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The use of mobile devices as means of data collection in supporting elementary school students' conceptual understanding about plants

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ABSTRACT

The purpose of this study was to examine the impact of mobile learning among young learners. Specifically, we investigated whether the use of mobile devices for data collection during field trips outside the classroom could enhance fourth graders' learning about the parts of the flower and their functions, flower pollinators and the process of pollination/fertilization, and the interrelationship between animals and plants, more than students' use of traditional means of data collection. For this purpose, we designed a pre–post experimental design study with two conditions: one in which participants used a mobile device for data collection and another using traditional means (e.g. sketching and note-taking). The sample comprised 48 fourth graders (24 in each condition), who studied the flower, its parts, and their functions. A conceptual test was administered to assess students' understanding before and after instruction. Moreover, the students' science notebooks and accompanying artifacts were used as a data source for examining students' progress during the study's intervention. The conceptual test and notebook data were analyzed statistically, whereas we used open coding for the artifacts. Findings revealed that using mobile devices for data collection enhanced students' conceptual understanding more than using traditional means of data collection.

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Introduction

Over the past decade, there has been growing interest in research that examines interaction and communication processes and how they translate into knowledge, primarily because of the increasing presence of mobile technologies (Cristol, Choi, Mitchell, & Burbidge 2015; Dubendorf, 2003; Kukulska-Hulme, 2005; Martin & Ertzberger, 2013; McGhee & Kozma, 2001; McKenzie, 2001; Schaal, Matt, & Grubmeyer, 2012; Zhang, 2015).

Researchers have identified the need to re-conceptualize learning through the lens of *mobile learning*, a term commonly used to mean learning on the move (Cristol et al., 2015). Sharples, Taylor and Vavoula (2005) argued that 'there is a need to reconceptualize

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learning for the mobile age, to recognize the essential role of mobility and communication in the process of learning, and also to indicate the importance of context in establishing meaning' (p. 1). As defined by Quinn (2000), 'mobile learning is learning through mobile computational devices'. Seppala and Alamaki (2003) summarized the distinctive features of mobile learning as that it takes place at any location and not necessarily in the classroom, and that it enables learners to access an information network by using a portable learning device and a wireless network.

Moreover, mobile learning promotes new ways of socializing, networking, and acquiring knowledge (Looi, Song, & Wong, 2012; Seipold & Pachler, 2011). Our understanding of these new ways of socializing, networking and acquiring knowledge through the use of mobile technologies is rooted in sociocultural theory that supports the idea that learning involves social and cultural processes (Seipold & Pachler, 2011). Mobile technologies have the potential to contribute to the formation of innovative learning environments 'by leveraging [on] the unique characteristics [affordances] of mobile technologies, namely, individuality, connectivity, context sensitivity, mobility and immediacy' (Song, Wong, & Looi, 2012, p. 680). These new learning environments that combine traditional sources of learning (e.g. books) with the unique affordances of mobile technologies (e.g. rapid data collection at any time and place) promote innovative instructional approaches with a significant impact on student learning (Liu, Scordino, et al., 2014; Pachler, Bachmair & Cook, 2010; Seipold & Pachler, 2011). However, a review of the related literature shows that there is a limited knowledge base about pedagogical approaches that use mobile technologies (Pollara & Kee Broussard, 2011). Looi et al. (2011) highlight the fact that we are still far from making mobile technology 'an integral and essential element in a school's curriculum with the teacher and students using mobile technologies in a routine way for their weekly lessons' (p. 269). Moreover, there is limited knowledge about the unique contribution to students' learning of each type of affordance provided by mobile devices, which makes the implementation of mobile devices in the school's curriculum even harder (Liu, Scordino, et al., 2014).

This study aimed to contribute to this research direction by providing empirical evidence of the impact of a particular mobile device affordance, namely, the capability of collecting and recording authentic observations and data (i.e. through photos and videos), on elementary school students' learning related to flower concepts. We selected this particular topic because the existing literature points to the fact that teachers find it challenging to deliver science content concerning concepts related to the flower (e.g. pollination and fertilization); these concepts traditionally cause several difficulties for students' understanding (Kinchin, 1999; Wandersee, 1986; Wood-Robinson, 1991). In addition, research on teaching issues of ecology in elementary school is limited, although the national curriculums of various countries expect young students (5–9 years old) to understand the life cycle of plants and their interaction with the environment, and to recognize the parts of the flower and their use, as well as the functions of pollination (e.g. Cyprus, Greece, Taiwan, and Singapore). Furthermore, according to Schussler (2008), who conducted a study analyzing the content of 69 science textbooks, science books do not help students to understand the basic concepts and functions of plants. Given the need to support students in learning about these concepts and understanding the parts and functions of plants, new approaches are needed.

Hence, this study aimed to examine the impact of an innovative unit that incorporated mobile technologies on a group of fourth graders' conceptual understandings of plants, their parts, and their functions. The unit combined an inquiry-based, experiential learning approach with the use of mobile technologies (i.e. smart phones and tablets), reinforcing the research around innovative educational practices that leverage mobile devices in educational practice (e.g. Jones, Scanlon, & Clough, 2013). More specifically, the purpose of this study was to investigate whether the use of a mobile device, especially its data recording affordances through the use of the photo and video capturing tools, enhanced fourth graders' learning about the flower, its parts, and their functions more than the use of traditional means of data collection (i.e. sketch-making). The study involved identical science lessons within authentic classes, combined with field trips (experiential learning) during which the two conditions of the study (i.e. photo and video capturing through a mobile device vs. sketching) were enacted.

We assumed that the enhancement of learning through the use of these data recording affordances of both conditions would result from *extending* students' memory and processing time (i.e. by re-accessing the recorded data, their mnemonic capabilities are extended and enhanced, and they have additional time for cognitive processing) (Smart, 2010) and enabling them to *re-see* their data (i.e. see things from new or different perspectives or observe something that was missed initially) (Girod, Rau, & Schepige, 2003). However, we conjectured that this *extension* of the memory and *re-seeing* of the data would be more enhanced in the case of the mobile devices than with the use of traditional means of data recording (i.e. sketching and note-taking), because only the recorded data of the mobile devices offer access to the original real-world objects and phenomena, which ensures the highest possible accuracy and resolution of the object or the phenomenon under study. With traditional means of observation and data recording (i.e. sketching and note-taking), there is a high possibility of recording observations or data with lower accuracy or poorer resolution, especially for young students (Louca & Zacharia, 2008, 2012; Louca, Zacharia, & Constantinou, 2011).

This experimental study was conducted to test the hypothesis that the study's experimental treatment (i.e. inquiry-based, experiential curriculum combined with the use of mobile devices for photo and video capture of authentic, concrete observations/data, and note-taking) would contribute more to students' conceptual understanding of the parts of the flower and their functions, flower pollinators and the process of pollination/fertilization, and the interrelationship between animals and plants, than the control treatment (i.e. inquiry-based, experiential curriculum combined with traditional means of data collection, i.e. magnifying glass, sketching, and note-taking). It should be noted that this study was conducted in the context of an authentic class, leaving the class and school routines intact (e.g. the science class was taught according to the curriculum and time schedule of the school, with a pre-planned visit to the school garden). The idea was to establish ecological validity and avoid the limitations of prior studies (e.g. limited time span; for more details, see Song et al., 2012).

Theoretical framework

The domain literature identifies several factors as far as the theoretical underpinnings that explain mobile learning's success in enhancing students' learning are concerned. Cristol et al. (2015) attributed their success to the sociocultural nature of learning, which involves interaction and communication in a diverse set of social contexts. They further argued, while drawing upon existing research evidence, that mobile learning's success comes from offering the potential to motivate student interest, enhance student memory, and foster students' critical thinking, collaboration, and creativity. Looi et al. (2009) also referred to the fact that mobile learning offers an efficient student-centered learning environment that aims at fostering personalized and self-directed learning. In this way, mobile learning provides the students with affordances that support enhanced learning and greater engagement in science (Zhang et al., 2010).

In the context of this study, we focused on using mobile device affordances that relate particularly to enhancing students' memory (i.e. capturing of photos and videos). The idea was to enhance their memory more through the ability to re-access recorded observations and data using their mobile devices, compared to what learners could store in their memory during their actual observations or through re-accessing the products of traditional means of data recording (i.e. paper-and-pencil sketches/drawings and notes).

A number of studies have illustrated how technology can serve not only as an aid for memory, but also as an extension of the mind. Clark and Chalmers (1998) proposed the *extended mind* hypothesis, which refers to the idea that the mind need not be contained only within the brain, but can extend to elements of the environment. Examples can be found in countless applications of mobile devices, which can be used for note-taking, for taking photos and videos of objects or events, and as repository for storing information. This extension of the mind in terms of memory essentially frees up cognitive resources (serves as an offloading mechanism) for other tasks such as problem-solving (Clark, 2008). In our case, we allowed students to use the photo and video recording affordances of their mobile devices when they were learning about flowers, in an attempt to *extend* their memory by making available for re-access at any time accurate observations through photos or videos of the actual physical object or the phenomenon under study. This was contrasted with *extending* students' memory through sketches/drawings and notes that usually included observations and data of low(er) accuracy/resolution (e.g. students could miss or misperceive aspects of the object or the phenomenon, and thus fail to record it or represent it correctly in their sketches, respectively), which could not be improved without repeated, in-person access to the original object or phenomenon. The latter is not easy to offer, especially when the object or phenomenon under study is far from your classroom learning environment.

Specifically, *extending* students' memory with accurate observations of the actual physical object or the phenomenon through mobile devices could be achieved by granting students the opportunity to re-access original observations from the real world through photos and videos, which essentially further extends and enhances their mnemonic capabilities (Smart, 2010). In addition, this re-accessing of the data could offer learners extended time for cognitive processing of aspects of their real-world observations, beyond the time they had during the actual observation on-site, as well as time for cognitive processing of these aspects with the support of tools that could even enhance observation and data collection (e.g. zoom-in and zoom-out features, seeing a video in slow motion, and freezing videos to more carefully study a scene). In other words, learners who do not have mobile devices for saving their actual observations, but use traditional means of data recording (i.e. sketches and note-taking) must rely solely on what has been stored using these traditional means and their memory for any further cognitive processing. Obviously, if certain parts or aspects of the object or phenomenon under study are missed and not documented, or certain parts or aspects of the observed object or phenomenon fail to be stored in a learner's memory, this will make learning less efficient or even impossible, compared to the learning of an individual who has repeated access to a highly accurate record of what was observed on-site, through photos or videos.

Moreover, providing students with the opportunity to capture and store their observations on a mobile storage device or using other traditional means could enable them to *re-see* a physical object or phenomenon. This idea of *re-seeing* things, suggested by Girod et al. (2003), moves beyond the idea of just observing the same physical object, system, or phenomenon again and again; it implies that offering the learners the opportunity to revisit their observations and data could result in their seeing this particular physical object/system or phenomenon from a new or different perspective (e.g. observing something that was not noticed initially could change the way we think about something). Needless to say, this *re-seeing* has a better chance to succeed and to provide accurate new insights when the actual object or phenomenon is re-accessed and re-observed by the students; this capability is only offered through photos and videos, as opposed to paper-and-pencil sketches and notes. As explained above, sketches and notes are usually of low accuracy/resolution, especially for younger students, which could lead to misleading conclusions during the *re-seeing* process.

Empirical underpinnings: the use of mobile learning at the elementary school level

Over the years, a number of studies have been conducted at the elementary school level concerning mobile technologies (e.g. handhelds, iPods, tablets, and global positioning system) and their effect on addressing various science-related cognitive and affective goals in different settings, such as the school classroom, outdoors, and museums (e.g. Bannan, Peters, & Martinez, 2010; Chu, Hwang, Tsai, & Tseng, 2010; Cristol et al, 2015; Hung, Lin, & Hwang, 2010; Hwang, Shi, & Chu, 2011; Hwang, Wu, & Ke, 2011; Klopfer, Sheldon, Perry, & Chen, 2012; Lai, Yang, Chen, Ho, & Chan, 2007; Lai, Yang, Chen, Ho, & Liang, 2009; Liu, Lin, & Paas, 2012, 2014; Rogers et al., 2004; Sha, Looi, Chen, Seow, & Wong, 2012).

The findings of most of these studies highlighted the added value of mobile learning in promoting aspects of students' affective (e.g. interest, attitudes) and cognitive (e.g. cognitive skills and conceptual understanding) development (Liu, Scordino, et al., 2014), in some cases through longitudinal studies (e.g. Looi et al., 2011). In terms of promoting students' understanding, which was one of the goals of our study, the findings from nearly all of these studies showed that the use of mobile devices could enhance students' conceptual understanding in science (e.g. Chang, Chen, & Hsu, 2011; Chen, Kao, & Sheu, 2003; Chu, Hwang, Huang, & Wu, 2008; Facer et al., 2004; Huang, Lin, & Cheng, 2010; Liao, Chen, Cheng, Chen, & Chan, 2011; Liu, Peng, Wu, & Lin, 2009; Looi et al., 2011; Song et al., 2012). These positive outcomes could be attributed to different affordances of the mobile devices (e.g. individuality, connectivity, context sensitivity, mobility, immediacy, content provision, collaboration, gaming, and rapid data collection; for a review of these affordances, see Liu, Scordino, et al., 2014). For instance, the gaming affordance of the mobile devices was found to have a positive effect on students' learning. In a study with ten 11–12-year olds, Facer et al. (2004) showed how a mobile gaming experience supported the development of children's conceptual understanding of animal behavior and interaction with the environment. Similar results were found by Liao et al. (2011), who investigated how the use of a handheld game (i.e. my-mini-pet) supported nine 10-year-old fourth-grade students' learning about their pets. The data analysis illustrated that students engaged in activities with great enthusiasm and interest, and that their engagement in the game supported their development of conceptual understanding as well as skills related to responsibility issues toward pets.

Another mobile device affordance found to have a positive impact on elementary school students' understanding in science is the provision of additional information at any time and place, especially during field trips, via the Internet (e.g. use of websites, use of WebQuests, and use of electronic libraries) or via mobile-based (offline) information-related apps (e.g. science ebooks and encyclopedias). For example, in a quasi-experimental study with 103 sixth-grade students separated into three conditions (traditional instruction, traditional instruction with WebQuest, and WebQuest instruction with going outdoors), Chang et al. (2011) showed how the use of mobile devices, along with the use of a WebQuest, enhanced sixth-grade students' learning about resource recycling and classification. Chu et al. (2008) identified positive effects of mobile learning environments with electronic library facilities on elementary school students' learning about butterfly features during various outdoor learning activities. Such positive learning outcomes were also found in a study done by Liu et al. (2009) with 46 fourth-grade students who studied aquatic plants by completing mobile natural-science learning activities based on the 5E (i.e. engagement, exploration, explanation, elaboration, and evaluation) learning cycle and accessing information from the researchers' Ecological Pool website through their mobile devices. Huang et al. (2010) conducted a study in which personal digital assistants (PDAs) equipped with a Mobile Plant Learning System (MPLS) were used by sixteen 11-year-old students, for an elementary school level botany course. This equipment provided both teachers and students with information about plants while in the field. The study's design was quasi-experimental in nature and focused on the effect of the use of the PDAs with MPLS on students' learning, compared to the traditional instruction received by the other 16 participants. The responses to questionnaires and interviews highlighted the added value of the PDAs and their functions, whereas the test results revealed that the PDAs and MPLS had a positive effect on the participants' learning.

One additional mobile device affordance found to positively influence elementary school students' experiential learning is rapid data collection and recording (e.g. taking photos and videos, as well as note-taking). For example, Song et al. (2012) involved 37 primary school students (primary levels 3 and 4) in a study about life cycles, to examine how the students' personalized learning about the life cycles of the spinach plant and the butterfly evolved. Due to the experiential nature of the study, data recording was essential to accommodate the needs of the learning processes involved (e.g. out-of-class field trip observation, data collection, and conceptualization of life cycles during the field trip). The analysis of the learning content, processes, and products revealed the value of the mobile device affordances (e.g. data collection during field trips) in promoting students' learning when studying life cycles. Chen et al. (2003) studied the use of mobile handheld devices and wireless technology to take photos of birds and communicate with teachers and other students during a bird-watching lesson. Overall, 86 elementary school students participated in this study, separated into an experimental group (42 students; use of mobile device—PDA and Bird-Watching Learning system) and a control group (44 students; use of guide-book). Analysis of the study's worksheets and tests showed that the students' learning benefited from the use of the mobile learning devices. Lai et al. (2007) used a learning activity script and a mobile technology system to facilitate students' experiential learning when studying a plant within the school's garden. A quasi-experimental study was conducted in two fifth-grade classes at an elementary school, which included an experimental group (using PDAs; 34 students) and a control group (no PDAs; 32 students). The results revealed that the mobile technology used enhanced students' new knowledge creation and awareness of learning in context and their conceptualization of knowledge through experience. Based on these findings, Lai et al. (2007) highlighted the value of the data recording affordance (i.e. rapid 'note-taking' through photos, audio, and video recording) in mobile learning contexts.

Despite the positive outcomes from these studies concerning mobile learning and its associated affordances, it should be noted that many of these studies did not follow a strict experimental design protocol when studying the aforementioned affordances (i.e. the conditions that were compared differed in more than one affordance), which makes the number of unconfounded studies investigating distinct mobile device affordances limited. Of course, this does not diminish in any way the positive impact that mobile learning has on students' learning in science. It simply restricts us from understanding the unique, specific contribution of each mobile device affordance to student learning. This restricted understanding also has implications for developing a framework that depicts how mobile technologies and their associated affordances could be integrated within a school's curriculum (Liu, Scordino, et al., 2014; Looi et al., 2011). For instance, we do not know, or have little information on, (a) whether certain mobile device affordances favor only certain concepts, (b) whether a certain number of affordances should be present at a given time (e.g. an increase in affordances might burden students' cognitive load), and (c) whether the effective use of certain affordances is age dependent (e.g. not all of the mobile device affordances were studied separately at the elementary school level). Obviously, such unresolved issues restrict us from understanding the unique, specific contribution of an affordance to student learning.

Another drawback of many of the studies conducted so far is that they lasted only a few days or weeks, and most of their treatments were implemented outside the context of the school's existing learning settings and curriculum, which negatively affects the ecological validity of these studies. Moreover, most research studies in this domain fail to connect their findings with learning theories that explain and interpret the effect of mobile learning on students' learning (Liu, Scordino, et al., 2014).

Overall, there is a consensus among many researchers about the significant role of the use of mobile devices in science teaching and learning. However, a number of drawbacks already mentioned, and the fact that many studies are confounded due to their research design, restrict us from reaching solid conclusions concerning the value of each particular mobile device affordance. This study aimed to contribute to this gap in the literature by exploring the effect of the affordance involving collection and recording of authentic data, without altering the context of the school's actual routines (i.e. we followed the school's actual time schedule, class, and curriculum) in an attempt to establish high ecological validity. We consider this particular affordance valuable for situations in which science teaching occurs once or twice per week and the science units last for a few or several weeks, as is the case for elementary school science teaching in Cyprus. The affordance involving collection and recording of authentic data provides the students with the opportunity to (re-)access and (re-)process the original observations and data gathered out in the field, especially through photos and videos, at any time throughout the course of a science unit, rather than solely relying on traditional means of data recording (i.e. sketching and note-taking) and their memory. Theoretically, the opportunity to access the original observations and data at any time over the course of time *extends* students' memory and, thus, better supports their learning (Smart, 2010). The latter is an important aspect of this study, because it situates this affordance within a theoretical context, namely, the *extended memory* theory, which several prior researchers failed to do (Liu, Scordino, et al., 2014). Another important aspect of this study is that it followed an unconfounded research design, in order to avoid a major limitation seen in prior studies in the mobile learning domain.

This study

The purpose of this study was to investigate whether the use of a mobile device, especially the data recording affordance provided through the use of photo and video capturing tools, enhances fourth graders' learning about the flower, its parts, and their functions more than the use of traditional means of data collection (i.e. sketch-making and note-taking).

In doing so, we used a pre–post experimental design, which involved two conditions during field trips at the school garden: one that used photo and video capturing through a mobile device for capturing and recording data and one that used paper-and-pencil sketching for capturing and recording data. The two conditions did not differ in any other way (e.g. same curriculum, teacher, and time framework; same opportunity for note-taking during the field trips in a notebook) throughout the intervention to ensure an unconfounded experimental design.

In particular, we aimed to answer the following research questions:

(1) Does the use of mobile devices, especially their data recording affordance through the use of photo and video capturing tools, enhance fourth graders' understanding about flowers more than the use of traditional means of data collection (i.e. paper-and-pencil sketches) during field trips? The indicator we used of participants' understanding was their performance scores on the conceptual knowledge pretest and posttest which focused on concepts related to the parts of the flower, pollinators, pollination/fertilization, and the interrelationship between animals and plants. Those in the experimental condition did not make paper-and-pencil sketches during the field trips, but they could take notes in their notebooks, as it was the case with the control condition.
(2) Does the use of mobile devices, namely, taking videos and photos to collect evidence for the topics under study, as opposed to making paper-and-pencil sketches to capture evidence for the same topics, yield different levels of scientific accuracy in fourth graders' responses to the curriculum tasks and questions used in this study? For this question, we assessed students' responses to the curriculum material questions in their science notebooks (paper-based for both conditions) and three artifacts produced

at particular pre-specified points in the curriculum. All three artifacts involved the creation of a list, which was accompanied by corresponding photos or videos (experimental condition), or sketches (control condition) (for an example, see Appendix 2).

Methods

Sample

The participants in the study were 48 nine-year-old students (25 boys, 23 girls; 47 Greek-Cypriots and 1 female student of Arabic descent) from two different classes (24 each) of a public elementary school in Nicosia, Cyprus. Each class served as a different condition in our study's design. One of the classes served as the experimental condition and the other as the control condition. Participants in the experimental condition used a mobile device for data collection during field trips, whereas the control condition used traditional means of data collection during the same field trips (e.g. magnifying glass and drawing sketches in notebooks). All other variables (e.g. curriculum, time-on-task, and paper-and-pencil note-taking in science notebooks) were kept the same. It should be noted that all of the study's participants had at least one year of prior experience with the use of mobile devices, including taking photos and videos, and that none of the participants in either conditions had had a formal science class on the flower before the study's intervention. The fact that all students had prior experience with mobile devices, including experience of their use for learning within the school context, was important for the study's research design, because we wanted to eliminate any learning gains arising from the enhancement of affective domain constructs, usually caused by the novelty effect of using a new technology for the first time in a learning environment (e.g. Looi et al., 2012; Staudt, 2005; Wu et al., 2012). In fact, no evidence was identified to show that the participants' interest and engagement differed between the two conditions during the study. Pretest scores also showed that the participants in the two conditions did not differ in their understanding of the concepts at hand before the study's learning activities (for more details, see the Data analysis section). Finally, all students worked in groups of four throughout the intervention. In the groups of four, each participant had his/her own mobile device (experimental condition) or made sketches (control condition) for collecting data. Thus, each student collected individual evidence and data, which were shared later on among all four members. In this way, we also, implicitly, introduced data triangulation/validation within students' work.

The teacher was also the same for both classes. We consider her to be an experienced teacher in this domain and suitable for our study. She has substantial experience in teaching science in elementary schools (19 years) and a strong educational background (doctoral student). She was also identified as an exemplary teacher by the school district (winner of several national science competitions). She has now been using mobile technologies in her teaching for 8 years.

Curriculum material

The students in both conditions used the same curriculum materials, which focused on the plant flower, its parts, and their functions. The curriculum materials were derived from the science textbook used across all fourth grades in public elementary schools in Cyprus. The overarching goal of the curriculum materials was for the students to get to know the basic parts of a flower and to understand that the flower is the reproductive organ of plants. More analytically, the aims of the curriculum materials were for students to:

- Learn the basic parts of a flower (petal, sepal, carpel, and stamen) and understand the basic function of each of these parts.
- Identify the carpel as the female plant reproductive organ and the stamen as the corresponding male one, in order to understand the process of pollination and reproduction.
- Describe the process of pollination (self-pollination and cross-pollination).
- Identify the basic pollinators in flowers.
- Identify the factors that attract the pollinator to a flower.
- Understand the interdependence of flowers and their pollinators.
- Understand reproduction, how it works, and its importance for life.
- Develop investigation, observation, and classification skills.

Each of these goals was associated with at least one activity, and these were combined to form the study's activity sequence (curriculum materials). The overall curriculum was separated in four parts: (a) the parts of the flower, (b) pollinators, (c) pollination and fertilization, and (d) the interrelationship between animals and plants.

Within this activity sequence there were pre-specified points (checkpoints) at which the students in both conditions had to reach conclusions and support their conclusions with data-based evidence (in this context, students sometimes created artifacts such as videos (experimental condition) and sketches (control condition), to accompany their conclusions). Overall, there were four checkpoints, one right after each of the four parts of the curriculum. The field trips to the school garden were also specified in the study's activity sequence (four field trips in total; one per part of the curriculum).

The instruction provided throughout the curriculum was the same for both conditions. The only difference was the way students collected data related to each of the four topics during field trips outdoors. In particular, the experimental condition participants used their mobile devices for collecting data (e.g. video of a flower while using zoom-in and zoom-out features, as well as close-up photos of a flower), whereas the control condition participants used a magnifying glass and their notebooks and colored pencils for capturing data (e.g. sketch of a flower). All of the data collection was driven by the curriculum materials, through the same explicit directions, in both conditions.

For example, in the first part of the curriculum, the first activity carried on outside the classroom required explicitly collecting data that could serve as evidence concerning the parts of a flower and then describing the flower in as much detail as possible. For the data collection, the students in the control condition used their notebooks and colored pencils to make sketches of a flower and complemented it with notes (for an example, see Appendix 2), whereas the students in the experimental condition took photos of the flowers and produced mini video clips using zoom-in and zoom-out features, accompanied by timely, orally articulated, observational information. The experimental condition participants were also allowed to use their notebooks for any note-taking (they were instructed about how to coordinate or associate the photos or videos with any corresponding notes taken in their notebooks).

The implementation of the whole activity sequence lasted a total of four 80-minute sessions for both conditions (for details, see the Procedures section). Finally, it should be noted that the activity sequence was inquiry oriented, meaning that students had to pose research questions, collect data, analyze data, communicate and share information with peers, reach conclusions, evaluate their conclusions, and so forth. For example, for the part of the curriculum that addressed *pollinators*, the students in both conditions had to state hypotheses concerning possible pollinators in class (*conceptualization* phase; from the Pedaste et al. 2015 inquiry framework), then move outside the classroom to collect data that could provide evidence about flower pollinators in order to test their hypotheses (*investigation* phase; from the Pedaste et al. 2015 inquiry framework), and finally return to the class for data analysis and reaching conclusions concerning the acceptance or rejection of their hypotheses (*conclusion* phase; from the Pedaste et al. 2015 inquiry framework). All of these phases were enacted in the context of group work, which involved reflection and communication among the group members during each of these phases (*discussion* phase; from the Pedaste et al. 2015 inquiry framework).

Materials

The study's conditions differed in terms of the materials used for collecting the data required by the curriculum being followed by the students in both conditions. In the control condition, the participants collected all their data through direct observation (with or without a magnifying glass) and by creating sketches with colored pencils, as well as by taking written notes in their science notebooks. After the data collection, students were able to revisit their sketches and notes at any time and as many times as they wanted. In the experimental condition, the participants used mobile devices and paper-and-pencil note-taking (in their science notebooks) for their data collection. Details on the mobile devices they used follow.

Mobile devices

Each of the students in the experimental condition used a mobile device. Each student had one of two different types of devices: a tablet (90% of the students) or a smart phone (10% of the students). All devices supplied the same features for students to use during their field trips and in class. In particular, the students using mobile devices used the magnifier (zoom-in) feature of the photo app, and the photo and video applications of their devices. Overall, the experimental condition differed from the control condition in that students had a tool that immortalized actual, real-world moments during learning (rather than sketches of low accuracy/resolution), through the collection of photo and video data, that interested them (Looi et al., 2011), and had meaning for them (Pachler et al., 2010). As such, the mobile technologies served as scaffolds for students' inquiries (Song et al., 2012). Specifically, the photo and video recording affordances were used during the field trips to scaffold (a) 'concrete experience' (e.g. taking photos of parts of a flower); (b) 'reflective observation' by videotaping the authentic phenomena and accompanying them with timely, orally articulated, observational information; and (c) 'abstract conceptualization' by (re-)visiting and (re-)organizing the captured information when studying and analyzing the field trip observations/evidence at any time (Song et al., 2012). After the collection of data through these mobile device features, students were able to revisit their photos, videos, and sound recordings at any time and as many times as they wanted.

Procedure

The study had four phases. The first phase involved the completion of a paper-and-pencil knowledge pretest. The results from this test were used to determine whether the two conditions differed in terms of students' prior knowledge concerning the parts of the flower and their functions, flower pollinators and the process of pollination/fertilization, and the interrelationship between animals and plants (week 1, one 40-minute session).

The second phase involved an introduction to the activity sequence, the field trips, and the process of collecting data either through the use of mobile devices (experimental condition) or through other traditional means (e.g. taking notes and making sketches—control condition) (week 1, one 40-minute session). During this phase, the students in both conditions were instructed how to take notes in their science notebooks to accompany their data collection for both outdoor and indoor activities.

The third phase involved the implementation of the inquiry-based activity sequence (weeks 2–5, four 80-minute sessions; one session per curriculum part and each session involved about 30-minute field trips). Activities were completed both inside and outside of the classroom. Students worked in their groups of four throughout the study's activities. The outdoor activities (field trips) involved data collection. The school garden was used for this purpose. During in-class activities, the students in both conditions studied the curriculum materials and addressed all of the accompanying questions in their science notebooks (paper-based for both conditions; this was a different notebook from what the students were using to take notes during the field trips). All student responses to these questions were collected and assessed, on an individual basis (despite the fact that students were working in groups), by the researchers, along with any other artifacts produced (e.g. videos and sketches), at the end of each part of the curriculum (at each of the four prespecified checkpoints). Each student was also required to construct three specific artifacts on an individual basis, one for each of the first three parts of the curriculum. All three artifacts involved the creation of a list. The first artifact was a list of the parts of the flower that a student could identify from a photo taken (experimental condition) or a sketch made (control condition), after the first field trip, without necessarily naming these parts (e.g. numbers were used to differentiate the identified parts; naming the identified parts was done later on with the help of the teacher); the second one was a list of the identified pollinators, and the third one was a list of evidence that showed that a flower had been pollinated. The idea behind checking students' science notebooks and artifacts was to examine the students' progress over the course of the learning activities.

Moreover, the feedback provided by the teacher in both conditions was similar. At no point did the teacher offer ready-made answers to the students. Her role at all times was to support her students when difficulties arose (e.g. unfamiliar vocabulary, or not knowing how to use a feature of the mobile device) and to prompt her students to complete all of the activities in the instructional materials.

The fourth phase involved the completion of the knowledge posttest and the collection of students' notebooks. The posttest was the exactly the same as the pretest (week 6, one 40-minute session).

Finally, the time-on-task was the same for both conditions (440 minutes over 6 weeks) and authenticity of the treatment checks (e.g. that the teacher implemented the lessons in the two classes as planned) was made for both conditions. The first author was meeting with the teacher right after each class meeting of each condition, across the four phases, to check if the activities planned for each meeting was enacted according to the plan described above. No diversions from the planned curriculum and time framework were observed in either condition. Our study's time frame followed the actual schedule of the classes involved, and all inside and outside of the classroom activities occurred in students' actual classrooms and the school garden, respectively, in order to establish ecological validity. The idea was to examine our research questions in an authentic school context.

Data collection

For the purposes of this study, we used three different data sources. The first was the paper-and-pencil, conceptual knowledge test administered before and after the learning activities and experimental manipulation involved in the study. This test included 17 items, of which 8 were open-ended (5 of them had open-ended sub-items) and 9 were close-ended (for examples of both types of item, see Appendix 1). The items on the test were separated for analysis into four parts, each one corresponding to one of the four parts of the curriculum: (a) the parts of the flower, (b) pollinators, (c) pollination/fertilization, and (d) the interrelationship between animals and plants. One item and 2 sub-items (2A, 2B, 4) concerned the parts of the flower and its functions; 3 items and 2 sub-items (1, 12, 15, 16A, 16B) concerned pollination and pollinators; 3 items and 2 sub-items (4, 6, 7, 17A, 17B) concerned reproduction, how it works, and its importance for life; and 6 items and 4 sub-items (3, 5, 8, 9, 10, 11, 13A, 13B, 14A, 14B) concerned the interdependence of flowers and their pollinators.

The second data source involved the students' science notebooks and the third was the three aforementioned artifacts. Specifically, in the case of the notebooks, the students' responses to questions included in the teaching material at pre-specified points of the activity sequence were assessed. The focus was on the scientific accuracy of the response. In the case of the three required artifacts, the focus for each artifact was on the scientific accuracy and the completeness of the lists developed (for a sample of one of these artifacts, see Appendix 2).

Two coders independently completed all coding; Cohen's kappa for the initial coding was .92 for the tests, .89 for the notebooks, and .90 for the artifacts. The differences in the assigned codes were resolved through discussion.

Data analysis

The data analysis of the conceptual knowledge test involved quantitative methods. In particular, all student tests were scored through the use of scoring rubrics (for an example, see Appendix 1), and the resulting student performance scores (indicator of student understanding) were analyzed using (a) independent samples t-tests to compare the pretest scores for the two conditions on each part of the test and overall, (b) paired samples t-tests to compare the pretest scores and posttest scores for each condition, and (c) one-way ANCOVAs for comparing the posttest scores of the two conditions. For the latter procedure, the students' pretest scores were used as the covariate. These statistical procedures were applied to the test as a whole, as well as to each of its four parts (corresponding to the four parts of the curriculum).

The aim of the first procedure was to determine whether participants in the experimental and control conditions were comparable in terms of level of prior knowledge concerning the flower, its parts, and their functions. The aim of the second procedure was to investigate whether the learning activities undertaken in the two conditions improved students' conceptual understanding about the flower. The aim of the third procedure was to investigate whether participants in the two conditions of the study differed on the outcome measures (understanding of concepts concerning the flower, its parts, and their functions). For the ANCOVA analyses, the effect size (partial η^2) is also reported.

The scientific accuracy of students' responses at all checkpoints was also determined through the use of scoring rubrics, and the resulting scores were analyzed by using independent samples *t*-tests. The aim was to investigate whether the scientific accuracy of students' responses differed between the two conditions.

Where we made multiple comparisons in the analyses, to keep the overall probability of family-wise error (Type I error) at a target level, we applied Holm's Sequentially Selective Bonferroni Method (Holm, 1979).

All tests were scored and coded blind to participant condition. Responses in the notebooks were assessed right after the four checkpoints described above. We took the individual student as the unit of analysis. The scoring of each item, sub-item, or notebook entry involved the use of a scoring rubric that included preset criteria (expected correct answer and expected correct explanation of reasoning; for an example of scoring of test items, see Appendix 1), which were used to score whether the elements of the participant's overall response (answer and its accompanying reasoning) were correct. The scoring of the accompanying reasoning was based only on whether students provided specific concepts or evidence that were needed to support their answer, as pre-specified in the scoring rubrics. A correct answer received one point, and its corresponding reasoning (wherever requested) was scored in accordance with how many of the preset criteria were met. Each pre-specified concept or piece of evidence present in the reasoning received a half point. However, it should be noted that students received points only when they provided a correct answer and a corresponding correct or partially correct reasoning. Students received no points for a correct answer accompanied by incorrect reasoning.

The maximum score for each item, sub-item, or notebook entry varied according to the number of pre-specified elements required to be present. An individual's total score on the test was derived by adding all the assigned item and sub-item scores for answers and for explanations and reasoning, and by adjusting the total to fit on a 100-point scale for easier comparison purposes. For the notebooks, a separate total score was calculated for each of the pre-specified checkpoints of the activity sequence (points at which students were expected to reach conclusions after an activity or a number of activities).

For the analysis of the artifacts, we used qualitative procedures. Specifically, for each of the three artifacts (listing of the parts of the flower, listing of the pollinators, and listing the evidence that showed that a flower had been pollinated), we used open coding, through which we identified all of the types of list elements present per artifact. Then we calculated the corresponding prevalence among participants for each type of list entry.

Finally, two independent coders reviewed about 20% of the data. The reliability measures (Cohen's kappa) for scoring of the test was .89 and for the notebooks .87 (the sampling was taken across the pre-specified points). As for the coding of the entries of each artifact of the three, the reliability measures (Cohen's kappa) were above .95.

Findings

Research question 1

By using paired samples *t*-tests, we found that students in both conditions improved their conceptual understanding for each part of the curriculum and for the curriculum as a whole ($p < .001$ for all comparisons, which is less than .005 (0.05/10), the lowest *p*-value given by the Holm–Bonferroni method; for the mean scores and standard deviations for both conditions and for the paired samples *t*-test results, see Table 1). This implies that both conditions had a positive effect on students' understanding of concepts related to the plant flower: (a) the parts of the flower, (b) pollinators, (c) pollination/fertilization, and (d) the interrelationship between animals and plants (Figure 1).

An ANCOVA was done for students' scores on the posttest, with the pretest score as covariate and condition as between-subjects factor. For the test as a whole, we found a main effect of condition, $F(1, 43) = 18.54$ ($p < .001$, which is less than .01 (0.05/5), the lowest *p*-value given by the Holm–Bonferroni method), partial $\eta^2 = .30$. A similar pattern was found for each part of the test, separately (Table 2). These findings indicate that the mean posttest scores of the experimental group were significantly higher than the mean scores of the control group, for the test as a whole and for each part of the test separately. Given these findings and the findings of the paired samples *t*-tests, it becomes apparent that the experimental condition was more conducive to students' growth in understanding than the control condition.

Table 1. Mean scores (standard deviations) and mean differences for knowledge pre- and posttest, overall and by parts, by condition, with paired samples *t*-test results.

Part of the test	Pairwise comparisons	Mean scores (SD) Pretest	Mean scores (SD) Posttest	Mean difference (posttest–pretest)	*t*	df	*p*	Cohen's *d*
Overall	Control group	8.88 (5.05)	22.50 (7.86)	13.62	6.68	23	<.001[a]	2.04
	Experimental group	9.50 (3.86)	32.18 (7.10)	22.68	15.07	21	<.001	4.06
Part 1[b]	Control group	1.50 (1.59)	4.83 (2.76)	3.33	4.90	23	<.001	1.51
	Experimental group	1.77 (1.15)	7.09 (2.14)	5.77	10.96	21	<.001	3.17
Part 2[c]	Control group	1.08 (0.93)	3.96 (2.42)	2.88	5.78	23	<.001	1.60
	Experimental group	0.82 (0.18)	7.22 (0.47)	6.4	12.2	21	<.001	18.4
Part 3[d]	Control group	2.58 (1.86)	6.12 (2.93)	3.54	4.41	23	<.001	1.47
	Experimental group	3.45 (1.87)	8.86 (2.96)	5.41	7.71	21	<.001	2.24
Part 4[e]	Control group	1.04 (1.55)	3.75 (2.38)	2.71	4.17	23	<.001	1.23
	Experimental group	1.18 (1.71)	5.68 (2.10)	4.5	7.71	21	<.001	2.40

[a]Less than .005 (0.05/10), the lowest *p*-value given by the Holm–Bonferroni method.
[b]Part 1 focused on the parts of the flower.
[c]Part 2 focused on pollinations and pollinators.
[d]Part 3 focused on fertilization.
[e]Part 4 focused on the interrelationship between animals and plants.

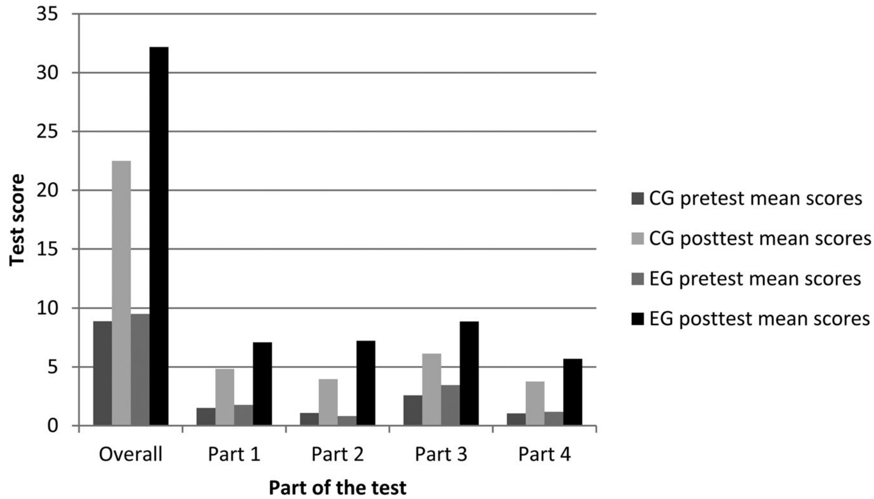

Figure 1. Mean scores on each of the parts of the study's test for both conditions.

The overall picture suggested by the comparisons in Table 2 is that the use of mobile devices for data collection during field trips by elementary school students emerges as more effective than the use of traditional means of data collection (i.e. paper-and-pencil note-taking and sketching). With regard to the different parts of the curriculum, we also see that there is a real advantage in all parts for using mobile devices rather than traditional means of data collection. A question raised at this point is why the experimental condition has a different effect on students' development of understanding than the control condition? In other words, what is the added value of using mobile devices for data collection rather than traditional means when studying the flower? We aimed to shed light on this issue in the qualitative analysis we performed for the purposes of addressing the second research question below.

Research question 2

Students' notebooks

Independent samples *t*-tests were used to compare the scientific accuracy of the checkpoint responses in the notebooks of the participants in the two conditions. For each of

Table 2. ANCOVA results for the knowledge test.

Part of the test	F	df	p	η^2
Overall	18.54	1, 43	<.01[a]	.30
Part 1[b]	9.28	1, 43	<.01	.18
Part 2[c]	21.91	1, 43	<.01	.34
Part 3[d]	10.14	1, 43	<.01	.19
Part 4[e]	8.72	1, 43	<.01	.17

[a]Less than .01 (0.05/5), the lowest *p*-value given by the Holm–Bonferroni method.
[b]Part 1 focused on the parts of the flower.
[c]Part 2 focused on pollinations and pollinators.
[d]Part 3 focused on fertilization.
[e]Part 4 focused on the interrelationship between animals and plants.

the study's checkpoints (right after completing each of the four parts of the curriculum), it was found that the experimental condition had more detailed and scientifically accurate responses than the control condition. The analysis revealed statistically significant differences (at the .01 p-level) across all checkpoints in favor of the experimental condition (for mean scores, standard deviations, and t-test results, see Table 3). It is important to notice that the results from the notebook analysis follow the same pattern as the test analysis, namely, the use of mobile devices enhanced the scientific accuracy of students' responses (Figure 2). It is reasonable to argue that the more scientifically accurate their responses in the notebook are, the better their test performance becomes (in our case, a Pearson correlation was calculated and found to be equal to 0.89 at $p < .001$). In other words, one possible explanation of the findings of research question 1 could be attributed to the better use of scientifically accurate data by the students in the experimental condition. Of course, in

Table 3. Mean scores (standard deviations) for each part of the notebook for both conditions, with independent samples t-test results.

Group	Checkpoint 1[a]	Checkpoint 2[b]	Checkpoint 3[c]	Checkpoint 4[d]
Experimental	2.58 (0.50)	9.7 (2.67)	5.92 (1.93)	8.86 (2.96)
Control	1.79 (0.41)	3.21 (1.23)	4.38 (0.82)	6.13 (2.94)
T	5.94	11.6	3.6	3.14
P	<.01[e]	<.01	<.01	<.01
Cohen's *d*	1.73	3.35	1.04	0.93

[a]Checkpoint 1 assessed the scientific accuracy of the notes included in students' notebooks for Part 1 of the curriculum (focused on the parts of the flower).
[b]Checkpoint 2 assessed the scientific accuracy of the notes included in students' notebooks for Part 2 of the curriculum (focused on pollinations and pollinators).
[c]Checkpoint 3 assessed the scientific accuracy of the notes included in students' notebooks for Part 3 of the curriculum (focused on fertilization).
[d]Checkpoint 4 assessed the scientific accuracy of the notes included in students' notebooks for Part 4 of the curriculum (focused on the interrelationship between animals and plants).
[e]Less than .01 (0.05/5), the lowest p-value given by the Holm–Bonferroni method.

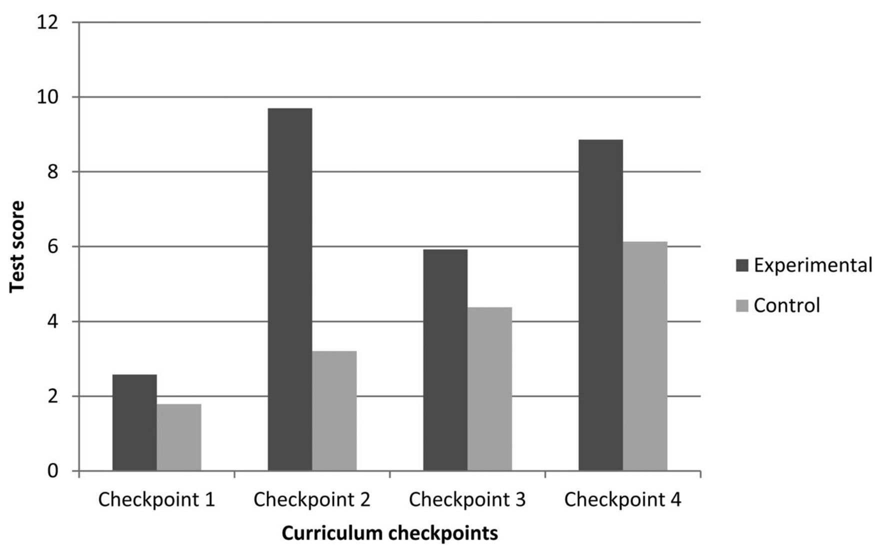

Figure 2. Mean scores on each of the parts of the notebook for both conditions.

the case of the experimental condition, this data collection process did not occur only during the field trip; it was enriched by the ability to revisit the material collected on the field trip (i.e. videos and photos). On the other hand, the students in the control group did not have the chance to revisit the phenomenon through similar materials. They only had access to the notes they had taken and sketches they had made during the field trips which, as explained above, were of lower accuracy/resolution than the photos and videos collected by students of the experimental condition. Hence, for the students of the control group, the possibility of enhancing the scientific accuracy of their responses was quite low (if not impossible).

Students' artifacts

For the artifact analysis we contrasted the three different artifacts, namely, the 'flower parts', 'pollinators', and 'pollinated flowers' artifacts, that each condition had developed. In the case of the 'flower parts' artifact, as shown in Table 4, students who used mobile devices managed at the end to include a higher number of flower parts (across a higher number of students) than students of the control condition, who used as a resource only the sketches they made and notes taken during their observations at the field trips.

From Table 4 we further concluded that the students in the experimental condition appeared to provide more precision concerning the numbers of certain parts (e.g. petals and sepals) and to identify parts that usually, because of their small size, are not evident during an observation (e.g. pollen). The latter was not an issue for the experimental condition students because the mobile devices allowed them to zoom-in significantly at any (re-)visit of the digital materials.

For the 'pollinators' artifact, the students in both conditions managed to identify and list about the same pollinators (Table 5). The only significant exception was that a significant number of students in the experimental condition (8) identified the wind as a

Table 4. Results for the 'parts of the flower' artifact for both conditions.

Part of the flower	Experimental condition[a] % of responses including this part (*N*)	Control condition[b] % of responses including this part (*N*)
Petals	100 (24)	100 (24)
Number of petals	87.5 (21)	66.67 (16)
Color of petals	100 (24)	100 (24)
Texture of petals	12.5 (3)	16.67 (4)
Shape of petals	100 (24)	83.33 (20)
Sepals	91.67 (22)	20.83 (5)
Number of sepals	62.5 (15)	0 (0)
Stem	100 (24)	91.67 (22)
Stamen	79.17 (19)	75 (18)
Filament	100 (24)	75 (18)
Anther	100 (24)	75 (18)
Pollen	62.5 (15)	0 (0)
Carpel	79.17 (19)	33.33 (8)
Stigma	66.67 (16)	33.33 (8)
Style	79.17 (19)	33.33 (8)
Ovary	62.5 (15)	0 (0)
Ovule	91.67% (22)	0 (0)
Odor	100 (24)	100 (24)

[a]The overall sample size was 24. The parts of the flower were documented from a video taken with a mobile device.
[b]The overall sample size was 24. The parts of the flower were documented from a sketch made by the students during the field trip.

Table 5. Results for the 'pollinators' artifact for both conditions.

Possible pollinators	Experimental condition[a] % of responses including this pollinator (*N*)	Control condition[b] % of responses including this pollinator (*N*)
Fly	87.5 (21)	83.33 (20)
Butterfly	100 (24)	41 (10)
Ant	62.5 (15)	66.67 (16)
Snail	54.17 (13)	50 (12)
Bee	100 (24)	100 (24)
Tits	62.5 (15)	41 (10)
Birds	50 (12)	58.33 (14)
Ladybug	12.5 (3)	0 (0)
Wind	33.33 (8)	0 (0)
Mosquito	20.83 (5)	33.33 (8)

[a]The overall sample size was 24. The pollinators were identified from videos and photos taken with a mobile device.
[b]The overall sample size was 24. The pollinators were identified through real-time observations (and note-taking) during the field trip.

pollinator, whereas no students in the control condition did so. Again, this was achieved because of certain affordances provided only by the mobile devices (e.g. use of slow motion and observation of small things carried by the wind).

For the 'pollinated flowers' artifact, it was found that more students in the experimental condition managed to identify pollinated flowers and provide the necessary evidence than the control condition students (Table 6). Additionally, the experimental condition students managed to list a type of evidence that was missed by the control condition students, namely, the presence of dried pollen on the petals.

The analysis of the artifacts points to several affordances that mobile devices provide that essentially explain the reasons the two conditions were found to vary in amount of learning.

Discussion and implications

As illustrated in the analysis of the data, the main finding of this study is that the experimental condition (i.e. use of mobile devices for data collection) was more conducive to students' learning than the control condition (i.e. use of traditional means of data collection). Specifically, the analysis of the data showed that the use of mobile devices, especially their authentic data recording affordance through the use of the photo and video capturing tools, enhanced fourth graders' learning about the flower, pollinators, fertilization, and the interrelationship between animals and plants, more than the use of traditional means of data collection (i.e. sketch-making, use of magnifying glasses, and note-taking) (research question 1). This finding is important not only because of the added value that the mobile

Table 6. Results for the 'pollinated flowers' artifact for both conditions.

Evidence that the flower had been pollinated	Experimental condition[a] % of responses including this evidence (*N*)	Control condition[b] % of responses including this evidence (*N*)
Withered petals	83.33 (20)	33.33 (8)
Dried pollen	37.5 (9)	0 (0)
Lack of petals	62.5 (15)	20.83 (5)

[a]The overall sample size was 24. Evidence that the flower had been pollinated was collected from videos and photos taken with a mobile device.
[b]The overall sample size was 24. Evidence that the flower had been pollinated was collected from observations (and note-taking) during the field trip.

device affordance of authentic data recording brought to students' learning, but also because the enhancement of learning concerned concepts that students traditionally have a hard time understanding (Schussler, 2008). This is in line with the findings of other studies using the same affordance and targeting concepts in the plant biology domain (e.g. Lai et al., 2007; Song et al., 2012). However, it should be noted that this study followed an unconfounded experimental design, without changing the school environmental settings (i.e. use of the actual science class and the school garden) and routines (e.g. same time schedule, science books, curriculum, and paper-and-pencil science notebooks) for establishing high ecological validity. This enables the results of this study to show clearly that the data-capturing affordance of the mobile devices benefits students' learning, when an experiential learning activity (e.g. field trip) is at the center of the learning process, more than the data-capturing affordance of traditional means does.

Moreover, this finding is aligned with the theoretical grounds set for our study. Specifically, we argued that the enhancement of learning through the use of the data recording affordances of both conditions would result from *extending* students' memory and processing time (Smart, 2010) and enabling them to *re-see* their data (Girod et al., 2003). However, we conjectured that this *extension* of the memory and *re-seeing* of the data would be more enhanced in the case of the mobile devices than with the use of traditional means of data recording (i.e. sketching and note-taking), because only the recorded data of the mobile devices offer access to the original real-world objects and phenomena, which ensures the highest possible accuracy and resolution of the object or the phenomenon under study. With traditional means of observation and data recording (i.e. sketching and note-taking), there is a high possibility of recording observations or data with lower accuracy or poorer resolution, especially for young students (Louca & Zacharia, 2008, 2012; Louca et al., 2011). Given the findings of our study, this conjecture, which was based solely on theoretical grounds, appears to turn into a valid hypothesis grounded on empirical underpinnings as well.

The study's notebook and artifact analyses also confirmed the aforementioned finding and the validity of our theoretical underpinnings. Specifically, the qualitative analysis of the notebook responses and artifacts illustrated three main findings: (a) the notebooks of the students in the experimental group included more detailed responses (e.g. more detailed descriptions of observations, which were also accompanied by printed photos) than the notebooks of the students of the control group; (b) the notebooks and artifacts of the students in the experimental group provided greater precision (e.g. concerning the numbers of certain parts of the flower, such as petals and sepals) and scientific accuracy (e.g. more parts of a flower were identified). The slow motion and zooming capabilities of the mobile devices helped in this regard, because they supported students in making more precise observations by zooming in on any of the parts of the object or phenomenon under study, or slowing down the enactment of a phenomenon (although students in the control condition could use magnifying glasses, these had a limited resolution, and there was no way for them to slow things down in order to see in greater detail what was happening); and, (c) only students in the experimental condition managed to identify aspects of the phenomena under study that were really hard to see or identify during real-time observations (the slow motion and zooming capabilities helped in this regard). Such observations became a reality after the students *re-examined* and *re-saw* the phenomena under study through videos (e.g. only students in the experimental condition identified the wind as a pollinator) (research question 2). These particular findings also explain why the participants of the experimental condition performed better on the knowledge posttest than the participants in the control condition (i.e. better notes and artifacts resulted in better performance in the test).

Furthermore, given the long duration of the activity sequence (4 weeks long with 80-minute sessions per week), the *extended* memory and *re-seeing* capability theoretical background appears to gain stronger grounds. All of the aforementioned findings appear to make perfect sense within this theoretical context, because the students had opportunities to revisit and re-examine the authentic data collected at any time throughout this four-week period. This conclusion has a significant implication for classroom practices when a science unit that includes experiential learning and data collection spreads out over several weeks. According to our findings, in such cases, the authentic data recording affordance of mobile devices should be preferred over traditional means of data recording (i.e. sketching and note-taking) because this can *extend* students' memory and allow them to revisit, *re-examine*, and *re-see* the authentic data collected at any time.

The findings of our study, similar to other studies with elementary school students and situated in a variety of science education contexts (e.g. Cristol et al, 2015; Klopfer et al., 2012; Liao et al., 2011; Liu et al., 2012; Looi et al., 2011; Sha et al., 2012; Song et al., 2012), provide evidence that the use of mobile devices has the potential to support student science learning, development of conceptual understandings about specific science concepts, and related skills (for a review, see Liu, Scordino, et al., 2014). As such, our study contributes to existing literature regarding the impact of the use of the data recording affordance of mobile devices in science teaching and learning, through an unconfounded experimental design, and strengthens the argument about its use as a learning scaffold in science education, especially when experiential science learning and data collection are involved, and offers specific implications for curriculum design and future research.

Moreover, this study provides a concrete example of the use of mobile devices in an elementary school in the context of a unit about plants carried out at the intersection of formal (i.e. school classroom) and informal environments (i.e. school garden). More such authentic classroom case studies are needed in a variety of learning environments and contexts in order to obtain a more diverse picture of the use of mobile devices in science teaching at the elementary school. We therefore suggest that future research should focus on examining the added value of each type of mobile device affordance in authentic learning contexts. Based on the findings of our study and limitations connected to its design (i.e. focusing on a single unit; not exploring the role of the teacher), we suggest that future research address the following questions: What implications does the use of specific affordances of mobile devices hold for science learning in various formal and informal contexts? How does the use of specific affordances of mobile devices in science teaching affect the role of the teacher? Given that the use of certain mobile device affordances affects student learning in different ways, what should mobile device-based curricular materials look like?

Obviously, research in this domain is crucial for better understanding how students interact with mobile devices and how the affordances of such technologies can be used in the design of mobile-enhanced curriculum materials and more essentially, to support science learning. Further research in the same direction as that of our study is recommended in order to determine the characteristics of design frameworks associated with mobile science learning, and to examine the complex processes by which students engage in and construct scientific knowledge through the use of mobile devices, which are both currently missing from the domain literature.

Disclosure statement

No potential conflict of interest was reported by the authors.

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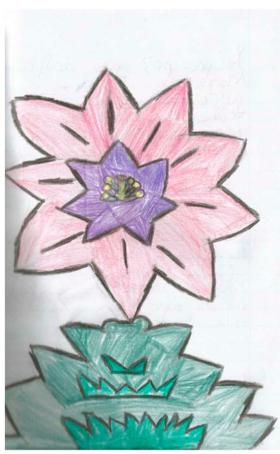
Appendix 1. Sample of close-ended and open-ended items from the paper-and-pencil test administered before and after the learning activities in the study

Item	Expected answer—scoring rubric (assigned points)	Example of an experimental group participant's answer on the posttest (score)
12. Pollen is produced in: a. stamen b. ovule c. stigma d. petal e. pistil	a. stamen (1) Total score: 1	a. stamen (1) Total score: 1
15. Pollen from one flower could be transferred to another by: a. the wind b. insects c. birds d. humans e. all the above	e. all the above (1) Total score: 1	b. insects (0) Total score: 0
16. Here is a photograph of a flower and a bee. a. Explain what the bee does. b. Is the flower benefitting from the bee's presence? 	a. The bee is looking for food/nectar (1). Pollen is attached to its body (1) b. The flower gets the pollen picked up from other flowers (1), which might lead to the pollination of the flower (1) Total score: 4	a. The bee collects pollen from the flower (1) b. The flower is pollinated (1) Total score: 2

Appendix 2. Sample of a student artifact from the control condition

Task	Expected information to be included in an answer	Example of an artifact	Information included in an actual answer[a]
Choose one flower and draw it with as many details as possible and then describe it in as much detail as possible.	(1) Petals (2) Color of petals (3) Number of petals (4) Texture of petals (5) Shape of petals (6) Odor (7) Sepals (8) Number of sepals (9) Stem (10) Stamen (11) (Male part) (12) Filament (13) Anther (14) Pollen (15) Carpel (16) (Female part) (17) Stigma (18) Style (19) Ovary (20) Ovule (21) Dimensions	 (Student 8, control group)	(1) Petals (2) Color of petals (3) Shape of petals (4) Odor (5) Stem (6) Stamen (7) (Male part) (8) Filament (9) Anther (10) Pollen (11) Carpel (12) (Female part) (13) Stigma (14) Style (15) Dimensions

[a]This information was included in either the sketch or the description.