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More isn't always better: The curvilinear relationship between inquiry-based teaching and student achievement in science

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Real science is a constant investigation of the unknown.
– Abhijit Naskar, Neuroscientist, author, and speaker

1. Introduction

The relation between the implementation of certain instructional approaches and student achievement has probably become the most relevant indicator of teaching effectiveness. For instance, science education communities have long advocated the importance of inquiry-based teaching in improving student learning (e.g., American Association for the Advancement of Science, 1994; Osborne & Dillon, 2008; Rocard et al., 2007). The trend towards inquiry-based teaching can be seen as an attempt to develop students' reasoning and thinking skills through inquiry activities that represent the heart of scientific method (Klahr & Dunbar, 1988). This effort is partly reflected by the recommendations to implement inquiry-based methods to improve the quality of science teaching across European countries, such as the Rocard report *Science Education Now: A Renewed Pedagogy for the Future of Europe* (2007), and the increasing focus on experimentation and inquiry skills in educational large-scale assessments (e.g., Programme for International Student Assessment [PISA], Trends in International Mathematics and Science Study [TIMSS]). Despite these developments, an important question remains: Does inquiry-based teaching result in higher science achievement?

A growing body of research has investigated the effectiveness of inquiry teaching for improving student achievement. However, this research abounds in conflicting findings. Whereas some studies have documented a positive trend favouring inquiry-based instructional practices (e.g., Minner, Levy, & Century, 2010; Schroeder, Scott, Tolson, Huang, & Lee, 2007), the results of more recent studies using international large-scale assessment (ILSA) data indicated that this teaching strategy is negatively associated with science achievement (see Cairns & Areepattamannil, 2017). These inconsistent results in the literature might be due to several possible challenges associated with the nature of inquiry teaching measure and the analysis of the resultant data.

First, most studies investigating the effectiveness of inquiry-based teaching employ a measure of inquiry that focused on its frequency aspect (i.e., how often inquiry activities occur) and assume that a *linear* relationship exists between the inquiry activities and student achievement (e.g. Stohr-Hunt, 1996). Instead of assuming that "more is always better (or worse)", Creemers and Kyriakides (2008) argue that researchers investigating teaching effectiveness should consider the possibility of *nonlinear* associations of the variables under investigation. For instance, the implementation of inquiry-based science teaching to only a limited extent misses out on an important aspect of scientific literacy (NRC, 2013). At the same time, the implementation of this approach requires ample lesson time (Guskey, 2000), and an overemphasis on inquiry activities might cut into time spent on other necessary teaching and learning practices. Hence, it is possible to expect the presence of a curvilinear relation between inquiry-based teaching and student achievement.

Second, the use of ILSA data has attracted great attention in recent decades because it provides unique opportunities for generalizing findings to a wide population and examining teaching effectiveness across countries and cultures (e.g., Nilsen, Gustafsson, & Blömeke, 2016; Strietholt & Scherer, 2017). Since the implementation of inquiry-based teaching depends upon the teachers, variance in this construct may be more likely explained by differences between classes rather than between schools. Hence, to investigate the link between teaching strategies and student outcomes, the appropriate level of analysis—that is, the classroom level—is needed (Marsh et al., 2012). This presents a challenge for ILSA studies such as PISA, which primarily focuses on the student, school, and country levels rather than the classroom or teacher levels.

The aim of this study is therefore to shed light on the relationship between inquiry-based teaching and student achievement in science, based on a large-scale data set that overcomes the challenges associated with the *type of relationship* (i.e., linear vs. curvilinear) and *level of analysis* (i.e., classroom level vs. alternative levels). More specifically, we present findings from the TIMSS 2015—the only ILSA study that collects data from a nationally representative sample of schools and students in their intact science classrooms—and examine the relation between inquiry-based teaching activities and students' achievement,

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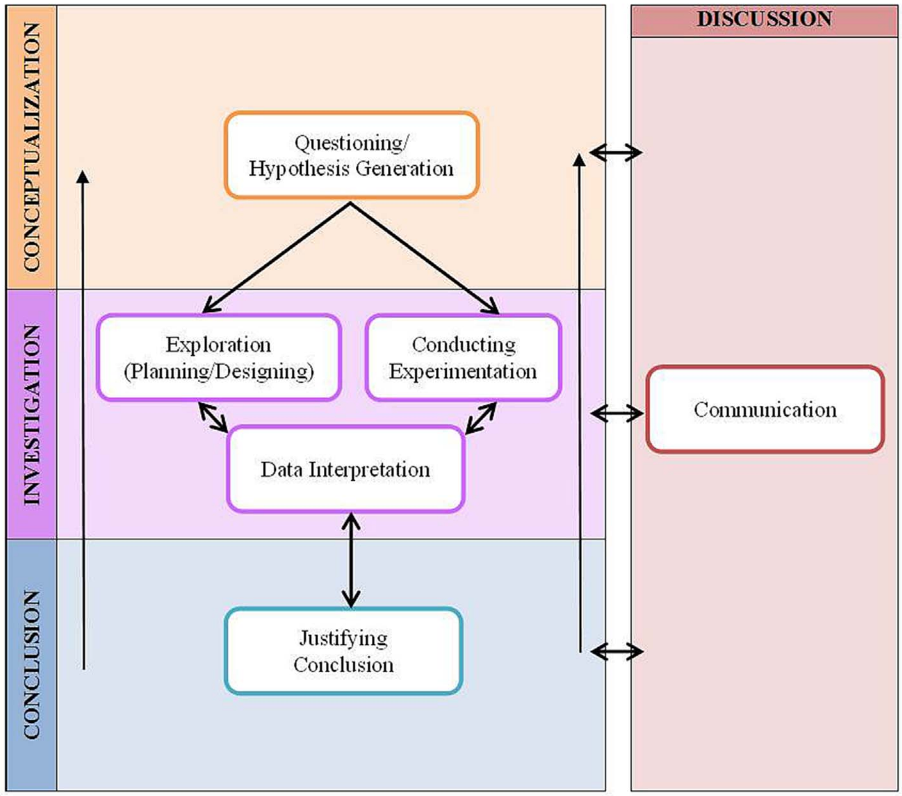

Fig. 1. The integrative phases of inquiry-based teaching activities in our study (a simplified inquiry-based learning framework from Pedaste et al., 2015, p. 56, p. 56).

considering the possible existence of nonlinear relations and the appropriate unit of analysis (i.e., classrooms). In addition, it is important to examine whether and to what extent contextual variables, such as students' socioeconomic status (SES) in a class, might influence this relationship. As such, the effectiveness of inquiry instruction might vary by classroom SES. These findings contribute to an understanding of the role of inquiry-based teaching in science education and create awareness of the methodological challenges associated with the analysis of self-reported data, especially ILSA data for studies of teaching effectiveness in the research community.

1.1. Defining inquiry-based science teaching

Inquiry has been interpreted in many different ways across studies and has become "one of the most confounding terms within science education" (Settlage, 2003, p. 34). Although there is a lack of agreement on the meaning of inquiry, it seems clear that this practice places a strong emphasis on promoting *active learning* and *student's responsibility for constructing knowledge* (de Jong & van Joolingen, 1998). Students are expected to acquire first-hand experience through inquiry practices in order to fully understand and appreciate how scientific knowledge is discovered (NRC, 2012).

In dealing with the non-uniform interpretations of inquiry, Abrams, Southerland, and Evans (2007) suggested focusing on the goals teachers have for applying inquiry in the classroom. In general, teachers implement inquiry practice so that their students can accomplish one or more of the following objectives: "to learn how to do science, learn about the nature of science, and learn science content"(NRC, 2000, p. 1). Based on the primary goal(s) of classroom inquiry, we define inquiry as the practice in which *students design or plan experiments, conduct experiments to collect evidence, interpret the evidence from the experiments, use the evidence to justify conclusions, and communicate the results of the experiments*. These activities frame inquiry as a student-centred approach by highlighting the importance of scientific investigations in achieving the goals of classroom inquiry.

We simplified the five phases of the inquiry-based learning framework developed by Pedaste et al. (2015) to illustrate various inquiry activities involved in our research. The original framework divided inquiry learning into five phases: Orientation, Conceptualization, Investigation, Conclusion, and Discussion. In our simplified phases of inquiry (see Fig. 1), we did not include the Orientation phase—which places more emphasis on teacher-centred approaches to stimulating students' interest in the scientific investigation at hand—since our definition of inquiry-based teaching views students as active learners who are responsible for their knowledge construction. Our adapted framework of inquiry starts with the Conceptualization phase, where students identify questions or formulate hypotheses to guide the inquiry process (Fig. 1). The research problems or hypotheses can be provided by the teacher, suggested by students, or identified by the teacher and students together. In the Investigation phase, students make discoveries related to their questions by designing their investigations, conducting experiments, and interpreting and evaluating the outcomes. While the focus in the Exploration and Experimentation sub-phase is to collect reliable data, the Data Interpretation sub-phase places a strong emphasis on the process of meaning-making and building new knowledge from the data (Bruce & Casey, 2012). The next stage can be characterized as the Conclusion phase, which focuses on the process of comparing inferences drawn from the data to justify a conclusion. Students evaluate whether the research problems have been answered through the evidence collected from the investigation (Scanlon, Anastopoulou, Kerawalla, & Mulholland, 2011). Finally, the Discussion phase is viewed as a process that occurs during all phases. This phase represents an external process of inquiry and its openness, in which students discuss their findings and conclusions with the teacher and other students and receive feedback that can be used to improve the inquiry activities. Inquiry is viewed as an *integrated* and *nonlinear* process in which every activity is linked with each other in complex ways (Krajcik et al., 1998).