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How is “Knowledge” Constructed During Science Activities? Detaching Instructional Effects of “Playing” and “Telling” to Optimize Integration of Scientific Investigations

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Abstract

Despite recommendations from science educational standards which claim that science teaching should engage students in scientific investigations the same way scientists practice their profession to discover the unknown, thereby allowing students to actively construct their own knowledge, a growing body of empirical evidence suggests that this may not be the most effective approach. The present research tests the separate effects of two instructional elements that often co-occur when characterizing scientific investigations in science activities: the role of interacting with investigation materials and the role of telling in teacher guidance. Kindergarten and first-grade students participated in one of four versions of a lesson on light in their classrooms: (1) students were either asked to physically interact with scientific investigations themselves or to watch the instructor perform them and (2) students were either directly told the concepts the investigations were designed to teach or they only heard neutral guidance. Learning was assessed through change in scores from the pretest to posttest. Results show that answers in teacher guidance resulted in more learning than neutral guidance. There was no effect from manipulating materials. Implications of these results for future research and real-world classroom practice are discussed.

Keywords Explicit instruction · Inquiry learning · Instructional guidance · Science teaching

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Introduction

Little in the world of education is as influential as constructivism. This viewpoint holds that learners play an active role in building and constructing their own knowledge. This philosophical position has shaped our view on the nature of knowledge, pedagogy, curriculum, and epistemology. Through the lens of constructivism, teachers should facilitate learners' knowledge construction during this process by engaging students in hands-on activities so they construct their own understandings rather than being simply told the answers. This view has been widely adopted as a guiding pedagogical principle for developing instructional activities.

Particularly for teaching science, involving students in scientific investigations provides learners with opportunities to build their own understanding of science and allows them to connect scientific concepts with investigation procedures. For decades, the integration of scientific investigations into science teaching and learning has been suggested. The National Research Council (NRC) developed science educational standards to outline the need for engaging students in scientific investigations and argued that science learning is an active process, "something students do, not something that is done to them" (1996, p. 20). Decades later, the newly developed Next Generation Science Standards (NGSS) (National Research Council 2013) continues to highlight "the power of integrating understanding the ideas of science with engagement in the practices of science" (National Research Council 2011, p. viii) and states that "students cannot comprehend scientific practices, nor fully appreciate the nature of scientific knowledge itself, without directly experiencing those practices for themselves" (pp. 2–5).

The emphasis on integrating scientific investigations into science teaching has remained clear over these years. Two generally agreed pedagogical principles have been used, either explicitly or implicitly, to guide the integration: (a) students learn better when being able to construct the knowledge on their own rather than being told the answer; and (b) this knowledge construction process can be better facilitated when students are engaged in hands-on investigation activities interacting with learning materials. Thus, scientific investigations are often characterized in science teaching as not simply or directly telling, but engaging students in hands-on investigation steps to find answers. The present study intends to test the effects of these two instructional elements that are often used to guide incorporating scientific investigations.

Review of the Literature

Constructivist View and Scientific Investigations in Science Teaching

Telling students well-established content has been criticized as it seems to only pour information into the students' heads and, thus, minimizes the active role learners could play. In contrast, led by John Dewey and many others in the 1930s, the constructivist view of learning promotes knowing as a self-driven construction process through experiences (Dewey 1938). Thus, in this framework, knowing is no longer a static mental representation. Rather, it is viewed as a process through which learners are actively involved in interacting with other elements in the context (Sawyer 2006). Built around these ideas, constructivism has developed into the most influential

philosophical view of learning and shaped the way instructional activities are presented to learners. Particularly in science teaching and learning over the past 30 years, science activities became viewed as a way for students to construct knowledge on their own and to come to their own understandings of science. Thus, science-related instructional activities, during this transition, have come to emphasize three perspectives—discovery learning, scientific processes, and individual learning experiences—in an intertwined way (Hodson 1996).

In the USA, there are two noticeable changes in the ways that scientific investigations get characterized in science teaching. Influenced by the constructivist view, science teaching in the 1990s took the hands-on, inquiry-based approach and scientific investigations were incorporated to promote students' involvement in inquiry, as suggested by the National Research Council (1996). This approach has been prominent ever since (Minner et al. 2010). Scientific investigations were then introduced in science teaching as an instructional approach and characterized as an inquiry process, including having students form investigative questions, make observations, collect/analyze data, and draw conclusions. Science teaching shifted from directly providing established content to facilitating the inquiry process by offering suggestions, hints, and feedback through teacher guidance. Thus, reflecting this theoretical view, scientific investigations in science classrooms often include holding off answers from students and providing neutral responses instead to promote hands-on inquiry (Furtak 2006). A great effort was made to implement these educational standards through a nation-wide curriculum reform. For example, a weather-related, inquiry-based program, Kids as Global Scientists (KGS), was simultaneously implemented in 258 classrooms with 240 teachers and 10,861 students from 40 states (Songer et al. 2002).

About three decades later, the focus has now shifted from inquiry to scientific practice. The framework used for designing the NGSS in the USA reiterates its emphasis on integrating scientific investigations into science learning, but characterizes the “integration” as engaging students in “scientific practice” undertaken by scientists (National Research Council 2011, 2013). The framework specifies eight scientific practices students should be engaged in, including asking questions, developing models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, constructing explanations, engaging in argument, and evaluating and communicating information. Despite the differences in the framing of the scientific steps listed in both sets of standards, the emphasis on integrating scientific investigations into science learning has remained. The NGSS characterizes investigations in science teaching as scientists practicing the science profession to discover the unknown. Thus, to mimic this process, providing neutral responses to and withholding answers from students continues to be used to introduce scientific investigations.

With less doubt, science teaching has developed over the past 30 years reflecting the constructivist view and values that notion that students will learn science better when being able to come up with the ideas on their own through their investigations. Scientific investigations, either characterized as inquiry or as scientific practice, have been incorporated in science teaching consistently as a way for students to construct science knowledge on their own. Thus, this approach portrays the learning process as an exploration where answers are not simply told to students, but obtained later by students as investigations evolve. This discovery aspect of incorporating scientific investigations to teach and learn science concepts, however, has raised concerns.

Studies on Constructivist Approach to Science Teaching

Empirical findings on the constructivist approach to science teaching are divided. A main body of literature suggests that the constructivist way of incorporating scientific investigation activities in science teaching improves students' learning of science while an emerging set of studies that utilize controlled experiments or analyze patterns over a large population find the opposite.

In the 1990s, large centers and programs were built as a result of the sweeping curriculum reform initiative carried out to promote hands-on inquiry. For example, the Web-based Inquiry Science Environment (WISE) is a well-known online learning platform that incorporates technology tools, media, and content resources to support science learning through scientific inquiry. WISE-supported inquiry-based investigations in the classroom have been found to improve students' understanding of science concepts (Linn et al. 2003; Williams and Linn 2002). The Center for Learning Technologies in Urban Schools (LeTUS) is another large inquiry-based learning program built during that period of time. By comparing students enrolled in LeTUS with those who were not, Geier et al. (2008) found that LeTUS inquiry-based science curricula improved students' learning of science. The team also concluded that engaging students in scientific inquiry through a set of investigation steps is an effective instructional approach and stated, "The results of this study suggest that it is also important to scale up the amount of exposure each student has to standards-based inquiry projects, by expanding the number of different curriculum units available as part of the middle school program" (pp. 935–936).

Undoubtedly, there is a considerable body of research in science education over the past two decades supporting the constructivist approach to scientific investigations and suggesting that engaging students in science learning through a set of investigation steps is effective. The results include improving students' understanding of science ideas, developing students' knowledge of scientific methods and steps undertaken by science professionals, supporting scientific reasoning as well as students' ability to solve problems, promoting students' ownership of knowledge, developing students' positive attitudes toward science, and providing students with learning opportunities in authentic contexts (Barton and Tan 2010; Edelson and Reiser 2006; Geier et al. 2008; Mistler-Jackson and Songer 2000; Shaffer 2004; Songer et al. 2002; Songer et al. 2003; Williams and Linn 2002). These suggestions have shaped science educational standards and continue to serve as the foundation for promoting the similar way of incorporating scientific investigations. For example, the NGSS (National Research Council 2011) argues that their suggestions are based on "a rich and growing body of research" on science teaching and learning over the past 20 years (p. ES-1).

Different from the constructivist approach that emphasizes students' self-construction of science knowledge through investigations, direct instruction presents answers, ideas, and relationships directly to learners. Techniques for direct instruction include telling students answers, having students watch demonstrations and listen to explanations, and directly reading answers from texts. A number of controlled studies which compare the constructivist approach with direct instruction find that students in direct instruction conditions demonstrate greater learning of the content and better transfer (Ashman et al. 2019; Klahr and Nigam 2004; Kruit et al. 2018; Matlen and Klahr 2013; Renken and Nunez 2010; Rittle-Johnson 2006; Stull and Mayer 2007; Zhang 2018, 2019). Thus, although involving students in scientific investigations has been shown to be helpful to scientific learning, direct instruction may be an even more effective technique for teaching science knowledge and skills.

International large-scale assessments, such as TIMSS (Trends in International Mathematics and Science Study) and PISA (Program for International Student Assessment), also run counter to the suggestions made in the science educational standards and find that lower science performance was associated with exposure to hands-on investigations in science teaching. And since the reform initiative to promote the constructivist approach to scientific investigations in 1990s, for over decades, this pattern seems to be only occurring over time, across countries, reported in the USA (Kaya and Rice 2010; Zhang and Li 2019), Qatar (Areepattamannil 2012), Finland (Lavonen and Laaksonen 2009), Australia, Canada, and New Zealand (McConney et al. 2014), England (Jerrim et al. 2019), Inner Mongolia, China (Gao et al. 2017), and 4780 schools in 54 countries across the globe (Cairns and Areepattamannil 2019). It is possible that this negative association might relate to the poor implementation by teachers due to the lack of support and resources for this type of pedagogy, as already articulated in the literature. However, this recurring pattern coupled with piles of consistent findings from intervention studies raises many questions about the commonly advocated way of characterizing scientific investigations and reveals the necessity of looking into this inconsistency in the literature.

Difficulty in Studying Science Activities and Significance of the Present Study

Instructional elements are often intertwined together, which leads to considerable difficulty in studying which elements are effective. For example, in order for students to experience the process, particularly to investigate through science activities, teachers may feel the need to withhold answers from them. It is important to note, however, that being involved in the situation might have different instructional effects from not being told the answers. Because these two instructional elements tend to co-occur, they have not been treated as two different instructional attributes and, thus, have not been examined separately.

Adding to the difficulty is the change of field to include even more instructional elements. What counts for effective science teaching continues to expand as the field develops. Through multiple rounds of curriculum reforms, the integration of scientific investigations extends and is now suggested to also include many other instructional elements, such as incorporating technologies as well as engineering design and promoting scientific arguments. More programs are built to include all these elements and studies tend to evaluate their program's effectiveness as a whole with all elements in it. As a result, it has been hard to identify which instructional element works and which do not.

As the integration of scientific investigations continues to be the focus of science teaching, there is an urgent need to detach the instructional elements that have shaped the way scientific investigations are currently characterized in science teaching. As reviewed earlier, two pedagogical suggestions from the constructivist view seem to be the focus: (a) students learn better when being able to construct the knowledge on their own rather than being told the answer; and (b) this knowledge construction process can be better facilitated when students are engaged in hands-on investigation activities interacting with learning materials. The goal of this study is to test the effects of these two instructional elements, physically manipulating investigation materials (simply referred to as “playing”) and being presented with answers (simply referred to as “telling”), combined and alone, on students' learning of two scientific concepts about light. In addition, we test the potential interaction between the two to see whether the two elements together produce better outcomes than each one alone. Because previous research is inconsistent, we make no specific hypothesis about which instructional

element will be most effective in the present study. In particular, we address the following research questions:

- Does hands-on “playing” or does “telling” lead to better learning of scientific concepts of light for young learners?
- Does the combination of both “playing” and “telling” lead to greater understanding of scientific concepts of light compared to experiencing one instructional element alone?

Methods

Participants

Students from five classrooms in two elementary schools (one public, one private and parochial) in the Northeast United States were invited to participate. Informed parental consent was received for 64 children. These students (52% female) were aged between 5.5 and 7.5 years old, either in kindergarten or first grade during the period of this study. Participants missing either the pretest or posttest were removed, resulting in a final sample of 53 participants, roughly evenly distributed between the four conditions (see Table 1).

An additional 46 children of the same age participated in an in-laboratory pilot version of this study. They were recruited from a database of families interested in research from the same geographic area as the schools were located. Informed parental consent was obtained for all children.

Design

This study aims to examine the effects of two independent variables on students’ learning of science concepts: playing vs. not playing and telling vs. not telling, simply called. Thus, the study followed 2 (playing vs. not playing) $\times$ 2 (telling vs. not telling) between-participants experimental design and the classes of students were randomly assigned to one of four conditions. This study also sought to measure changes in student learning about two scientific concepts. Thus, it employed a within-participants pretest-intervention-posttest design.

Pilot Phase The pretest, posttest, and intervention were developed and tested to ensure that they were effective and appropriate for this age group through an iterative pilot testing process. In this phase, participating children experienced the pretest, intervention, and posttest in one, approximately 45-min session in an on-campus laboratory. Participants were randomly

Table 1 Descriptive statistics

Conditions	Light needed to see things	Light travels in a straight line	Concepts combined
	<i>M</i> (SD)	<i>M</i> (SD)	<i>M</i> (SD)
<i>Playing+telling</i> (<i>n</i> =11)	38.64 (25.08)	30.81 (12.26)	34.72 (16.23)
<i>Playing+not telling</i> (<i>n</i> =12)	46.18 (28.29)	27.78 (15.89)	36.98 (17.14)
<i>Not playing+telling</i> (<i>n</i> =15)	32.78 (22.21)	22.96 (12.58)	27.87 (12.21)
<i>Not playing+not telling</i> (<i>n</i> =15)	37.78 (18.33)	34.44 (19.72)	36.11 (14.06)

assigned to an intervention condition in this phase. During this process, experimenters met regularly to discuss their experiences conducting the assessments and interventions. Based on these experiences and data, the assessments and the intervention were revised. The final assessments and interventions used in the main study (described below) were the result of several revisions. This pilot phase was ended when participants' pretest scores were low with good variability; when the pre- and posttests seemed to be accurately capturing conceptual knowledge, not just surface-level knowledge; and when the intervention was engaging and developmentally appropriate.

Intervention Structure and Content The intervention was specifically designed to mimic a real science lesson that kindergarteners and first-graders might experience. Specifically, the lesson contained two sections, a large-group introduction followed by small-group investigations. The intervention lessons taught participants two science concepts about light. Section 1 focused on basic ideas about light. The purpose was to notify students the goal of the lesson and encourage them to have general discussions about light. The experimenter led a discussion with questions like: What do you think light is good for? Can you think of a time when you have used light? Section 1 also contained instruction teaching students basic knowledge about light, including the two target concepts that people need light to see things and that light travels in a straight line. To teach the two concepts, the experimenter prompted the real-life examples where light is necessary to see things and used a laser pointer to demonstrate that light travels in a straight line. The experimenter had a discussion with students and led to the conclusion of the two concepts. For example, students were asked what they would do when going into a dark room and why they need to turn on the light. The experimenter led to the key concept, saying "That's right. You need light to see things." The experimenter also asked students to use their finger to illustrate how light travels in a straight line after the laser pointer demonstration. Section 1 was the same across the four conditions. While it is true that all students heard some direct instruction about the target concepts during this section, we chose to include this section in order to preserve ecological validity; we wanted to test our hypotheses in the types of lessons that are likely to be delivered in real classrooms.

Section 2 contained three hands-on investigations where students needed to (1) line up pieces of foam board just right to allow light travel through small holes in the foam; (2) identify a mysterious object in a dark box; and (3) find a small, hidden sticker in a dark tent. Investigation 1 focused on the target idea that light travels in a straight line. Investigation 2 focused on the target idea that light is necessary to see things. Investigation 3 involved both ideas. The four conditions were different in terms of how students were involved in the investigations. They varied on whether students physically interacted with the materials versus watched the experimenter conduct the investigations and whether the answers to the investigation questions (e.g., Do you think you can see the hidden objects without your flashlight? If you are pointing your flashlight to this direction when the objects are in the other direction, do you think you can see them?) were given to students versus only scaffolding feedback and suggestions.

Specifically, (1) in the *playing + telling condition*: students physically interacted with the investigation materials, including moving around the boards, turning on and off the flashlight, and pointing it in different directions, and the answers to their investigations were told to them; (2) in the *playing + not telling condition*: students physically interacted with materials and the experimenter provided scaffolding guidance, such as feedback and suggestions, rather than

telling the answers directly. Students were expected to construct the solutions based on the feedback; (3) in the *not playing + telling condition*: students watched the experimenter conduct the three investigations and the answers were told to them; (4) in the *not playing + not telling condition*: students watched the investigations and the experimenter provided only scaffolding guidance suggestions. The intervention lessons were scripted to avoid the variation in teaching. The intervention lessons lasted about 30 min. The four conditions were kept the same as much as possible except for the two factors that were manipulated.

Materials and Measures

The primary dependent variables were students' understanding of the two target concepts that light is needed to see things and that light travels in a straight line, which were assessed with a 12-question interview developed by the team. Half of the questions targeted each concept. Questions centered around contexts students were familiar with in real life, rather than the situations involved in the intervention investigations. Thus, students were not able to answer these questions from direct recall of the investigations' findings. For example, other than asking the questions relating to the investigations involving flashlights, boxes, and foam boards etc., we asked students whether they could see a book far away in a dark basement.

The questions were designed to capture both concrete knowledge through forced-choice answers (yes or no), as well as deeper, conceptual knowledge through open-ended questions asking for participants' explanations. Both their direct answers and explanations were coded and included as part of the assessment data. Two versions of the interview were created, one for the pretest and one for the posttest. The two versions were structurally identical but contained different details. For example, in the pretest one question asked about a "silver ball" and in the posttest the same question asked about a "yellow shirt."

Secondary dependent variables were participants' inhibitory control and working memory. They were collected as they measure children's executive function skills and are well-known cognitive predictors of success in early education (i.e., Ponitz et al. 2009). We assessed these skills using standard, age-appropriate measures. For all tasks, participants experienced practice trials first with feedback to ensure they understood the rules before test trials began.

To measure inhibitory control, students participated in the Head-Toes-Shoulders-Knees (HTSK) task (Ponitz et al. 2008) and a Delay of Gratification task (Hongwanishkul et al. 2005). In the HTSK task, participating children were asked to stand up and touch their head, toes, knees, and shoulders to confirm they know all those body parts. Then, they were instructed to touch the opposite body part from what the experimenter said, (e.g., "When I say 'touch your head', I actually want you touch your toes! When I say 'touch your knees', I actually want you to touch your shoulders!"). Participants completed 12 test trials (three of each body part) in a random order without feedback. In the Delay of Gratification task, desirable objects were laid out on the table in front of the participants and they were given a choice between getting "one now or three later". Three test trials were conducted using dimes, stickers, and the chance to ring a hotel bell.

The working memory tasks included a Backwards Digit Span (for verbal working memory) and a Counting Recall task (for visual-spatial working memory) (Alloway et al. 2006). In the Backwards Digit Span task, participants were asked to repeat lists of single digits backwards, (e.g., "I am going to say some numbers, and then I want you to repeat them back to me, but backwards. So, if I say 4,7 you say 7,4."). Lists started with two numbers and gradually increased. The Counting Recall task assessed visual-spatial working memory. Participants saw

large laminated cards (8.5×11 in.) showing varying numbers of red circles and blue triangles arranged haphazardly. Participants were then asked to count and remember how many red circles were on each card in a set. At the end of each set, they were asked to recall the number of circles on each card in order. Sets started with one card and increased in length as long as participants could succeed on the task. For both tasks, if participants got at least one of the trials of a given level correct, they advanced to the next set. The task was stopped when they failed both lists/sets of a given length.

Procedure

At the first testing time, participants completed the pretest to measure their baseline understanding of light and participated in the inhibitory control and working memory tasks measuring their executive function skills. Tasks were given in a fixed order: pretest, HTSK, Delay of Gratification, Backwards Digit Span, Counting Recall. To control for participants' varying levels of reading and writing abilities, all participants were assessed verbally sitting one-on-one with a researcher. The researcher recorded participants' responses to all questions and tasks in writing during the procedure.

At time 2, which occurred about 1 month later, interventions were implemented by the research team in the participants' classrooms. The two small classrooms of participants in the parochial school were combined to approximate the classroom size of the public school. The four classrooms were then randomly assigned to one of four intervention conditions. The four conditions varied on whether students physically interacted with materials and on whether the answers were told.

First, all the experimenters reintroduced themselves to the students. One experimenter invited all the students to join her on a rug in the classroom. She then conducted section 1 of the intervention, as described above, in which she introduced the goal of the lesson and conducted a general discussion with all students about light. Recall that this section was the same for all four conditions. This section took approximately 10 min. Next, students were divided into three similarly sized groups. Each group was sent to one of three investigation stations. A different experimenter led each investigation. Recall that there were three investigations where students needed to (1) figure out how to make light travel through small holes in foam boards, (2) identify a mysterious object in a dark box, and (3) find a small sticker in a dark tent. The experimenter leading each investigation made sure that each child fully participated in the activity. When all students finished, the groups rotated stations until all participants experienced all three stations. Each investigation took about 7 min.

The posttest was conducted individually with each participant about an hour after the intervention occurred.

Coding

For the pre- and posttests, participants received one point for each correct answer on forced-choice questions. Open-ended explanation questions were scored from 0 to 3. The full 3 points were awarded only when students correctly and explicitly communicated the target concept (i.e., "you need light to see things" or "light always travels in a straight line"). Two points were given if students' response was mostly correct and/or they indirectly referred to the concept (e.g., "you can't see it because it's too dark" or "the light gets blocked at this bend in the tube"). One point was given if they hinted at the correct concept (e.g., "it would be hard to see because it is dark, but you can see a little because you know it's there" or "light goes through

the tube”). No points were given for totally incorrect or nonsensical answers (e.g., “you can see it because it’s shiny” or “because it is like this”). All pre- and posttests were coded by two researchers in the team who were different from the researcher who tested the student. Coding discrepancies were resolved through discussion. Finally, all participants’ test scores were converted to a 100-point scale.

For inhibitory control measures, participants received one point for correct responses, no points for incorrect responses, and a half point if they spontaneously corrected an initially incorrect response. Thus, the possible range for HTSK was 0–12 and the possible range for Delay of Gratification was 0–3.

The working memory measures for both the verbal and visual-spatial were each scored two ways: (1) the number of trials individual students passed and (2) the highest digit list length or card set size individual students were able to reach. These scores were highly correlated. Thus, only the highest digit list length measuring the verbal working memory and the card set size measuring the visual-spatial one were used in the final analyses.

Results

Preliminary Analyses

A one-way ANOVA was conducted to compare participants’ pretest scores and to determine if there were any pre-existing conditions. Descriptive statistics about participants’ knowledge of the two target concepts, either combined or separated, across the four conditions are provided in Table 1. The results showed that there was no significant difference in participants’ knowledge about the two target concepts across the four conditions before the intervention, when considering the two target concepts combined (for playing $F(1, 49) = .89, p = .35$, and for telling $F(1, 49) = 1.64, p = .21$) or when considering the concepts separated (for concept 1, playing $F(1, 49) = 1.21, p = .28$, and telling $F(1, 49) = .94, p = .34$; for concept 2, playing $F(1, 49) = .02, p = .89$, and telling $F(1, 49) = .95, p = .33$). This finding suggests that participants in the four conditions were statistically the same at the start of the study.

Main Analyses

We analyzed participants’ posttest scores using a 2 (playing vs. non-playing) $\times$ 2 (telling vs. not telling) analysis of covariance (ANCOVA) with participants’ pretest scores and their total inhibitory control as well total working memory scores as covariates. We first analyzed participants’ learning of the two concepts combined and then separated. When analyzing them combined, the concepts were equally weighted.

Two Concepts Combined For posttest scores combining the two target science concepts, after controlling for the differences in participants’ executive function skills and pretest scores, there was a main effect of telling vs. not telling the answers ($F(1, 45) = 4.33, p = .04$, partial $\eta^2 = .088$). Participants scored about 10 points higher on a 100 scale when they were told the answers than when they were not. There was no main effect of physically interacting with the learning materials ($F(1, 45) = .80, p = .38$, partial $\eta^2 = .017$). Moreover, there was no significant interaction between the two independent variables, playing and telling ($F(1, 45) = 1.32, p = .26$, partial $\eta^2 = .028$), suggesting that playing did not strengthen or weaken the effect of being told the answers to the investigations.

Two Concepts Separated For the concept “light is necessary to see things,” the same pattern with a stronger relationship was found. After controlling for the executive function and pretest scores, there was a significant difference in participants’ posttest scores resulted from telling vs. not telling the answers ($F(1, 45) = 9.64, p = .003$, partial $\eta^2 = .176$). Participants scored about 20 points higher when they were told the answers. No significant difference resulted from whether participants physically interacted with the learning materials ($F(1, 45) = .28, p = .60$, partial $\eta^2 = .006$), and no interaction between playing and telling was found ($F(1, 45) = 1.53, p = .22$, partial $\eta^2 = .033$).

In contrast, for the concept “light travels in a straight line,” a different pattern was identified. Controlling for the executive function and pretest scores, there was no main effect of physically interacting with the materials on students’ learning of the concept ($F(1, 45) = .98, p = .33$, partial $\eta^2 = .021$) nor telling students the answers ($F(1, 45) = .08, p = .78$, partial $\eta^2 = .002$). Furthermore, there was no interaction between playing and telling ($F(1, 45) = .04, p = .84$, partial $\eta^2 = .001$).

Discussion

The purpose of this study was to detach two instructional elements that often co-occur in characterizing scientific investigations in science teaching, playing and telling, and to test their effects on students’ learning of science concepts. To answer our first research question, we found that providing students with opportunities to physically interact with investigation materials did not make a difference in students’ learning of the science concept, but directly telling answers affected student learning significantly and positively. To our second question, we found that the two elements did not meaningfully interact, suggesting that students demonstrated better understanding consistently when the answers were told to them, no matter whether they were allowed to play or not.

First, our findings indicate that even though withholding answers and having students physically interact with materials often co-occur in science teaching activities, they have different instructional effects on student learning and should be treated separately. When designing science instructional activities, it might be natural to think that students will gain more information and understand concepts better when being able to experience the whole scientific process, including conducting the investigation and transferring data into relationships. However, the results of the present study suggest that performing an investigation is not the same as withholding answers in teacher guidance and, thus, should be treated as a separate process. Indeed, our findings suggest that withholding information might hinder students’ learning. As a result, the potential benefits of a fun, rewarding learning context might end up being negated because of the deleterious effects of withholding answers. This could be one of the reasons for the inconsistent findings in previous studies.

Second, our findings on “playing” are consistent with prior work that also compared hands-on manipulations with alternatives (Klahr et al. 2007; Stull and Mayer 2007). For example, Stull and Mayer (2007) examined students’ understanding of science-related texts through active “doing” vs. passive “viewing” and found that active “doing” did not lead students to a better understanding of the scientific concepts from the texts. These researchers questioned the theoretical assumptions that students learn better by “doing” and concluded, “we found no support for the general proposition that learning by doing will always lead to deeper learning

than learning by viewing” (p. 817). We share concerns with these researchers and raise questions on the “hands-on” components that are often promoted in science learning curricula and teaching practice.

It is important to note, however, that manipulating materials did not hinder student learning in the present study. It is easy to imagine why allowing students to conduct investigations themselves might have negative effects on student learning: the materials may be distracting, the materials may provoke classroom management challenges, the materials may not work as desired, to name a few. If students become too focused on the materials themselves, they may not be able to extract the larger scientific concepts that the materials are designed to convey. However, in this study, being able to perform the investigations was a neutral addition to the intervention. For everyday practice, this suggests that teachers can have considerable freedom to choose when to involve students in investigations and when they should just watch without sacrificing student learning.

Third, our study suggests the importance of telling students answers and challenges the approach to scientific investigations that withhold answers. Schwartz and Bransford (1998) tested the effects of giving answers and insisted that there is a time for telling during teaching. Examining investigation activities in science lessons, Abrahams and Millar (2008) noted the same issue and argued that conceptual understanding of science concepts does not come from observations and operations in scientific investigations and that concepts should be explicitly introduced to learners. A series of controlled studies also found that directly and explicitly presenting the content to learners is critical, including simply telling students answers, having students watch demonstrations and listen to explanations, and directly reading answers from texts (Ashman et al. 2019; Klahr and Nigam 2004; Kruit et al. 2018; Matlen and Klahr 2013; Renken and Nunez 2010; Rittle-Johnson 2006; Stull and Mayer 2007; Zhang 2018, 2019). Our findings add to this growing body of work which contradicts what has been commonly suggested in the field of science education—“don’t tell and let students investigate.” Our findings also raise questions on a widely adopted science teaching practice that teachers are encouraged to provide neutral responses along with feedback as well as suggestions to engage students in hands-on investigations. Our study did not find evidence supporting this practice. Rather, we found that even though suggestions, feedback, and hints were provided in teacher guidance, withholding answers led to lower outcomes.

Furthermore, the beneficial effect of directly telling students answers and the lack of effect of playing was equal in students with low and high executive function skills. Allowing students to interact with materials is sometimes theorized to benefit children with low self-regulatory ability who may have trouble sitting still and focusing on direct instruction. However, others argue that materials are too distracting for children with poor self-regulation. For working memory, one might imagine that children with low working memory capacity may not have the ability to self-construct knowledge as the result of participating in an investigation since doing so would seem to require holding many pieces of information in mind and putting them together correctly in order to arrive at the desired answer. The present results hint that all such concerns are unfounded and that all children benefited (or did not benefit) from the instructional elements equally. Telling helps, even for children with low inhibition and children with high working memory.

Finally, it is important to note that the positive effect of telling was not consistent in this study. Recall that we found different patterns when the two scientific concepts were considered separately, which may provide some insight into understanding the role of telling answers in student learning. Specifically, telling improved students’ understanding that light is necessary to see things, but not their understanding that light always travels in a straight line. This might

be that telling works especially well for concepts which are more concrete and easily observable in the investigation. In the present study, it was more obvious to students that they were not able to see the objects when light was not provided than the fact that the light was always traveling in a straight line. Telling the answers possibly allowed students to effectively orient their attention during the investigation process to the relevant pieces of information and ignore extraneous information. Furthermore, telling the answers might have given students the correct language to describe what they were observing, which, in turn, might have allowed them to effectively connect this new knowledge with their extant knowledge about light. Relatedly, it may be that telling works best when learners do not have contradictory pre-existing beliefs about a concept. The concept of needing light to see things seemed consistent to students with their lived experiences. But, to many students, light always traveling in a straight line did not fit with their current, naive beliefs of what happens when one turns on a light or how sunlight reaches Earth. Thus, telling may be an especially effective teaching strategy when students are able to assimilate new knowledge, but not when they have to accommodate it. Our findings seem to suggest that for the more abstract or counterintuitive science ideas, not only the concepts need to be taught to students but also the specifics about the underlying connections should be made explicit to learners.

There were several limitations to this study. For one, we chose to structure the intervention as close as we could to what might happen in an actual kindergarten or first grade classroom by having all children start with an introduction to the concepts in a large group before breaking up into smaller groups to perform/watch the scientific investigations. Thus, it is true that all children in the study experienced some “telling” in that all children were directly told the two scientific concepts in the first section of the lesson. It is important to note, however, that our research goal of testing “telling” vs. “not telling” has been designed to be achieved through telling vs. not telling students the answers to the investigation questions. As a result, the first section of the lesson might have reduced the effect of our telling manipulation during the hands-on investigations. Perhaps children in the “not telling” conditions relied on their memory of the large-group lesson to help them make some sense of what they were doing/seeing during the investigations. It is possible that we would have seen a larger difference between “telling” and “not telling” if the investigations had taken place without an introduction to the concepts first. This is especially true for the concept “light travels in a straight line”: maybe the reason we did not see a difference between groups for this concept was because the laser pointer demonstration in the large-group phase was particularly compelling to students. Yet, it is striking that we saw a benefit of the “telling” manipulation despite the fact that all children heard some, albeit limited, direct instruction prior to the investigations.

However, the ecological validity of the study was limited in that the intervention lessons were implemented by the researchers following the scripts, not by the real classroom teachers. We did so to avoid introducing other factors that could be results of various teaching styles and knowledge levels of different teachers. Future studies would be helpful in determining if similar effects are found using lessons given by actual teachers. Of course, additional studies are also needed to replicate the effects found in this research. It is important to note that only one classroom of children experienced each version of our intervention, and thus, our manipulations were confounded with classroom-level variables, even with random assignment. Further research would help ensure that the effects seen in this research were not due to idiosyncrasies of individual classrooms.

In summary, the integration of scientific investigations has remained the focus of science teaching over decades. Influenced by the constructivist view, scientific investigations are

viewed as a tool for students to construct their own knowledge and are often characterized in science teaching as not directly telling answers, but engaging students in hands-on investigations to find the answers. Our study raises concerns with this approach and provides insightful information into understanding science instructional activities that incorporate investigations. We hope our study can provide some preliminary data to start a discussion on whether other approaches to scientific investigations should be developed and explored to broaden our view.

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