*, 273-304. doi:10.1207/s15327809jls1303_2

Sancristobal, E., Martín, S., Gil, R., Orduña, P., Tawfik, M., Pesquera, A., . . . Castro, M. (2012). *State of art, initiatives and new challenges for virtual and remote labs.* Paper presented at the 12th IEEE International Conference on Advanced Learning Technologies, Rome, Italy.

Schraw, G., Crippen, K. J., & Hartley, K. (2006). Promoting self-regulation in science education: Metacognition as part of a broader perspective on learning. *Research in Science Education, 36*, 111-139. doi:10.1007/s11165-005-3917-8

Schunk, D. H. (1996). *Learning theories*. New Jersey: Prentice Hall Inc.

Simons, K. D., & Klein, J. D. (2007). The impact of scaffolding and student achievement levels in a problem-based learning environment. *Instructional Science, 35*, 41-72. doi:10.1007/s11251-006-9002-5

SLO Nationaal Expertisecentrum Leerplanontwikkeling. (2016). *Karakteristieken en kerndoelen: Onderbouw voortgezet onderwijs* (Characteristics and headline targets:

Lower secundary education. Report number: OBVO/16-023). Retrieved from Enschede: http://downloads.slo.nl/Documenten/karakteristieken-en-kerndoelen-onderbouw-vo.pdf

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. doi:10.1080/10494820.2012.693102

Tuovinen, J. E., & Sweller, J. (1999). A comparison of cognitive load associated with discovery learning and worked examples. *Journal of Educational Psychology, 91*, 334-341. doi:10.1037/0022-0663.91.2.334

van Joolingen, W. R., & de Jong, T. (1991). Supporting hypothesis generation by learners exploring an interactive computer simulation. *Instructional Science, 20*, 389-404.

van Riesen, S. A. N., Gijlers, H., Anjewierden, A. A., & de Jong, T. (2018). Supporting learners' experiment design. *Educational Technology Research and Development, 66*, 475-491. doi:10.1007/s11423-017-9568-4

Veenman, M. V. J., Elshout, J. J., & Meijer, J. (1997). The generality vs domain-specificity of metacognitive skills in novice learning across domains. *Learning and Instruction, 7*, 187-209. doi:10.1016/S0959-4752(96)00025-4

Veermans, K., de Jong, T., & van Joolingen, W. R. (2000). Promoting self-directed learning in simulation-based discovery learning environments through intelligent support. *Interactive Learning Environments, 8*, 229-255. doi:10.1076/1049-4820(200012)8:3;1-D;FT229

Veermans, K., van Joolingen, W. R., & de Jong, T. (2006). Use of heuristics to facilitate scientific discovery learning in a simulation learning environment in a physics domain. *International Journal of Science Education, 28*, 341-361. doi:10.1080/09500690500277615

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 when using virtual and remote labs in science: A literature review. *Educational Technology Research and Development, 63*, 257-302. doi:10.1007/s11423-015-9370-0

Zimmerman, B. J. (2002). Becoming a self-regulated learner: An overview. *Theory Into Practice, 41*, 64-70. doi:10.1207/s15430421tip4102_2

4

The Influence of Prior Knowledge on Experiment Design Guidance in a Science Inquiry Context

Study 3

This chapter is based on:

van Riesen, S. A. N., Gijlers, H., Anjewierden, A. A., & de Jong, T. (2018). The influence of prior knowledge on experiment design guidance in a science inquiry context. *International Journal of Science Education, 40,* 1327-1344. doi: 10.1080/09500693.2018.1477263.

Abstract

Designing and conducting sound and informative experiments is an important aspect of inquiry learning. Students, however, often design experiments that do not allow them to reach conclusions. Considering the difficulties students experience with the process of designing experiments, additional guidance in the form of an Experiment Design Tool (EDT) was developed, together with reflection questions. In this study, 147 pre-university students worked in an online inquiry learning environment on buoyancy and Archimedes' principle. Students were randomly assigned to one of three conditions, each of which contained a different version of the EDT. Since students' prior knowledge has been found to influence the amount and type of guidance they need, the versions of the tool differed with respect to the level of guidance provided. A pre- and post-test were administered to assess students' conceptual knowledge. No overall differences between conditions were found. In a subsequent analysis, students were classified as either low, low-intermediate-, high-intermediate, or high prior knowledge students. For Archimedes' principle we found that low-intermediate prior knowledge students gained significantly more conceptual knowledge than low prior knowledge students in the fully guided condition. It is hypothesised that students need at least some prior knowledge in order to fully benefit from the guidance offered.

Introduction

Educators prepare learners for the world, and must use teaching methods that allow students to gain knowledge and acquire useful skills. In science education, teaching methods in which students have an active role increase students' performance on assessments compared to traditional lecturing (Freeman et al., 2014). According to Freeman et al., actively building one's own knowledge results in deeper and more meaningful learning, and students perform better on examinations when they learn actively than when they merely attend lectures. One effective active learning method is guided inquiry learning, during which students get acquainted with and practice inquiry skills and processes in order to gain knowledge about a domain by engaging in scientific investigations (Lazonder & Harmsen, 2016; Minner, Levy, & Century, 2010; Pedaste et al., 2015).

In inquiry learning, students commonly work through an inquiry cycle that is comprised of several inquiry phases. Different versions of these inquiry phases have been specified by scholars, many of whom have created their own inquiry cycle (e.g., de Jong, 2006a; Kuhn & Pease, 2008; Lim, 2004; National Research Council, 1996; White & Frederiksen, 1998). Pedaste et al. (2015) summarised these different approaches in a review study on inquiry cycles; on the basis of the phases they found, they distilled a set of core inquiry phases: orientation, conceptualisation, investigation, conclusion, and discussion. In the *orientation phase* the topic of investigation is explored by the student. For learning through conducting inquiry to occur, it is crucial for the student to have a basic understanding of the topic of investigation. If the student does not have at least basic knowledge about the topic, it is very difficult or even impossible to formulate meaningful research questions and to design useful experiments (e.g., Quintana et al., 2004). In the *conceptualisation phase* students formulate research questions or hypotheses to investigate. During the *investigation phase*, which can be seen as a pivotal phase, students design and conduct experiments. Based on those experiments, they then draw conclusions in the *conclusion phase*. The *discussion phase* can take place, as described by Pedaste et al. (2015), at the end of each previously described phase, or at the end of the entire inquiry cycle. In this phase students reflect upon their inquiries and communicate their findings. In the current study, students participated in an online inquiry learning environment that contained information about the topic of investigation, provided them with research questions, contained an online lab in which they could conduct their designed experimental trials, and that had a conclusion input box for them to formulate their conclusions to the experiments in. We specifically focussed on the effect of different forms of guidance to aid learners in applying useful strategies for selecting variables and assigning values to them in the investigation phase. The investigation phase is at the heart of the inquiry model of Pedaste et al. (2015), and serves as a bridge between the hypothesis or research question and the conclusion (Arnold, Kremer, & Mayer, 2014).

An important aspect of designing experiments is the selection and manipulation of variables that are expected to have an effect on the dependent variable. Students can apply various strategies that allow them to connect experimental results to the influential variable or to explore the boundaries of a domain. First of all, when students choose the dependent, independent and control variables, they can apply the Control of Variables Strategy (CVS), which entails that all variables, except for the manipulated variable, should be controlled for (Chinn & Malhotra, 2002; Klahr & Dunbar, 1988). It is important for students to understand that any variable that is not controlled for can influence the outcome of an experiment, resulting in the inability to ascribe an observed effect to a specific variable. Second, it is useful for students to be familiar with strategies for choosing values for variables within an experiment design. Two of those strategies that are often applied by scientists are 1) the use of extreme values and 2) equal increments between trials (Veermans, van Joolingen, & de Jong, 2006). Using extremely low or high values allows exploration of the boundaries of a domain, whereas using equal increments between trials provides information about if and when an effect occurs, and about the strength of an effect, if present.

To design informative experiments, students need to have prior knowledge about the domain of investigation. Prior knowledge has been found to be the most important factor for learning and performance in general (e.g., Ausubel, 1968; Kalyuga, 2007), and there is a positive correlation between students' prior knowledge and their ability to apply higher-order cognitive skills, as in designing experiments (Hailikari, Katajavuori, & Lindblom-Ylanne, 2008). Students with little prior domain knowledge who participate in inquiry learning use less sophisticated strategies and need more experiments to reach conclusions than their more knowledgeable peers, who employ more well-structured goal-oriented inquiry strategies (Alexander & Judy, 1988; Hmelo, Nagarajan, & Day, 2000;

Schauble, Glaser, Raghavan, & Reiner, 1991). These findings were confirmed by Hattie and Donoghue (2016), who, in a recent paper, based on a meta-synthesis of a large set of meta-analyses, stated that active forms of learning such as inquiry learning, that promote the acquisition of deep knowledge have a profound effect, but only when they are offered to learners after they have acquired the necessary prerequisite knowledge. Moreover, they highlight the importance of active learning methods such as inquiry learning in order to gain deep-level understandings in science education, because future learning in science education usually builds upon this knowledge.

Taken together, a lack of prior knowledge and/or little command over experiment design makes designing informative experiments difficult for many students. They often tend to design experiments that have nothing to do with their research question or that have design flaws that interfere with their ability to draw conclusions. Common mistakes include using irrelevant variables that have no relationship with the research question, leaving out relevant variables, varying too many variables at the same time, and not considering control variables (de Jong, 2006b). Considering the difficulties students experience, it is not surprising that inquiry learning has been found to be ineffective when students are minimally prepared and guided; however, inquiry approaches are effective and even superior to other instructional methods when proper guidance is given (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; d'Angelo et al., 2014; Hmelo-Silver, Duncan, & Chinn, 2007). Guidance allows students to achieve tasks they could not have accomplished on their own (Zacharia et al., 2015). In computer-supported learning environments, tools are among the best-documented forms of guidance (de Jong & Lazonder, 2014; Zacharia et al., 2015). They simplify or take over part of the task, allowing students to gain higher-order skills (de Jong, 2006b; Reiser, 2004; Simons & Klein, 2007).

Students' prior knowledge not only influences the quality of their spontaneous experimental designs, it also influences the type and amount of guidance that is beneficial. Many studies have demonstrated that students with diverse levels of prior knowledge benefit from different types of guidance (Kalyuga, 2007; Lambiotte & Dansereau, 1992; Tuovinen & Sweller, 1999). For example, Tuovinen and Sweller (1999) found that guidance in the form of worked examples was superior to exploration for low prior knowledge students who were learning to use a database program; however, no differences in learning were found for high prior knowledge students, because they already possessed well-developed domain schemas. Lambiotte and Dansereau (1992) provided students with different forms of guidance during lectures (i.e., knowledge maps, outlines, and lists with key terms), and compared their recall of the material. They found that the most effective type of guidance for low prior knowledge learners was the least effective type for high prior knowledge students. Low prior knowledge students performed significantly better when they received knowledge maps then when they received an outline or a list with key terms, whereas the opposite was true for high prior knowledge students who performed best with the list containing key terms. Kalyuga (2007) found that some forms of guidance that are beneficial for students with low prior knowledge can be redundant or even have negative effects for high prior knowledge students, which is referred to as the "expertise reversal effect". There seems to be a general consensus that low prior knowledge students benefit from higher levels of guidance than high prior knowledge students (Lazonder, Wilhelm, & Hagemans, 2008), but guidance can also add to the difficulty of a task when the guidance itself is hard to understand (Roll, Briseno, Yee, & Welsh, 2014; van Joolingen & de Jong, 1991). In some situations, low prior knowledge students perform better when they first enact trial-and-error types of behaviours, after which they can make better sense of the provided guidance and use it to their benefit (Roll, Briseno, et al., 2014; Roll, de Baker, Aleven, & Koedinger, 2014).

To guide students in designing experiments when performing an inquiry task with online labs, we designed a tool, the Experiment Design Tool (EDT), which was demonstrated to have a positive effect on conceptual learning gains for low and low-intermediate prior knowledge students in two previous studies (van Riesen, Gijlers, Anjewierden, & de Jong, submitted). The EDT guides students in designing their experiments by providing them with a predefined list of domain-related variables that are relevant for the experiments students are expected to design. The tool guides students in the process of specifying the independent, dependent and control variables, and in assigning values to the independent and control variables. It supports students in following a CVS approach, in that for each independent variable, students specify one value per experimental trial, and for each control variable they select one value that is automatically assigned to all trials within an experiment (for a detailed description of the EDT, see the Method section).

In the current study we further investigated the value of the EDT for inquiry learning and, following the considerations above, we varied the level of guidance by providing not only a full version of the EDT in which variables had to be assigned to the categories of independent, dependent, and controlled, but also a minimalist version in which this distinction was not included. We wanted to explore whether this version was more beneficial for students with a high level of prior knowledge. In addition, we introduced a new component in the EDT, namely, a structured reflection about the experiment design.

Designing experiments (often as a series of trials) should be performed as a thoughtful and planned activity. This experiment design process can be facilitated by reflection about the process and the strategies used. A large body of research has demonstrated the importance and advantages of reflection for successful learning. Reflection can lead to deeper learning, help students integrate new and existing knowledge, allow them to gain more complex knowledge, and assist them to produce better experiments (Davis, 2000; Kori, Mäeots, & Pedaste, 2014). In inquiry learning, the goal of designing and conducting experiments is to gain knowledge and/or skills, which requires students to differentiate, integrate, and restructure ideas. Reflecting on original ideas, obtained experiment results, and relationships between ideas and results can help students to successfully process all the information and build a coherent understanding (Linn, Eylon, Rafferty, & Vitale, 2015), on the basis of which they can revise their experimentation strategies and develop more effective strategies for designing experiments (Davis, 2000; Linn et al., 2015; Pedaste et al., 2015). In order to increase the quality of students' reflections, students can be prompted to evaluate their experimental designs based on a set of carefully chosen criteria (Kori et al., 2014; White & Frederiksen, 1998). In the current study, we evaluated a Reflection Tool that prompted students to carefully screen their experiments and consider lessons learned for future experiment design.

In two previous studies (van Riesen et al., 2018; van Riesen et al., submitted), different versions of the EDT were found to have a positive effect on conceptual learning gain for low and low-intermediate prior knowledge students. In the current study, we aim to acquire a better understanding of how the EDT can be adapted and used to benefit students with all levels of prior knowledge. For this purpose, in the current study we compare three versions of the EDT: a minimalist version of the EDT, a regular version of the EDT, and a regular version of the EDT with incorporated reflection questions.

Method

The current study focused on the effect of different types of guidance for designing and conducting experiments on students' gain in knowledge about the physics topics of buoyancy and Archimedes' principle. Three conditions were compared, each of which involved third-year pre-university students who worked in an online inquiry learning environment incorporating a virtual lab, but with a different version of the Experiment Design Tool in each case.

Participants

A total of 167 third-year pre-university students, approximately 15 years of age, participated in the current study. Twenty students were excluded from the analyses: eighteen because they missed a session, one because this student's difference score on the test about Archimedes' principle deviated more than 2 SDs from the overall mean, and one because this student's difference score on the test about Archimedes' principle deviated more than 2 SDs from the mean of the low-intermediate prior knowledge group to which the student belonged. This left a total of 147 students whose data were taken into account for analyses. All students had already learned about buoyancy within their regular science classes, but the topic of Archimedes' principle was new to them. Buoyancy was included in the learning environment so that the students could familiarise themselves with the learning environment and to activate their prior knowledge about buoyancy, which is a prerequisite to learn about Archimedes' principle. The students participated in the experiment during their regular science classes and participation was obligatory.

Domain and Learning Environment

Students in all conditions worked in an online inquiry learning environment created with the Go-Lab software (Gillet, Rodríguez-Triana, de Jong, Bollen, & Dikke, 2017) revolving around buoyancy and Archimedes' principle. Three versions of the same online inquiry learning environment were created. All environments were organised with three types of tabs: the method tab, two orientation tabs (one for buoyancy and one for Archimedes' principle), and a set of experiment tabs (see Figure 4.1). In the method tab, information was provided about navigating through the inquiry learning environment, about the type and purpose of the inquiry learning, and about actions students could perform and how they could do that. The orientation tabs contained materials such as texts, images, and videos, and was intended to activate (prior) knowledge about buoyancy and Archimedes' principle. Each experiment tab contained a research question (e.g., "How do the mass, the volume, and the density of a floating ball influence the amount of water that is displaced in terms of mass and volume?") together with a version of the EDT that enabled students to design their own experiments, an online laboratory called Splash, and a conclusion text box.

Figure 4.1. The learning environment.

The three inquiry learning environments that were developed for use in this study were identical, and differed only with respect to the type of guidance provided for designing experiments and the texts related to that. The guidance students received in the different conditions is described in detail in the section on Experiment Design.

Online Virtual Lab: Splash

Splash is a virtual laboratory about buoyancy and Archimedes' principle (see Figure 4.2). In Splash, several fluid-filled tubes are shown, in which balls can be dropped. The density of the fluids in the tubes, as well as the mass and volume (and therefore the density) of the balls can be manipulated. Mass divided by volume equals density; therefore, mass and volume of the balls could be specified by the user. Density of the balls was automatically calculated by Splash, based on the values students had chosen for mass and volume.

After specifying the mass and volume variables for the balls and the density of the fluid, students could drop the balls in the tubes and observe whether the balls sank, suspended, or floated in the fluids. The labs about buoyancy allowed students to refresh their knowledge about the relationships between mass, volume and density, and between the density of an object, the density of the fluid, and floatability. The labs about Archimedes' principle (see Figure 4.2) allowed students to additionally inspect the mass and volume of the displaced fluid, as well as the forces involved.

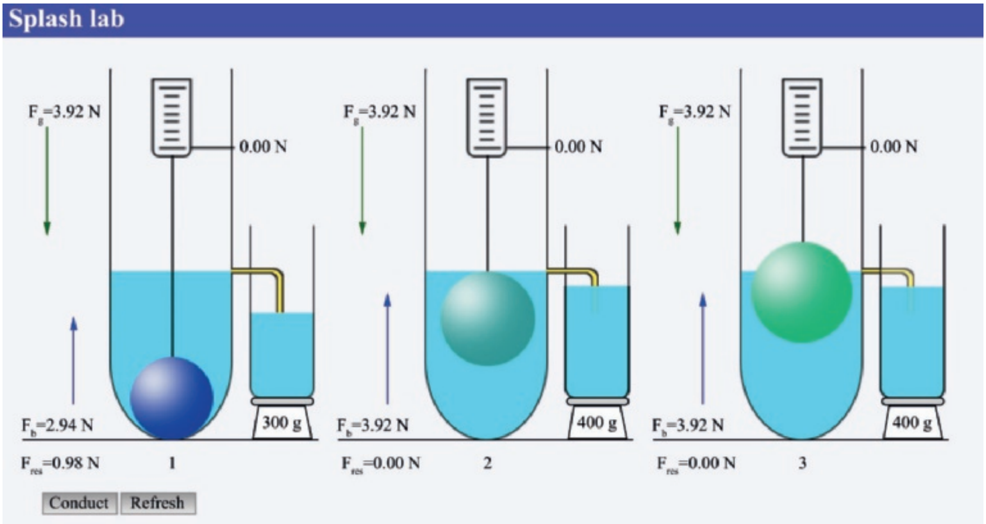

Figure 4.2. Online virtual laboratory Splash.

Experiment Design

The three conditions differed with respect to the tool (EDT) that guided students in the design of their experiments: 1) in the EDT condition students used the full version of the EDT, 2) in the EDT+ condition, students worked with the Reflection Tool in addition to the regular EDT, and 3) students in the EDT- condition worked with a minimalist version of the EDT.

Experiment Design Tool

The Experiment Design Tool (Figure 4.3) in its full version presented students with a predefined list of domain-related variables that were relevant for the experiments students had to design in order to be able to answer research questions.

For each variable, students could drag and drop the variable into one of three boxes (see Figure 4.3). This indicated whether they wanted to vary it (independent variable), keep it constant (control variable), or measure it (dependent variable). For each independent variable students specified one value per experimental trial, and for each control variable they selected one value that was automatically assigned to all trials within an experiment. Students could only choose values within a given range in order to restrict their choices. The trials that students designed in any EDT were automatically transferred to the lab, so that students could run an experiment without having to retype the values they had chosen for the input and control variables. After the students had conducted their experimental trials based on the values they assigned to the variables, they could observe the resulting effects, and enter their results in the tool. The designed experiments were automatically transferred to the Splash lab so that students did not need to enter the values for the input and control variables again; however, to force the students to take good notice of the experimental outcomes, the obtained values for the dependent variable were not automatically filled in, but had to be entered by the students themselves. Students were encouraged to design and conduct as many experiments as necessary to be able to draw a conclusion.

At any time, students could view all their previously designed and conducted experimental trials by pressing the table icon (Figure 4.3, top left). In the table, they could sort their data per variable in ascending or descending order, making it easier to compare trials.

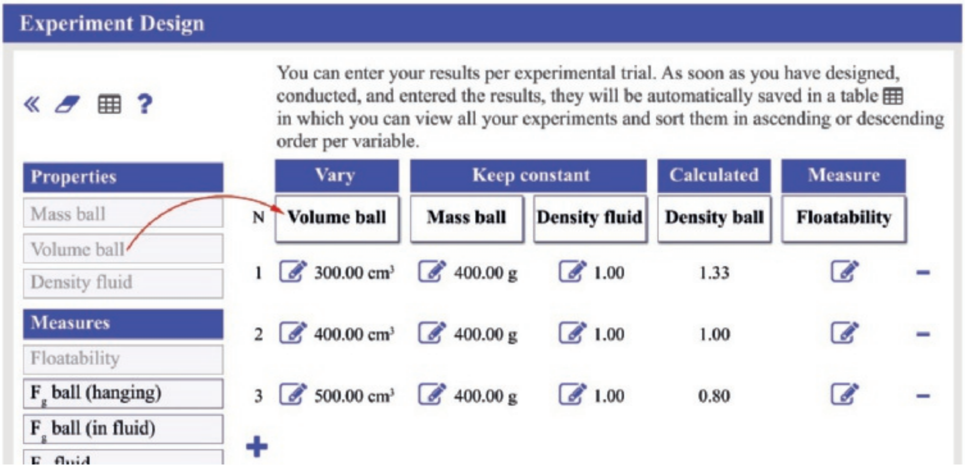

Figure 4.3. Experiment Design Tool.

Minimalist Experiment Design Tool

In the EDT- condition students had to design their experiments using a minimalist version of the Experiment Design Tool (Figure 4.4). The only difference from the full version of the EDT is that the minimalist EDT did not distinguish between independent and control variables. Instead, students could simply drag variables into the table and assign a value to each variable in each trial. The minimalist EDT provided students with the same variables as the full EDT, as well as an identical range of values to assign to the variables.

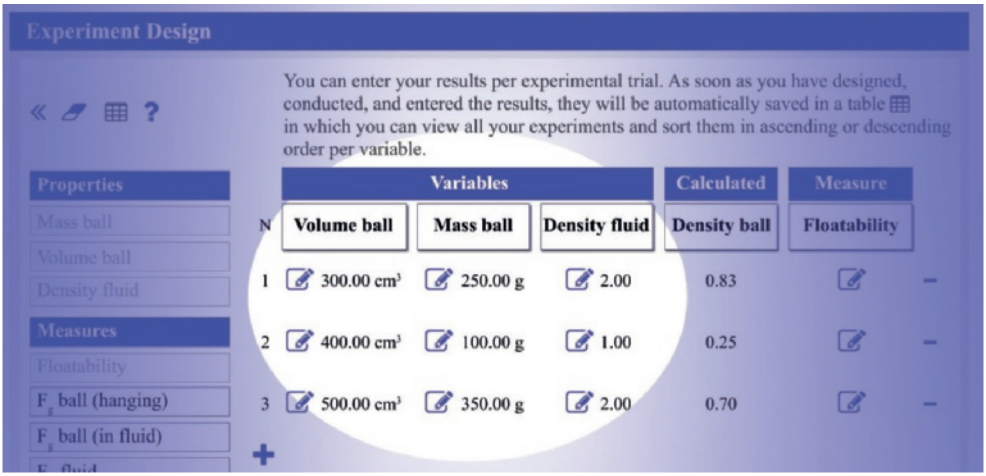

Figure 4.4. Minimalist Experiment Design Tool.

Experiment Design Tool with Integrated Reflection Tool

In the EDT+ condition a reflection component was integrated in the EDT. After students designed an experiment and conducted at least three trials, they had to answer reflection questions that were based on the design of their experiment. For example, students were asked whether they had designed relevant trials and enough trials to be able to answer the research question completely. If they indicated that they did, the Reflection Tool extracted information about the number of varied variables from the student log files to ask specific questions about why students varied one or more variables in their experiment. Subsequent reflection questions were again based on students' designed experiment and concerned strategies that students had used for assigning values to the variables. For example, students who changed one variable were asked why they had chosen to assign 1) extreme values, 2) values with the same increment between trials, 3) values within a small range, or 4) another strategy. They could enter their conclusions on the research question only after they had entered their response to the reflection questions. The reflection procedure is visualised in Figure 4.5. Please note that students had to continue designing, conducting and reflecting on their experiments until they reached the conclusion input box in which they could type their conclusion.

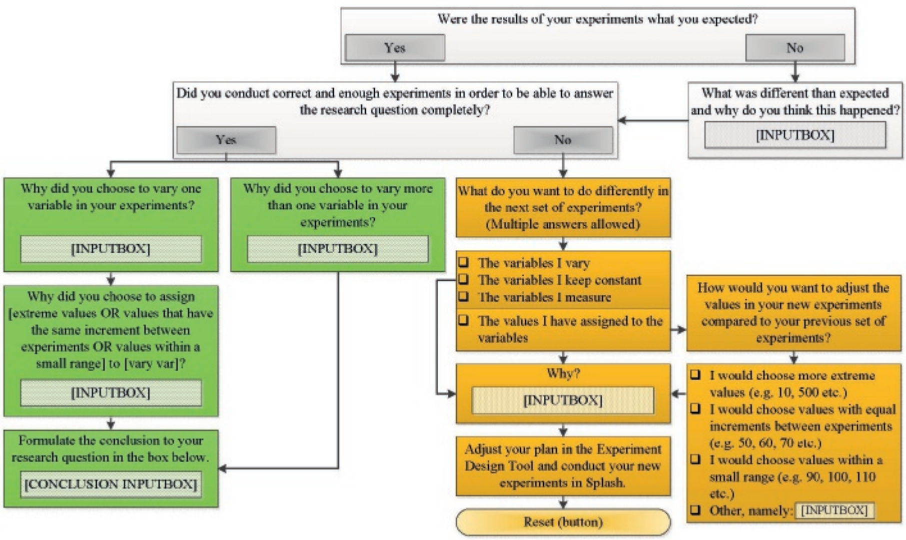

Figure 4.5. Flowchart reflection questions.

Knowledge Test

A paper-based test measured students' knowledge about buoyancy and Archimedes' principle. The parallel pre- and post-test version of the test each allowed students to gain a total of 25 points for open questions concerning buoyancy and 33 points for open questions concerning Archimedes' principle. An example of a question is: "A ball is being placed in a tube filled with water. This causes the water to be displaced. The displaced water is caught in a measuring cup. Below you can see the set-up before the ball is released. Provide the amount of displaced water and the values displayed on the spring balance and the scale after the ball has been released in the tube". Students could receive one point for each correct value they provided, meaning that they could obtain four points for the entire question in the example. Students could obtain a total of 58 points. Cronbach's Alpha was .933 for the pre-test about buoyancy and .893 for the pre-test on Archimedes' principle, .898 for the post-test on buoyancy and .910 for the post-test on Archimedes' principle, meaning that the reliabilities of the tests are very high.

Procedure

The study involved four sessions of 45-50 minutes each, which all took place inside the classroom within a timeframe of two and a half weeks. We chose to conduct our study inside the classroom, because this provides us with valuable insights into students' learning within their natural environment where the tool will ultimately be used. Students' prior knowledge about buoyancy and Archimedes' principle was measured during the first session. They were given thirty minutes to complete the pre-test; all of them finished within this time limit. After the test, students were assigned to their conditions; they were ranked based on their previous physics grade and then assigned to a condition to create three comparable participant pools for each condition. The remaining time was used to instruct students within their condition on how to work with the learning environment. Each group of students was shown the learning environment they were going to work with. The experimenter first showed the method tab and discussed all the information in this tab (i.e. what they were going to do and why, how they would do it, and a step-by-step procedure for conducting an experiment). It is important for students to understand the purpose of the activity and how to perform the activity, which is why everything was discussed thoroughly and they were encouraged to ask any questions they had. Then the orientation tab was shown and students were told that they could find any information they might need to successfully conduct their experiment there. Third, the research tab was shown, which included the research question, the EDT, a conclusion text box, and in the EDT+ condition the reflection tool. A demonstration of the EDT was given, in which all the options were used and explained. In the EDT+ condition, the reflection tool was also demonstrated and they were told that the questions were meant so that they would carefully think about their experiments. Students could get clarifications if they did not understand a question. For example, one reflection question asked them if they had conducted correct and enough experiments in order to be able to answer the research question; students were informed that correct and enough experiments meant that their conclusions to the research questions were based on the results they obtained from their experiments and that they should conduct as many trials as necessary to eliminate chance. During the second session, students worked with the learning environment on the topics of buoyancy and water displacement. At the start of the session, they were encouraged to read the research questions in the experiment tabs very carefully, in order to design useful experiments so that they could draw conclusions. All necessary prior domain information could be found in the learning environment, as well as instructions they had already received orally in the first session. Then, students started to work on experiments related to the domains of buoyancy and part of Archimedes' principle (water displacement). During the third session, students worked with the learning environment on experiments related to the domain of Archimedes' principle. In the fourth session, students again had thirty minutes to complete the post-test about buoyancy and Archimedes' principle.

Results

Our first analysis addressed whether students had learned from working with the learning environments, and if there was a difference in learning gains between conditions. A one-way repeated measures ANOVA with the pre- and post-test as time factors showed a significant learning gain for buoyancy, $F(1,144) = 65.62$, $p < .0005$; Wilk's $\Lambda = 0.687$, partial $\eta^2 = .31$, and for Archimedes' principle, $F(1, 144) = 119.82$, $p < .0005$; Wilk's $\Lambda = 0.546$, partial $\eta^2 = .45$. No significant differences were found between conditions for buoyancy, *F*(2, 144) = 0.20, p = .822; Wilk's Λ = 0.997, partial η^2 = .003 or Archimedes' principle, *F*(2, 144) = 0.33, p = .718; Wilk's Λ = 0.995, partial η^2 = .005. The mean scores and the standard deviations on the pre- and post-test, as well as the difference scores between pre- and post-test, are shown in Table 4.1. These scores seem to indicate that students had greater prior knowledge of buoyancy than of Archimedes' principle and also that they ended up with greater knowledge of buoyancy than of Archimedes' principle.

Table 4.1

Test scores per condition

	EDT (*n* = 52)		EDT+ (*n* = 48)		EDT- (*n* = 47)		Total (*n* = 147)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Buoyancy (max = 25)								
Pre-test	16.04	7.31	15.40	7.78	17.28	6.93	16.22	7.34
Post-test	20.69	4.16	19.54	6.27	21.15	4.79	20.46	5.14
Difference score	4.65	6.92	4.15	5.66	3.87	6.24	4.24	6.28
Archimedes' principle (max = 33)								
Pre-test	7.33	6.66	7.15	5.36	7.45	5.56	7.31	5.88
Post-test	13.71	8.59	12.77	6.92	12.83	6.88	13.12	7.50
Difference score	6.38	6.25	5.63	7.24	5.38	5.65	5.82	6.39

Our second main interest was the effect of prior knowledge on students' gain of conceptual knowledge when receiving different levels and types of guidance for designing experiments. Based on their pre-test scores, students were classified as low prior knowledge (L) students, low-intermediate prior knowledge students (LI), high-intermediate prior knowledge students (HI), or high prior knowledge students (H). Table 4.2 shows the classification of students based on their prior knowledge. Students were classified as to their knowledge level for buoyancy and Archimedes' principle separately, meaning that a student could, for example, be a high prior knowledge student for buoyancy, but a low prior knowledge student for Archimedes' principle.

Table 4.2

Classification of students based on their prior knowledge

Type of student	Pre-test buoyancy	Pre-test Archimedes' principle
Low prior knowledge	0-6 correct	0-8 correct
Low-intermediate prior knowledge	7-12 correct	9-16 correct
High-intermediate prior knowledge	13-18 correct	17-24 correct
High prior knowledge	19-25 correct	25-33 correct

For buoyancy, the number of students in the categories were 21, 32, 29 and 65 (from low to high, respectively). Because the data were not normally distributed, independent samples Kruskal-Wallis tests were performed for each category, and no significant differences were found between conditions for gain in conceptual knowledge, see Table 4.3.

Table 4.3

Statistics of students within their prior knowledge group

Buoyancy knowledge gain

PK	Test values			Condition											
				EDT-			EDT			EDT+			Total		
	H	o	*p*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*
L	5.404	2	.067	5	11.20	5.26	7	16.00	4.97	9	8.33	6.02	21	11.57	6.25
L-I	0.358	2	.836	9	8.22	6.12	11	8.18	5.29	12	7.08	5.87	32	7.78	5.59
H-I	2.555	2	.279	8	6.50	4.72	13	3.46	4.91	8	5.00	4.72	29	4.72	4.81
H	0.111	2	.946	25	0.00	3.86	21	-0.24	2.90	19	-0.53	2.12	65	-0.92	3.08

Archimedes' principle knowledge gain

PK	Test values			Condition											
				EDT-			EDT			EDT+			Total		
	H	o	*p*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*
L	0.536	2	.765	31	6,.16	5.70	32	6.00	6.56	29	6.90	8.03	92	6.34	6.74
L-I	6.204	2	.045	14	3.86	5.76	15	8.67	4.98	17	4.41	5.26	46	5.63	5.63
H-I	-	-	-	2	4.00	2.83	3	-0.33	6.66	2	-2.50	3.54	7	0.29	5.06
H	-	-	-	-	-	-	2	5.50	0.71	-	-	-	2	5.50	0.71

For Archimedes' principle, student numbers were not evenly divided over the different categories, with 92 and 46 students in the two low prior knowledge categories and only 7 and 2 students in the two high prior knowledge categories (from low to high, respectively). Consequently, no analysis could be performed or conclusions drawn for the two highest categories for Archimedes' principle. Independent samples Kruskal-Wallis tests for Archimedes' principle showed a significant difference between conditions in gain of conceptual knowledge for low-intermediate prior knowledge students, $H(2) = 6.20$, $p = .045$, but not for the low prior knowledge students, $H(2) = 0.54$, $p = .765$. Follow-up Mann-Whitney analyses for the low-intermediate prior knowledge students showed significant differences between the EDT condition and the EDT- condition, ($U = 153.00$, $p = .037$), as well as between the EDT condition and the EDT+ reflection condition, ($U = 69.50$, $p = .027$), both in favour of the EDT condition. Table 4.4 shows the means and standard deviations of the pre- and post-test scores, as well as difference scores, for Archimedes' principle for the low and the low-intermediate groups.

Table 4.4

Test scores of students with low and low-intermediate prior knowledge about Archimedes' principle

Low prior knowledge students								
	EDT (*n*=32)		EDT+ (*n*=29)		EDT- (*n*=31)		Total (*n*=92)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Pre-test	3.13	3.12	3.62	3.28	4.35	3.37	3.70	3.26
Post-test	9.13	6.46	10.52	7.02	10.52	6.21	10.03	6.52
Difference score	6.00	6.56	6.90	8.03	6.16	5.70	6.34	6.74
Low-intermediate prior knowledge students								
	EDT (*n*=15)		EDT+ (*n*=17)		EDT- (*n*=14)		Total (*n*=46)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Pre-test	11.60	1.99	11.94	2.30	12.57	3.11	12.02	2.46
Post-test	20.27	5.75	16.35	5.45	16.42	5.75	17.82	5.81
Difference score	8.67	4.98	4.41	5.26	3.86	5.76	5.63	5.63

Conclusion and Discussion

In the current study, third-year secondary students designed and conducted experiments in an online inquiry environment to learn about buoyancy and Archimedes' principle. Three types of guidance were compared in terms of students' gain of conceptual knowledge. Overall, no differences were found between conditions. However, when we took prior knowledge level into account, we found a significant difference between conditions for low-intermediate prior knowledge students (who had 26-50% correct on the pre-test about Archimedes' principle) for Archimedes' principle. Low-intermediate prior knowledge students who worked with the regular Experiment Design Tool had an increase in score from pre- to post-test that was almost double the increase of students in both of the other conditions.

Among scholars, there is a general consensus that low prior knowledge students benefit from additional guidance (Kalyuga & Renkl, 2009). Guidance can act as a substitute for the knowledge and skills that are required to accomplish a task (Tuovinen & Sweller, 1999). Results of the current study partly support this view, but also add a few nuances to this overall conclusion. For the buoyancy domain, we did not find differences between conditions for any of the prior knowledge level categories. This may have been caused by the fact that buoyancy was a topic that students had studied before and that overall did not give them too many problems, as became clear from the average scores on the pre- and post-test for buoyancy. All of the learning environments may have refreshed students' memories about the subject matter, given the relatively high knowledge gains in all groups. So, if a domain is relatively simple for students they can succeed without too much guidance. For Archimedes' principle, the situation was different. Here, students scored much lower on the pre-test, to the extent that we did not have enough students in the two high prior knowledge level categories to do analyses. Still, interesting patterns emerged from the analyses for the low prior knowledge and low-intermediate prior knowledge students only. Low-intermediate prior knowledge students using the Experiment Design Tool in the regular version that distinguished independent and control variables performed better than low-intermediate prior knowledge students in the EDT- condition who used the minimalist version of the Experiment Design Tool, which did not provide students with that distinction. In the regular EDT, a clear distinction is made between independent and control variables, encouraging students who worked with this tool to consider control variables and design more structured experiments. In contrast, students in the EDT- condition had to think about controlling variables on their own, and thus had to be aware of the advantages of designing more structured experiments. Arnold et al. (2014) analysed difficulties students (aged 16-19) encountered in designing experiments, and found that 75% of the students failed to consider control variables. They suggested guiding students in this by showing them how they can control variables, which is what the Experiment Design Tool does.

Low-intermediate prior knowledge students who worked with the Experiment Design Tool but who also were required to reflect upon their experiments also showed lower increases in scores from pre- to post-test than students who used the regular version of the Experiment Design Tool, comparable to students in the EDT- condition. This may be explained by the difficulties students often experience when they have to reflect upon their learning; reflection can be considered to be a task by itself (Kori et al., 2014). In the current study, students who had to reflect upon their experiment designs, were instructed on how to use the reflection tool but they did not receive extensive training about reflection. Considering the already difficult processes involved in designing experiments and the students' limited prior knowledge about the subject matter, the additional task of reflection may have made it too difficult without extensive reflection training, resulting in limited conceptual knowledge gains.

Another outcome we want to highlight is that we found a significant difference between conditions for the topic of Archimedes' principle only for low-intermediate prior knowledge students, and not for low prior knowledge students. A fair share of scholars have found that students with low prior knowledge benefit from higher levels of guidance (e.g., Lazonder et al., 2008), based on which we expected that low prior knowledge students would benefit the most, and high prior knowledge students the least, from additional guidance for designing experiments in terms of knowledge gain, but this was not supported by our data. We hypothesise that students need to possess at least some prior knowledge, or time to gain this knowledge, in order for them to benefit from guiding tools in online learning environments. In the current study, students were provided with orientation materials on the topic being investigated, but familiarising themselves with the topic meant that they could spend less time on their experiments. Low prior knowledge students had to acquire the required prior domain knowledge, and in addition had to apply this knowledge by designing and conducting informative experiments from which they could extract knowledge. Alternatively, they could skip the step of getting familiar with the subject matter, and start designing and conducting experiments immediately, which is rather difficult or even impossible without the necessary prior knowledge. In both scenarios, low prior knowledge students had more time to learn about the subject matter than their more knowledgeable peers. In addition to this, low prior knowledge students often apply less sophisticated strategies and require more trials to reach conclusions than students with more prior knowledge (Alexander & Judy, 1988; Klahr & Dunbar, 1988). All of this may have prevented them from utilising the offered additional guidance to their benefit.

Our study demonstrates that the type of guidance that is expected to be effective for students with different levels of prior knowledge needs to be considered very carefully, because the boundary between what works and what does not work can be very narrow. This also calls for a flexible and adaptive design of guidance. Software developers should develop guidance that is configurable by the teacher or that automatically adapts to students' levels of learning. In our study we used an EDT that we adapted to create three versions simply by changing the configurations which can easily be done by teachers themselves. This allows them to use the same tool in the classroom for learners with distinct levels of prior knowledge and to adapt the tool when necessary. Ideally, students' knowledge and skills should be monitored regularly in order to make a good fit between guidance and students' needs. Our results suggest that for guidance to have an effect, prior knowledge needs to be at a level such that the guidance can build upon the students' initial knowledge and skills but it should stay within the students' capabilities of handling the guidance.

References

Alexander, P. A., & Judy, J. E. (1988). The interaction of domain-specific and strategic knowledge in academic performance. *Review of Educational Research, 58*, 375-404. doi:10.3102/00346543058004375

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. doi:10.1037/A0021017

Arnold, J. C., Kremer, K., & Mayer, J. (2014). Understanding students' experiments: What kind of support do they need in inquiry tasks? *International Journal of Science Education, 36*, 2719-2749. doi:10.1080/09500693.2014.930209

Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. New York: Holt, Rinehart & Winston.

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86*, 175-218. doi:10.1002/sce.10001

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.

Davis, E. A. (2000). Scaffolding students' knowledge integration: prompts for reflection in KIE. *International Journal of Science Education, 22*, 819-837. doi:10.1080/095006900412293

de Jong, T. (2006a). Scaffolds for scientific discovery learning. In J. Elen & R. E. Clark (Eds.), *Dealing with complexity in learning environments* (pp. 107-128). London: Elsevier Science Publishers.

de Jong, T. (2006b). Technological advances in inquiry learning. *Science, 312*, 532-533. doi:10.1126/science.1127750

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* (2nd ed., pp. 371-390). Cambridge: Cambridge University Press.

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*(23), 8410-8415. doi:10.1073/pnas.1319030111

Gillet, D., Rodríguez-Triana, M. J., de Jong, T., Bollen, L., & Dikke, D. (2017). *Cloud Ecosystem for Supporting Inquiry Learning with Online Labs: Creation, Personalization, and Exploitation.* Paper presented at the Experiment@ International.

Hailikari, T., Katajavuori, N., & Lindblom-Ylanne, S. (2008). The relevance of prior knowledge in learning and instructional design. *American Journal of Pharmaceutical Education, 72*, Article 113. doi:10.5688/aj7205113

Hattie, J. A. C., & Donoghue, G. M. (2016). Learning strategies: A synthesis and conceptual model. *npj Science Of Learning, 1*, 16013. doi:10.1038/npjscilearn.2016.13

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist, 42*, 99-107. doi:10.1080/00461520701263368

Hmelo, C. E., Nagarajan, A., & Day, R. S. (2000). Effects of high and low prior knowledge on construction of a joint problem space. *The Journal of Experimental Education, 69*, 36-56. doi:10.1080/00220970009600648

Kalyuga, S. (2007). Expertise reversal effect and its implications for learner-tailored instruction. *Educational Psychology Review, 19*, 509-539. doi:10.1007/s10648-007-9054-3

Kalyuga, S., & Renkl, A. (2009). Expertise reversal effect and its instructional implications: Introduction to the special issue. *Instructional Science, 38*, 209-215. doi:10.1007/s11251-009-9102-0

Klahr, D., & Dunbar, K. (1988). Dual space search during scientific reasoning. *Cognitive Science, 12*, 1-48. doi:10.1207/s15516709cog1201_1

Kori, K., Mäeots, M., & Pedaste, M. (2014). Guided reflection to support quality of reflection and inquiry in web-based learning. *Procedia - Social and Behavioral Sciences, 112*, 242-251. doi:10.1016/j.sbspro.2014.01.1161

Kuhn, D., & Pease, M. (2008). What needs to develop in the development of inquiry skills? *Cognition and Instruction, 26*(4), 512-559. doi:10.1080/07370000802391745

Lambiotte, J. G., & Dansereau, D. F. (1992). Effects of Knowledge Maps and Prior Knowledge on Recall of Science Lecture Content. *The Journal of Experimental Education, 60*, 189-201. doi:10.1080/00220973.1992.9943875

Lazonder, A., W., & Harmsen, R. (2016). Meta-analysis of inquiry-based learning: Effects of guidance. *Review of Educational Research, 86*, 681-718. doi:10.3102/0034654315627366

Lazonder, A., W., Wilhelm, P., & Hagemans, M. G. (2008). The influence of domain knowledge on strategy use during simulation-based inquiry learning. *Learning and Instruction, 18*, 580-592. doi:10.1016/j.learninstruc.2007.12.001

Lim, B. (2004). Challenges and issues in designing inquiry on the Web. *British Journal of Educational Technology, 35*(5), 627-643. doi:10.1111/j.0007-1013.2004.00419.x

Linn, M. C., Eylon, B. S., Rafferty, A., & Vitale, J. M. (2015). Designing instruction to improve lifelong inquiry learning. *Eurasia Journal of Mathematics, Science & Technology Education, 11*, 217-225. doi:10.12973/eurasia.2015.1317a

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. doi:10.1002/Tea.20347

National Research Council. (1996). *National science education standards*. Washington, D.C.: National Academy Press.

Pedaste, M., Mäeots, M., Siiman, L. A., de Jong, T., van Riesen, S. A. N., Kamp, E. T., . . . Tsourlidaki, E. (2015). Phase of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review, 14*, 47-61. doi:10.1016/j.edurev.2015.02.003

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., . . . Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences, 13*, 337-386. doi:10.1207/s15327809jls1303_4

Reiser, B. J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. *Journal of the Learning Sciences, 13*, 273-304. doi:10.1207/s15327809jls1303_2

Roll, I., Briseno, A., Yee, N., & Welsh, A. (2014). *Not a Magic Bullet: The Effect of Scaffolding on Knowledge and Attitudes in Online Simulations.* Paper presented at the International Conference of the Learning Sciences, Boulder, Colorado, USA.

Roll, I., de Baker, R. S. J., Aleven, V., & Koedinger, K. R. (2014). On the Benefits of Seeking (and Avoiding) Help in Online Problem-Solving Environments. *The Journal of the Learning Sciences, 23*, 537-560. doi:10.1080/10508406.2014.883977

Schauble, L., Glaser, R., Raghavan, K., & Reiner, M. (1991). Causal models and experimentation strategies in scientific reasoning. *Journal of the Learning Sciences, 1*, 201-238. doi:10.1207/s15327809jls0102_3

Simons, K. D., & Klein, J. D. (2007). The impact of scaffolding and student achievement levels in a problem-based learning environment. *Instructional Science, 35*, 41-72. doi:10.1007/s11251-006-9002-5

Tuovinen, J. E., & Sweller, J. (1999). A comparison of cognitive load associated with discovery learning and worked examples. *Journal of Educational Psychology, 91*, 334-341. doi:10.1037/0022-0663.91.2.334

van Joolingen, W. R., & de Jong, T. (1991). Supporting hypothesis generation by learners exploring an interactive computer simulation. *Instructional Science, 20*, 389-404.

van Riesen, S. A. N., Gijlers, H., Anjewierden, A. A., & de Jong, T. (2018). Supporting learners' experiment design. *Educational Technology Research and Development, 66*, 475-491. doi:10.1007/s11423-017-9568-4

van Riesen, S. A. N., Gijlers, H., Anjewierden, A. A., & de Jong, T. (2018). *The Influence of Prior Knowledge on the Effectiveness of Guided Experiment Design*. Manuscript submitted for publication.

Veermans, K., van Joolingen, W. R., & de Jong, T. (2006). Use of heuristics to facilitate scientific discovery learning in a simulation learning environment in a physics domain. *International Journal of Science Education, 28*, 341-361. doi:10.1080/09500690500277615

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction, 16*, 3-118. doi:10.1207/s1532690xci1601_2

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 when using virtual and remote labs in science: A literature review. *Educational Technology Research and Development, 63*, 257-302. doi:10.1007/s11423-015-9370-0

5

General Conclusion and Discussion

Introduction

This dissertation aimed to investigate the effects of several types and levels of support for designing experiments within inquiry learning environments on learning gains of learners with distinct levels of prior knowledge. For this purpose, the Experiment Design Tool (EDT) was developed based on the Scaffolding Design Framework of Quintana et al. (2004). By means of heuristic evaluations with four educational design experts and four usability experts, combined with semi-structured interviews with Dutch physics teachers, the first version of the EDT was evaluated and adjusted accordingly. The effectiveness of that EDT in terms of learning gain, overall and for different prior knowledge groups, was first assessed in the study discussed in Chapter 2. No overall differences were found, but as expected, when prior knowledge was taken into account, low prior knowledge learners significantly benefited from support of the EDT. The EDT was further developed in an attempt to make it effective for higher prior knowledge learners as well, resulting in two refined versions of the EDT, the Constrained and the Open EDT, of which the effects on learning gain of different prior knowledge learners were compared to a control condition without an EDT and analysed in the study described in Chapter 3. Results of that study showed a significant effect for low-intermediate prior knowledge learners in favour of the Open EDT. Moreover, even though results for other prior knowledge groups were not significant, descriptive statistics indicated that each group of prior knowledge learners benefited from a different form of support, or no support at all; low prior knowledge learners performed best with the Constrained EDT, and high-intermediate prior knowledge learners performed best without an EDT. These results are comparable to, and complement, results of the first study. Like in the first study, where low prior knowledge learners performed best with the EDT, low prior knowledge learners in the second study also performed best with the Constrained EDT which is the most similar to the first EDT. Additionally, low-intermediate learners were found to perform significantly better with the less restrictive Open EDT. In the third study, described in Chapter 4, the Open EDT was again used, but was compared to a simplified version of the EDT, and to the Open EDT with an embedded Reflection Tool. Again, results showed a significant effect for low-intermediate prior knowledge learners in favour of the Open EDT. No effects were found for low prior knowledge learners in the third study, but it should be noted that no EDT was embedded in a learning environment that offered learners the same level of restrictions as the two versions that were previously discussed.

In the following sections of this chapter, first the limitations of the studies are outlined, then the guiding principles in the EDTs are discussed, and finally implications for teachers and tool developers are provided.

Limitations

In this dissertation the reported studies are comparable in terms of similar background conditions, and therefore results of the studies actually demonstrate what works for low- and low intermediate prior knowledge learners. However, this also entails that these factors should be considered when considering the generalisability of the results.

All participants in the studies were Dutch third-year pre-university students, meaning that they were approximately 15 years old and took all of their courses on pre-university level, which is the highest possible level in Dutch education. Learners can only enter the pre-university track if their primary school results are high enough and if their primary teachers recommend it. Given the high qualification standards of this level of education, one should be careful when applying the implications of this dissertation to learners of less advanced levels of education. It may not be sufficient to only take prior knowledge about the subject matter into account, but one may also want to consider other factors, such as differences in cognitive skills and interest in STEM education, that were not considered in this dissertation.

Despite the presumed high cognitive skills of the participants, some participants may have been better at physics than others. Up to and including the third year of the pre-university track, all students are obliged to take a wide range of courses in the arts, languages, exact sciences and economics, etc. In contrast to many other countries in which learners can choose the level of education for each course, learners following the pre-university track have to take all course at the highest level. In the Netherlands, some learners may, therefore, be better motivated and/or skilled in specific courses than other learners.

Guiding Principles in the Studies

Results of the three studies in this dissertation indicate that the effectiveness of different types and levels of support for experiment design to gain knowledge is largely dependent on learners' prior knowledge. In this section, the conditions are discussed that may have positive or negative effects on learning. The EDT was developed based on the Scaffolding Design Framework of Quintana et al. (2004), refined between the studies, and tested against several conditions. Even though the experimental and control conditions were slightly different between the three studies in this dissertation, they have many commonalities, such as the topics of investigation (i.e., buoyancy and Archimedes' principle), the foundation of the learning environment, the parallel knowledge test that was only slightly adjusted between studies, the setup and number of sessions, the level of education and the age of the participants, and all studies were conducted in-class. Considering the comparable background conditions in all studies as discussed above, and the results in terms of effectiveness of the offered support for specific prior knowledge students, a closer look was given to the specific differences between the different versions of the EDT in order to gain more understandings about which guiding principles work for which type of prior knowledge learner. Table 5.1 provides an overview of the guiding principles that were included in the different conditions of the three studies. Two principles, CVS and the distinction between independent and control variables, are discussed in more detail.

Table 5.1

Support for designing experiments per condition

Support	**Study 1**			**Study 2**			**Study 3**		
	No EDT – Main	No EDT – Specific	EDT_1*	Open EDT_2*	Constrained EDT_1	No EDT_3	Open EDT_2*	Simplified EDT	Reflection EDT
A set of (relevant) variables is provided	X	X	X	X	X	X	X	X	X
Values for the control and independent variables are restricted	X	X	X	X	X	X	X	X	X
Conducted experimental trials, including documented results, are presented in the form of a history table that allows to sort variables in ascending or descending order	-	-	X	X	X	-	X	X	X
Independent, control, and dependent variables are clearly distinguished and treated as such; i.e., all control variables only have to be assigned a value once that will be automatically assigned to all trials within the experiment, and all independent variables must be assigned a value per experimental trial	-	-	X	X	X	-	X	-	X
CVS is required	-	-	X	-	X	-	-	-	-
A minimum of 3 trials is required for each run	-	-	X	-	X	-	-	-	-
Feedback is provided on learners' actions	-	-	X	-	-	-	-	-	-
The process of experiment design is broken down into four smaller steps	-	-	X	-	-	-	-	-	-
Learners are required to reflect upon their learning	-	-	-	-	-	-	-	-	X

Note: * = A significant effect was found in favour of the marked condition for the specific prior knowledge group. X = Guidance present. $_{1, 2, 3}$ = Condition was best for $_{1)}$ low prior knowledge learners, $_{2)}$ low-intermediate prior knowledge learners, or $_{3)}$ high-intermediate prior learners.

Control of Variables Strategy (CVS)

The Dutch curriculum for pre-university students in the first three years of secondary education includes learning how to do research, so the students who participated in the studies were already familiar with CVS (SLO Nationaal Expertisecentrum Leerplanontwikkeling, 2016). The EDT was meant to guide students in designing and conducting experiments, and in some versions required or reminded them to apply CVS, but its goal was not necessarily to teach them the basics of CVS. Therefore, participants in the studies did not receive additional direct instruction about CVS which has found to be more effective to acquire CVS (Klahr & Nigam, 2004), but the principles of CVS were built into some versions of the EDT. Requiring learners to apply CVS and plan at least three experimental trials by means of built-in restrictions in the EDT benefited learners with low prior knowledge in both studies, i.e., Studies 1 & 2, in this dissertation that included a condition requiring learners to do so before they could conduct their experimental trials in the laboratory.

Low prior knowledge learners lack theoretical knowledge about the domain and about relationships between important variables. Buoyancy and Archimedes' principle are both common phenomena in everyday life, which entails that learners have a general idea about the topics, but for low prior knowledge learners these are often based on false beliefs (Loverude, 2009; Loverude, Kautz, & Heron, 2003). An example of a frequently adhered false belief held by learners is that heavy objects sink and light objects float, where they neglect to consider other aspects like the interaction between the mass and volume of the object, and the interaction between the density of the object with the density of the fluid (Driver, Squires, Rushworth, & Wood-Robinson, 1994, in Loverude, 2009; McKinnon & Renner, 1971, in Loverude et al., 2003). Prior incorrect beliefs can be harmful for learning because they can result in biased experimentation behaviour where the learner only focuses on experimentation results that confirm their prior ideas. Results that conflict with their prior ideas are then ignored, and learners instead focus on variables and experimental results that do confirm their ideas (Kuhn, 2007). The EDTs that required learners to apply CVS and design a minimum of three experimental trials may have prevented them to simply shift their explanation from one variable to another, but instead force them to consider each variable individually. For example, learners can discover that there is a turning point for mass with regard to the floatability of the object, if they conduct a series of experimental trials in which the volume of the object that is placed in water is kept constant but the mass is varied. The same is true when the mass of the object that is placed in water is kept constant, but the volume is varied. When learners combine results of both series of experimental trials, they should be able to discover that the relationship between volume and mass, i.e., density, of an object is the determining factor for its ability to float in water.

Low-intermediate prior knowledge learners, as opposed to low prior knowledge learners, performed best when they worked with the Open EDT that was used in two of the studies, i.e., Studies 2 & 3, in this dissertation. These results are worth to further explore considering that the EDTs mainly differed in the requirement to apply CVS and to design of a minimum of three experimental trials. One possible explanation may be that low prior knowledge learners still need to learn the very basics of the domain and investigate the influence single variables can have on experimental results. Without the requirement to apply CVS low prior knowledge learners might be tempted to vary more than one variable at a time. Low-intermediate prior knowledge learners on the other hand, already have some basic knowledge about the most important variables and their relationships, but do not yet understand underlying theories and conditions in which these theories hold. These learners may make better progress when they are not obliged to adhere to a specific strategy, but instead have the possibility to further explore the domain by applying different strategies. Sao Pedro (2013) analysed learners' experimentation behaviours within simulations and found that learners successfully applied a diversity of strategies. For example, one strategy was similar to the strategy embedded in the more restricted versions of the EDT where learners run repeated experimental trials and observe what happens, change one variable and run another set of repeated trials, change one variable, and so on. Another strategy learners engaged in was to perform pairwise experiments to search for interaction effects. The Open EDT supports diverse experimental strategies and does not force the application of one single strategy. Having at least some understanding of the influence of the variables within a domain may have allowed low-intermediate prior knowledge learners who worked with the Open EDT to further explore the domain using diverse strategies such as CVS and pairwise experiments, without getting lost in interaction effects of the buoyancy domain.

Distinction of Independent and Control Variables

Related to the possibility to easily apply CVS, is the clearly visible and functional distinction between independent and control variables that was incorporated in all versions of the EDT except for the simplified version from Study 3. This distinction entailed that learners could decide to vary variables between trials or to keep them the same, the latter meaning that learners could choose one value and all trials were automatically assigned that value. The third study in this dissertation revealed that this clear distinction between independent and control variables significantly benefited low-intermediate prior knowledge learners, which may be attributed to the visible distinction and/or the automatic handling of non-salient tasks (Quintana et al., 2004). The columns in the EDT which specifically stated "vary" or "keep the same" makes expert knowledge explicit and serves as a reminder not to vary everything at once. Moreover, because the control variables were automatically kept the same by the EDT, learners were liberated from actions that take time and could distract them from meaningful cognitive tasks.

Interestingly, the third study showed that high-intermediate learners performed better when this function was not present in the EDT, albeit not significant. Nonetheless, this should be further explored in future studies, considering the non-significant but noticeable difference in knowledge gain between conditions, and a large body of literature stating that more guidance can be redundant or even have a negative learning effect on more knowledgeable learners (e.g., Kalyuga, 2007; Kalyuga & Renkl, 2009). No effects were found for high prior knowledge students, but they already correctly answered 75-100% of the questions on the pre-test. Instead of further focusing to develop guidance that also supports high prior knowledge students, it might be better to teach them additional learning material.

Implications and Recommendations

The reported studies in this dissertation suggest that prior knowledge and the effectiveness of support are very much intertwined, and that it does not suffice to think of learners as having either low or high prior knowledge, but that it is more nuanced than that. In this section implications and recommendations are provided for teachers and tool developers who want to effectively guide learners' inquiry learning.

For Teachers

In order to provide learners with guidance for designing experiments that is most effective to them, their prior knowledge about the topic should be evaluated before they start with their inquiry learning activities. Prior knowledge of participants in this dissertation was measured with a pen-and-paper knowledge test, but their prior knowledge can also be evaluated by an electronically administered test which has the advantage that it is less time-consuming to evaluate the results and that results can be shown immediately after the test was taken. If learners have no to very little prior knowledge about the topic, it is recommended to let them discover the effect of one variable at a time, i.e., to require them to apply CVS. In the EDT this can be done by setting the configurations in such a way that students 1) are only allowed to drag one variable in the "vary"-column, and 2) have to design a minimum amount of trials with that one varied variable, which automatically prevents students to conduct their trials otherwise. In case learners have slightly more knowledge about the topic, they should be provided with a visible reminder of the usefulness to control for variables they do not want to influence the results and they should be offered some freedom to apply strategies other than CVS. Both objectives can be obtained by presenting learners with a column for variables they want to keep the same and a column for variables they want to vary without requiring them to vary only one variable at a time. In the EDT this can be accomplished by 1) not limiting the number of variables students can drag in the "vary"-column, and 2) not limiting the minimum amount of trials they should design before they can conduct them in the laboratory. The EDT can thus easily be configured for low- and low-intermediate prior knowledge learners.

For Inquiry Tool Designers

When designing tools, the Scaffolding Design Framework of Quintana et al. (2004) has found to be very useful as a starting point, especially for low prior knowledge learners. However, results of the studies in this dissertation also showed that in order for tools to be effective for learners with more prior knowledge about a topic, one should be careful not to develop tools that are too restrictive and/or directive. Instead, it is advised to design tools that are manually or automatically adjustable in order to reach a larger group of learners.

Concluding Remarks

The studies in this dissertation have revealed a fine line between what works and what doesn't work in terms of guidance for experiment design for different groups of prior knowledge learners. In general, results of the studies comply with other literature that learners with less knowledge benefit from guidance that offers more structure and is more directive, but it also suggests that for each level of prior knowledge a specific form of guidance is the most optimal, which underscores the need for dedicated and specialised instructional designs.

References

Kalyuga, S. (2007). Expertise reversal effect and its implications for learner-tailored instruction. *Educational Psychology Review, 19*, 509-539. doi:10.1007/s10648-007-9054-3

Kalyuga, S., & Renkl, A. (2009). Expertise reversal effect and its instructional implications: Introduction to the special issue. *Instructional Science, 38*, 209-215. doi:10.1007/s11251-009-9102-0

Klahr, D., & Nigam, M. (2004). The equivalence of learning paths in early science instruction: Effect of direct instruction and discovery learning. *Psychological Science, 15*, 661-667. doi:10.1111/j.0956-7976.2004.00737.x

Kuhn, D. (2007). Reasoning about multiple variables: Control of variables is not the only challenge. *Science Education, 91*, 710-726. doi:10.1002/sce.20214

Loverude, M. E. (2009). A research-based interactive lecture demonstration on sinking and floating. *American Journal of Physics, 77*, 897-901. doi:10.1119/1.3191688

Loverude, M. E., Kautz, C. H., & Heron, P. R. L. (2003). Helping students develop an understanding of Archimedes' principle. I. Research on student understanding. *American Journal of Physics, 71*, 1178-1187. doi:10.1119/1.1607335

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., . . . Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences, 13*, 337-386. doi:10.1207/s15327809jls1303_4

Sao Pedro, M. (2013). *Real-time assessment, prediction, and scaffolding of middle school students' data collection skills within physical science simulations.* (PhD.), Worcester Polytechnic Institute, Worcester, MA.

SLO Nationaal Expertisecentrum Leerplanontwikkeling. (2016). *Karakteristieken en kerndoelen: Onderbouw voortgezet onderwijs* (Characteristics and headline targets: Lower secundary education. Report number: OBVO/16-023). Retrieved from Enschede: http://downloads.slo.nl/Documenten/karakteristieken-en-kerndoelen-onderbouw-vo.pdf

6

English Summary

Introduction

Inquiry learning is an active learning approach, which allows students to learn and practice inquiry skills to build their own knowledge by means of engaging in processes such as designing and conducting experiments. Provided that students receive the right amount and type of support for their inquiry activities, this method has shown to be effective for learning. However, what the right amount and type of support is depends on several factors. A key factor that influences the effectiveness of guidance, is students' prior knowledge. In general, research has shown that low prior knowledge learners benefit from higher levels of guidance than high prior knowledge learners. For this dissertation one tool called the Experiment Design Tool (EDT) was developed with the goal to guide students of different levels of prior knowledge in designing and conducting experiments. In order to be able to support students that differ in prior knowledge with just one tool, the EDT was made configurable. This dissertation investigated the effects of different configurations of the EDT on learning gain of students with distinct levels of prior knowledge that was measured with a pre-test.

About the Studies

In all studies reported in this dissertation, students had to design and conduct experiments within an online inquiry learning environment about buoyancy and Archimedes' principle. The experiments were performed in an online virtual laboratory, called Splash, that was part of the learning environment. The studies consisted of four sessions of 50-60 minutes each. The sessions took place in students' regular classrooms during school lessons. The participants were Dutch third year pre-university students of approximately 15 years old, who were selected because at this age, based on the Dutch curriculum, it is important to master the skill of designing and conducting experiments. Third year students were selected because they were expected to have different levels of prior knowledge about buoyancy and Archimedes' principle. During the first session of each study, students took a pre-test that consisted of questions about the topics of buoyancy and Archimedes' principle. They also received instructions about what they would be doing during the next sessions. In the second and third session they individually worked in an online inquiry learning environment, where they had to design and conduct experiments in order to answer research questions about buoyancy and Archimedes' principle. In the fourth and final session, they took a post-test.

The learning environments, although they differed slightly between studies, all contained the same components; 1) instructions about the learning environment, 2) a set of research questions that students had to answer, 3) a virtual laboratory called Splash, and 4) a conclusion input box. The experimental conditions also included an EDT.

The virtual laboratory Splash was designed to cover the topics of buoyancy and Archimedes' principle. In Splash, students could drop balls that would either float, suspend or sink in fluid-filled containers. Students could select the mass, volume and/or density of the balls, as well as the density of the fluid. Splash showed the amount of fluid displacement, and the forces that are important in the domains of buoyancy and Archimedes' principle.

The EDT was meant to guide students in designing experiments, and developed for the studies in this dissertation. Its design was based on the Scaffolding Design Framework of Quintana et al. (2004). It presented students with a list of pre-defined variables they could use in their experiment design. For each variable they had to decide if they wanted to vary it within a set of experimental trials, keep it the same, or if they wanted to measure or observe what happened to that variable. After specifying the roles of the variables, students had to choose the values that the variables took on, which they could choose within a pre-fixed range. The EDT allowed students to add up to six experimental trials at once. Once students were satisfied with their experiment design, they could send the experimental trials to Splash to observe what happened and to write down what they observed. If they could not answer the research question based on their results, they could design more experimental trials, conduct them in Splash, etc., until they had gathered enough evidence to draw a conclusion.

Study 1

The first study in this dissertation investigated the effectiveness of the first version of the EDT on students' learning gain. In the experimental condition, the EDT was implemented in an online inquiry learning environment as described above. Students in this condition had to answer 1) a set of main questions as mentioned in the previous paragraph, and 2) a set of more detailed research questions that were meant to give them direction for their experiment designs. The experimental condition was compared to two control conditions that did not contain the EDT. In the first control condition, students received both the set of main and detailed research questions, while in the second control condition, students only had to answer the five main research questions. Results showed that all students gained knowledge, and that there was a significant difference in learning gain between conditions for low prior knowledge students learning about Archimedes' principle in favour of the experimental condition which included the EDT.

Study 2

For the second study the EDT was adjusted based on findings from the first study. Two configurations of the EDT were created and assessed, and embedded in two online inquiry learning environments. In one configuration called the Constrained EDT, students were obliged to design a minimum of three experimental trials where only one variable could be varied, before they could conduct those in Splash. In the other configuration called the Open EDT, students could design as few or as many experimental trials as they wanted, and they were allowed to vary more than one variable at a time. The two experimental conditions were compared to a control condition in which no EDT was embedded in the learning environment. A significant effect was found for low-intermediate prior knowledge students, in favour of the Open EDT that offered students more freedom. Interestingly, albeit non-significant, descriptive results showed that low prior knowledge students had the lowest learning gain when they worked with the Open EDT and the highest when they worked with the Constrained EDT. High-intermediate prior knowledge learners gained most knowledge when they were working in a learning environment that did not contain an EDT at all (non-significant).

Study 3

Because of the significant results for low-intermediate prior knowledge students that were found in the second study, the Open EDT was used in the third study again in one condition. In a second condition, a reflection tool specifically designed for this study was added to that EDT. In a third condition, a simplified configuration of the EDT was embedded in the learning environment. This configuration did not display the difference between independent variables and control variables, but instead students had to choose a value for each variable per experimental trial. Again, there was a significant effect for low-intermediate students, who performed best when working with the Open EDT. Another result that might be interesting, was that high-intermediate prior knowledge students seemed to perform best when they worked with the Simplified EDT, but these results were not significant and should be further investigated in future studies.

Conclusion

For this dissertation, an Experiment Design Tool was developed, and its effectiveness in terms of learning gain for students with different levels of prior knowledge was assessed. Moreover, the effect of different configurations of the EDT was compared, which revealed some interesting results and some pointers leading to future research. Results showed that students who have low prior knowledge of the topic of inquiry, gain most knowledge when they are forced to apply CVS by designing experiments that contain a minimum of three experimental trials in which only one variable is varied. Low-intermediate prior knowledge students on the other hand, learn most when they have the visual reminder and functionality that variables can be varied or controlled for, but when they are not required to apply CVS. They benefit more from having the possibility to apply different strategies, and being allowed to apply a more open approach to explore the domain. High-intermediate prior knowledge learners seem to learn most when they have limited guidance. Even though results for this group of learners were non-significant, there are indications that they should be provided with less directive guidance than lower prior knowledge students, which is something that should be assessed in future studies. The studies reported in this dissertation provide insights in the guiding principles that are effective when included in tools for inquiry learning. An important implication is that guidance should match students' prior knowledge, in order for it to help them gain better learning results, and this dissertation has shown insights in guiding principles that can be embedded in guidance for different groups of prior knowledge students.

7

Nederlandse Samenvatting

Introductie

Onderzoekend leren is een leermethode die actief leren centraal stelt, waarbij leerlingen onderzoeksvaardigheden opdoen en oefenen om op die manier zelf kennis te verwerven door middel van onderzoeksprocessen zoals het ontwerpen en uitvoeren van experimenten. Wanneer leerlingen de juiste hoeveelheid en type ondersteuning krijgen bij deze onderzoeksactiviteiten, is onderzoekend leren een effectieve leermethode. Meerdere factoren bepalen echter wat de juiste hoeveelheid en type ondersteuning is. Een hoofdfactor die de effectiviteit van de ondersteuning beïnvloedt, is de voorkennis die leerlingen hebben. Over het algemeen heeft onderzoek aangetoond dat leerlingen met weinig voorkennis profiteren van een hogere mate van ondersteuning dan leerlingen met veel voorkennis. Voor dit proefschrift is een tool ontwikkeld, genaamd de Experiment Ontwerp Tool (EDT – *Experiment Design Tool* in het Engels) met als doel om leerlingen met verschillende niveaus van voorkennis te ondersteunen bij het ontwerpen en uitvoeren van experimenten. Om leerlingen met verschillende niveaus van voorkennis te kunnen ondersteunen, was de EDT configureerbaar gemaakt. Dit proefschrift onderzocht de effecten van verschillende configuraties van de EDT op de kennistoename van leerlingen met verschillende niveaus van voorkennis die was gemeten met een voorkennistoets.

De Studies

In alle studies die in dit proefschrift zijn gerapporteerd, moesten leerlingen experimenten ontwerpen en uitvoeren binnen een online onderzoekend leeromgeving over drijfvermogen en de Wet van Archimedes. De experimenten werden uitgevoerd in een online virtueel laboratorium genaamd Splash, dat onderdeel was van de leeromgeving. De studies bestonden uit vier sessies van elk 50 tot 60 minuten. De sessies vonden plaats tijdens de reguliere les van de leerlingen in hun eigen klaslokaal. De participanten waren Nederlandse derdejaars vwo-leerlingen van ongeveer 15 jaar oud en zij waren geselecteerd omdat op die leeftijd, gebaseerd op het Nederlandse vwo-curriculum, het voor hen belangrijk is om de vaardigheden van het ontwerpen en uitvoeren van experimenten te oefenen en bezitten. Tijdens de eerste sessie van elke studie, werd er een voorkennistoets afgenomen met vragen over de onderwerpen drijfvermogen en de Wet van Archimedes, welke correspondeerden met wat zij konden leren in de online onderzoekend leeromgeving door middel van het ontwerpen en uitvoeren van experimenten. Tevens ontvingen zij instructies over wat zij zouden moeten doen tijdens de volgende sessies. In de tweede en derde sessie werkten zij individueel in een online onderzoekend leeromgeving, waar zij experimenten moesten ontwerpen en uitvoeren om onderzoeksvragen te kunnen beantwoorden over drijfvermogen en de Wet van Archimedes. In de vierde en laatste sessie, werd er een nakennistoets afgenomen.

De leeromgevingen, ondanks dat zij enigszins verschilden tussen de studies, bevatten allemaal dezelfde componenten; 1) instructies over de leeromgeving, 2) een set onderzoeksvragen die de leerling moest beantwoorden, 3) een virtueel laboratorium genaamd Splash, en 4) een conclusie tekstvak. De experimentele condities bevatten ook een EDT. Tijdens de eerste studie staken meerdere leerlingen hun hand op om vragen te stellen over sleuteltermen uit de domeinen die zij moesten begrijpen om experimenten te ontwerpen, welke vervolgens klassikaal aan hen uitgelegd werden in alle condities. Om deze reden was er in de leeromgevingen van de tweede en derde studie ook de nodige algemene informatie over drijfvermogen en de Wet van Archimedes te vinden, zonder hierbij antwoorden op de onderzoeksvragen weg te geven.

Het virtuele laboratorium Splash was ontworpen om de onderwerpen drijfvermogen en de Wet van Archimedes te dekken. In Splash konden leerlingen ballen loslaten in buisjes gevuld met een vloeistof en observeren of die ballen dreven, zweefden of zonken. Leerlingen konden de massa, het volume en/of de dichtheid van de ballen bepalen, evenals de dichtheid van de vloeistof in het buisje. Splash toonde de hoeveelheid vloeistofverplaatsing, en de krachten die van belang waren in de domeinen drijfvermogen en de Wet van Archimedes.

De EDT was bedoeld om leerlingen te begeleiden bij het ontwerpen van hun experimenten, en ontwikkeld en verfijnd voor de studies in dit proefschrift. De eerste versie was gecreëerd op basis van het *Scaffolding Design Framework* van Quintana en collega's (2004). De EDT toonde leerlingen een lijst met voorgedefinieerde variabelen die zij konden gebruiken in hun experiment ontwerp. Voor elke variabele moesten leerlingen bepalen of zij die wilden variëren binnen een reeks experimentele opstellingen, hetzelfde wilden houden, of dat zij wilden observeren wat er zou gebeuren met die variabele. Nadat zij een rol aan de variabele hadden toegekend, moesten zij de waarden kiezen die de variabele aan zou nemen, welke zij konden kiezen binnen een beperkt spectrum. Leerlingen konden in de EDT tot zes experimentele opstellingen per keer klaarzetten. Wanneer leerlingen tevreden waren met hun experiment ontwerp, konden zij deze naar Splash sturen om te observeren wat er gebeurde, en noteren wat zij observeerden. Als zij de onderzoeksvraag nog niet konden beantwoorden op basis van hun resultaten, konden zij meer experimentele opstellingen ontwerpen, deze uitvoeren in Splash, etc., tot zij genoeg bewijs hadden verzameld om een conclusie te kunnen trekken.

Studie 1

De eerste studie in dit proefschrift onderzocht de effectiviteit van de eerste versie van de EDT met betrekking tot de leerwinst van leerlingen. De EDT was in de experimentele conditie geïmplementeerd in een online onderzoekend leeromgeving zoals in de Introductie is beschreven. Leerlingen in deze conditie moesten 1) een set hoofdvragen beantwoorden zoals genoemd in de vorige paragraaf, en 2) een set meer gedetailleerde onderzoeksvragen beantwoorden met als doel om hen een richting te bieden voor hun experiment ontwerpen. De experimentele conditie werd vergeleken met twee controle condities die geen EDT bevatten. In de eerste controle conditie, ontvingen leerlingen zowel de hoofdvragen als de gedetailleerde vragen, terwijl in de tweede controleconditie leerlingen slechts de vijf hoofdvragen hoefden te beantwoorden. Resultaten toonden leerwinst voor alle leerlingen, met een significant verschil in leerwinst tussen condities voor leerlingen met weinig tot matige voorkennis over de Wet van Archimedes in het voordeel van de experimentele conditie die de EDT bevatte.

Studie 2

Voor de tweede studie was de EDT aangepast op basis van resultaten van de eerste studie, en op basis van informele observaties waaruit bleek dat enkele aspecten van de EDT frustratie opriepen bij leerlingen. De basis van de EDT was hetzelfde gehouden als bij de eerste versie, maar de aspecten waar leerlingen gefrustreerd door raakten waren veranderd of verwijderd. Daarnaast was de EDT configureerbaar gemaakt. Twee configuraties werden onderzocht, en geïmplementeerd in twee online onderzoekend leeromgevingen. In één configuratie genaamd de Restrictieve EDT, waren leerlingen verplicht om minimaal drie experimentele opstellingen te ontwerpen waarbij zij slechts één variabele mochten variëren, voordat zij deze konden uitvoeren in Splash. In de andere configuratie genaamd de Open EDT, konden leerlingen zo veel of weinig experimentele opstellingen ontwerpen als zij wilden, en konden zij bovendien meer dan één variabele variëren. De twee experimentele condities werden vergeleken met een controle conditie waarin geen EDT was geïmplementeerd in de leeromgeving. Een significant effect was gevonden voor leerlingen met weinig tot matige voorkennis, in het voordeel van de Open EDT die studenten meer vrijheid bood. Een interessant punt, maar niet significant, is dat beschrijvende statistieken toonden dat leerlingen met geen tot weinig voorkennis de laagste leerwinst hadden wanneer zij met de Open EDT werkten, en de hoogste leerwinst wanneer zij met de Restrictieve EDT werkten. Leerlingen met matige tot veel voorkennis hadden de grootste kennistoename wanneer zij in een leeromgeving werkten waarin geen EDT zat (niet-significant).

Studie 3

Door de significante resultaten voor leerlingen met weinig tot matige voorkennis die waren gevonden in de tweede studie, werd de Open EDT ook in de derde studie gebruikt in een conditie. In een tweede conditie werd een speciaal voor deze studie ontworpen reflectietool toegevoegd aan de Open EDT. In een derde conditie werd een gesimplificeerde configuratie van de EDT geïmplementeerd in de leeromgeving. Deze configuratie gaf het verschil tussen onafhankelijke- en controlevariabelen niet weer, maar leerlingen moesten in plaats daarvan een waarde kiezen voor elke variabele voor elke experimentele opstelling. Opnieuw werd een significant effect gevonden in het voordeel van de Open EDT voor leerlingen met weinig tot matige voorkennis. Een ander resultaat dat mogelijk interessant was, was dat leerlingen met matig tot veel voorkennis het beste leken te presteren met de Gesimplificeerde EDT, maar deze resultaten waren niet significant en dienen verder onderzocht te worden in toekomstige studies.

Conclusie

Voor dit proefschrift was een Experiment Ontwerp Tool (EDT, *Experiment Design Tool* in het Engels) ontwikkeld, waarvan de effectiviteit met betrekking tot leerwinst van leerlingen met verschillende niveaus van voorkennis onderzocht werd. Het effect van verschillende configuraties van de EDT werd vergeleken, waarbij interessante resultaten werden gevonden, alsmede enkele aspecten die in toekomstig onderzoek verder onderzocht dienen te worden. Resultaten toonden aan dat leerlingen met geen tot weinig voorkennis over het onderwerp van het experiment, de hoogste leerwinst behaalden wanneer zij verplicht werden één variabele per keer te variëren waarbij zij minimaal drie experimentele opstellingen moesten ontwerpen. Leerlingen met weinig tot matige voorkennis leerden het meest wanneer de tool hen visueel en functioneel herinnerde aan het feit dat variabelen gevarieerd of gecontroleerd kunnen worden, maar de tool hen niet dwong slechts één variabele per keer te variëren. Zij leverden betere leerprestatie wanneer zij de mogelijkheid hadden verschillende strategieën toe te passen, waaronder het toepassen van een explorerender aanpak om het domein te verkennen. Leerlingen met matige tot veel voorkennis leken het meest te leren wanneer zij slechts beperkt ondersteund werden. Ondanks dat de resultaten voor deze groep leerlingen niet significant waren, zijn er aanwijzingen gevonden dat zij het beste ondersteuning kunnen ontvangen die minder directief van aard is dan ondersteuning die geschikt is voor leerlingen met geen tot weinig voorkennis. Dit zou verder onderzocht moeten worden in toekomstige studies.

De gerapporteerde studies in dit proefschrift geven inzicht in de effectiviteit van principes die worden toegepast in ondersteunende tools voor onderzoekend leren. Een belangrijke implicatie uit dit proefschrift is dat de ondersteuning die leerlingen ontvangen moet passen bij de voorkennis die zij bezitten, om zo betere leerresultaten te kunnen behalen. Daarnaast biedt dit proefschrift inzicht in principes die kunnen worden toegepast in ondersteunende tools groepen leerlingen met verschillende niveaus van voorkennis effectief te kunnen ondersteunen.

UNIVERSITY OF TWENTE.

Inquiry learning can be an effective learning method, provided that students receive the right amount and type of support. For this dissertation the Experiment Design Tool was developed to support students with one of the main activities of inquiry learning; designing and conducting useful experiments that allow them to draw conclusions to their research questions.

The effects of distinct versions of the Experiment Design Tool on students' learning gains about buoyancy and Archimedes' principle was assessed in the studies reported in this dissertation. Special attention was paid to the influence of students' prior knowledge about the topics, in order to study whether and how prior knowledge influences the effects of different amounts and types of support.

Results from the studies in this dissertation indicated that support that is offered to students should match their level of prior knowledge. The results provide a basis for designing guidance that aligns with students' prior knowledge.