Article

Journal of Educational Computing Research
2019, Vol. 57(6) 1400–1435

DOI: 10.1177/0735633118794515
journals.sagepub.com/home/jec
SAGE

Developing Elementary Students' Digital Literacy Through Augmented Reality Creation: Insights From a Longitudinal Analysis of Questionnaires, Interviews, and Projects

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Abstract

This mixed-method case study investigated digital literacy (DL) development among 32 elementary-level students who created multimodal, contextual, and interactive augmented reality (AR) artifacts in a 20-week after-school program in Northern Taiwan. The instructional design combined situated and spiral learning experiences with AR, implemented through a blended learning environment. Data sources included pre- and post-program digital learning student surveys, student and teacher interviews, classroom observations, and AR artifact assessments. Results indicated statistically significant increases with moderate effect sizes in five areas of students' DL practices: information management; collaboration; communication and sharing; creation; and evaluation and problem-solving. Students did not increase DL in one area: ethics and responsibility. The situated and spiral learning-by-design approach

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offered increasingly complex AR creation projects in which students developed and transferred their DL. The face-to-face and online learning settings offered multiple ways to collaborate and facilitated the development of students' DL. The AR technology enabled students to develop DL through designing AR using three types of representation features: multimodal, interactive, and contextual. Practical and theoretical implications for adapting or enhancing this instructional design in future DL programs and for future research are discussed.

Keywords

augmented reality, digital literacy, elementary school students, project-based learning, learning by design

With the rapid development of information communication technologies (ICT), the required competencies for the workforce in the 21st century are fundamentally different from those in the 20th century (Shute & Becker, 2010). People need digital literacy (DL) not only to participate in and benefit from digital opportunities in society but also to reduce exposure to risks and threats in everyday digital environments related to device protection, personal data and privacy protection, and health and well-being (Vuorikari, Punie, Carretero Gomez, & Van Den Brande, 2016). Despite broad claims that current students are digital natives (Prensky, 2001), technology skills are not universal among all young children (Bennett & Maton, 2010; Bennett, Maton, & Kervin, 2008). Thus, it is essential to cultivate youths' DL to help them effectively and creatively use existing ICT in our technology-driven society (Ferrari, 2012; Ng, 2012).

Several explorations of teaching DL in classroom settings have articulated advantages for learners who participate in multimodal group projects that enable students to reinforce their DL by using digital tools for communication, collaboration, creation, and problem-solving in a social, interactive context (Hafner, 2014; Kimbell-Lopez, Cummins, & Manning, 2016; Price-Dennis, Holmes, & Smith, 2015). Learning through engagement in group projects creates a socially situated learning experience (Sadik, 2008). Also, we can implement spiral learning by involving students in a series of projects with increasing complex tasks, which Vemuru, Khorbotly, and Hassan (2013) referred to as a "spiral learning" model. This spiral learning model is a pedagogy that demands students transfer knowledge and skills from preceding learning tasks to subsequent, more difficult tasks. Examining the trajectory of knowledge development across a set of activities provides a holistic view of spiral learning. However, prior studies related to DL and multimodal artifact creation primarily focused on students' development of a single digital artifact rather than multiple, sequential opportunities for artifact creation. To help students establish transferable DL knowledge, skills, and attitudes (Martin & Grudziecki, 2006), a spiral learning approach that engages students in creating multiple projects with increasing complexity may yield better learning outcomes than a single project.

Augmented reality (AR) is an emerging technology that overlays virtual objects in the real world and allows users to concurrently see the real world with virtual objects (Azuma, 1997), yielding educationally valuable, multimodal, contextual, and interactive representations (Dunleavy & Dede, 2014; Kolsch, Bane, Hollerer, & Turk, 2006; Santos et al., 2014). Research on the affordances of AR for DL education is nascent (Hagerman & Spires, 2017). Existing studies predominantly articulate the instructional effectiveness of AR content *consumption* rather than AR-based content *creation* (Akçayır & Akçayır, 2017; Laine, Nygren, Dirin, & Suk, 2016; Wu, Lee, Chang, & Liang, 2013). Yet, a digitally literate person must effectively create and apply digital content (Jacobs, Castek, Pizzolato, Reder, & Pendell, 2014; The New London Group, 1996). Research has yet to establish the instructional effectiveness of students' AR content creation and their DL development.

Thus, this study developed and examined a pedagogical approach mixing situated and spiral learning approaches with AR to facilitate DL development at the elementary school level. The pedagogy was designed based on the social constructivist DL framework (Reynolds, 2016) and spiral learning theory (Gagne, 1968), which informed the instructional design to arrange learning tasks sequentially in a project-based learning (PBL) environment.

Literature Review

Defining DL in a Social Constructivist Environment

DL refers to a series of knowledge, skills, and attitudes required to use ICT and digital media to solve problems and create content (Ferrari, 2012). After analyzing 15 different conceptual and pedagogical frameworks for the development of DL, the European Commission's framework (Ferrari, 2012) was selected to frame our conceptualization of DL with the following key competencies: (a) information management, (b) collaboration, (c) communication and sharing, (d) creation of content and knowledge, (e) ethics and responsibility, (f) evaluation and problem-solving, and (g) technical operations. Many research efforts have sought to improve DL among K-12 learners through digital content consumption, creation, and communication (Chou, Block, & Jesness, 2012; Hagerman & Spires, 2017; Kimbell-Lopez et al., 2016; Moore, 2013; Ng, 2012). Multimodal creation and communication are particularly essential for DL development in the 21st century (Lotherington & Jenson, 2011). Hill (2014) empirically established the vital role of composing and creating a multimodal artifact in developing K-12 DL education. Yet, Reynolds (2016) proposed that DL needs to be socially constructed, such as through a task-driven, digital artifact design/creation approach with collaborative peer inquiry and guided discovery. Reynolds' framework defined DL as six practices: (a) create, (b) manage, (c) publish, (d) socialize, (e) research, and (f) surf/play. Reynolds' DL framework excluded "technical operation" to distinguish DL from traditional computer skills (Bawden & Robinson, 2002, p. 738). Reynolds' framework further positioned that DL education should be pedagogically centered around task-driven practices in a social constructivist environment, such as when a group of students apply a digital tool in support of a real project. Therefore, our study synthesized Reynolds' concept of social constructivist task-driven practices with the European Commission's DL framework and conceptually defined DL as the following six practices:

1. Information management: Plan, identify, locate, access, retrieve, store, and organize information meaningfully and systematically;
2. Collaboration: Collaborate with others in online and face-to-face contexts to work toward specific goals;
3. Communication and sharing: Exchange information using online tools, considering privacy, safety, and netiquette;
4. Creation: Retrieve and reorganize previous knowledge and integrate obtained information to construct new knowledge or digital artifacts using technology and media;
5. Evaluation and problem-solving: Identify appropriate technology and media to solve problems, search resources through appropriate digital means, and evaluate obtained information critically; and
6. Ethics and responsibility: Behave in an ethical, responsible, legally aware way when participating in digital interactions.

The combination of the European Commission's and Reynolds' frameworks enables an integrated lens to conceptually categorize students' learning processes and to comprehensively measure students' DL development into separate practices when participating in digital artifact creation within a social constructivist environment.

Learning By Design Using Situated and Spiral Learning

Situated learning acknowledges the crucial role the situational context has on learning (Lave & Wenger, 1991). Students' learning is a product of the context, activity, and culture within which it is developed and used (Brown, Collins, & Duguid, 1989). Knowledge construction can be situated in a socially interactive and problem-centered environment (Stein, 1998). Baytak and Land (2011) established the promising effectiveness of fifth graders' knowledge-building through situated learning activities in a learning-by-design context. The students effectively developed programming abilities within a short time frame by designing a computer game. In a multimodal learning-by-design context, learning results from knowledge processes that apply multimodal media to externalize thinking (Cope & Kalantzis, 2015). Further, learning by design has effectively enabled development of creativity (Bonnardel & Zenasni, 2010) and problem-solving skills (Akcaoglu & Koehler, 2014). Several DL practices (e.g., information management, communication, and collaboration) also have been contextually developed within a collaborative artifact design process (An, 2016). Thus, we adopted the concept of situated learning to reflect the contextualization of learning that is facilitated by collaborative inquiry and guided discovery.

A spiral curriculum, proposed by Bruner (1960), emphasized a continual deepening of a learner's understanding of basic concepts of a topic through learning to use them in progressively more complex forms. Bruner suggested that curriculum should revisit these basic concepts repeatedly, increasing the degree of content complexity, to help learners reinforce and solidify the breadth and depth of learning outcomes. In other words, early learning outcomes serve as building blocks that assist learners in categorizing relevant features of concepts and then judiciously transferring previously obtained knowledge and skills to solve new problems in different contexts. Baytak and Land (2011) indicated that the learning-by-design process offers natural conditions for students to need to learn more to further improve their artifact designs. Baytak and Land also suggested an iterative learning process in which the knowledge and skills developed from preceding activities might advance students' design capacity in subsequent tasks, which corresponds with our conception of embedding spiral learning in learning-by-design projects. The combination of spiral learning and PBL has been empirically proven effective in higher education contexts for helping college students reinforce their learning gains (DiBiasio, Comparini, Dixon, & Clark, 2001; Jaime et al., 2016; Vemuru et al., 2013). However, this approach is nascent at the K-12 level as well as for DL education. Therefore, our study adopted the spiral learning-by-design approach to probe how students develop their DL when creating AR artifacts through spiral project experiences in a social constructionist setting.

AR Artifact Creation in Educational Settings

Many studies have reviewed AR applications for educational purposes at different educational levels (Akçayır & Akçayır, 2017; Cheng & Tsai, 2013; Klopfer & Squire, 2008; Laine et al., 2016; Saidin, Halim, & Yahaya, 2015; Santos et al., 2014; Wu et al., 2013). Some studies have shown the incorporation of AR technology into K-12 education effectively reinforces students' learning achievement, motivation, and engagement (Akçayır & Akçayır, 2017; Chiang, Yang, & Hwang, 2014a). In addition, students' abilities to communicate and interact also improved when learning with AR. For example, Chiang, Yang, and Hwang (2014b) discovered an AR-based inquiry learning activity effectively promoted peer interaction and communication among fourth graders in a knowledge construction process. Students were situated in a natural context that required them to exchange opinions to solve the AR-based inquiry problems. While studies indicate AR activities can benefit K-12 education, these findings are primarily based in instructional pedagogy that position students as consumers of AR content produced and arranged by researchers or instructors (Klopfer & Squire, 2008), as opposed to positioning students as creators of AR content. Fewer studies explore the benefits of a "learner-as-creator" approach, which often has been used in game design.

For example, Kafai (2006), inspired by constructionism and learning by making (Papert, 1980), argued that the game design process increases opportunities for students to improve technological fluency and construct knowledge. Creating AR artifacts is a similarly complex design process that could lead to similar technological fluency. For example, students as AR designers need to consider (a) what mode of representation, information, or narrative should be included to effectively convey the creators' ideas (multimodal aspect); (b) what contexts necessitate virtual objects to provide richer and more intuitive content with which users can interact (contextual aspect); and (c) how to apply AR's technological features to design interactive user experiences (interactive aspect; Dunleavy & Dede, 2014). Designers who integrate these aspects take advantage of AR's multimodal, contextual, and interactive representation features. Integrating AR technology in a learning-by-design pedagogy at the K-12 level was pioneered by Mathews (2010) who found high school students' new literacies could be facilitated through engagement in AR-based game design. Students connected authentic community issues to their learning in AR-based game development. They used the real-world connection along with interactive and multimodal representation AR features in game development. Ultimately, students developed collaboration, communication, and problem-solving skills through the situated, collaborative game development project. In another case study with high school students, Bower, Howe, McCredie, Robinson, and Grover (2014) combined AR creation with a learning-by-design approach and found students developed higher order thinking capabilities, creativity, and critical analysis.

The Mathews (2010) and Bower et al. (2014) studies indicate promise for developing DL through combining AR creation activities through a learning-by-design pedagogy. However, previous research measured students' learning outcomes qualitatively, focused on high school participants, examined students' single instances of AR creation, and put less emphasis on the affordances of AR technology in learning-by-design pedagogy. Thus, there is a need for research to diversify learning assessment methods and student populations to fully discover the educational potential of K-12 students as AR designers for developing students' DL. Further investigation is warranted to determine (a) the effectiveness of spiral learning when students create multiple AR artifacts with increasing degree of complexity over time and (b) the contribution of spiral learning to DL education.

Based on the literature, we developed an instructional design framework that enabled situated and spiral learning with AR creation to guide DL education at the elementary school level. This framework was verified through a previous proof of concept involving AR artifact creation in elementary students' DL development (Hsu, Zou, Hughes, & Wang, 2018). The following research questions guided the current study:

1. How do elementary students develop DL through situated and spiral learning with AR creation?
2. How does the focus on AR technology in the learning-by-design context influence students' DL?

Method

Case Study

This mixed-methods explanatory case study (Yin, 2009) explored how elementary students developed DL in one Taiwanese after-school program that implemented our instructional design framework. The case study approach, involving the collection of multiple data sources, enables an in-depth understanding of students' learning experiences and social interactions in the program and facilitates triangulation of the research findings (Creswell, 2013).

Participants

The participants ($n = 32$) included twenty-four 11-year-olds (15 boys and 9 girls) and eight 12-year-olds (5 boys and 3 girls) who enrolled in the 20-week after-school program (2 hours per week) in an elementary school in Taipei, Taiwan. All students were from middle-class families and were familiar with ICT through daily life experiences and from 2 to 3 years of school computer education. All student participants and their parents or guardians consented to participate according to university Institutional Review Board stipulations, and no incentive was provided. This after-school program was taught by two experienced computer science teachers respectively with 5 and 7 years of experiences of teaching DL. They were also well informed by the first author about the research design and the DL framework used this study.

Instructional Design

Blended learning environment. The instructional design of this 20-week after-school program aimed to develop students' DL through situated and spiral learning experiences in a blended learning environment (see Figure 1). An education social media platform, Edmodo, was used as a digital platform to support student learning beyond the physical classroom. On Edmodo, teachers deployed course resources, including software and hardware tutorials and learning activities, before face-to-face classroom meetings. Students were asked to watch tutorials and complete learning activities via Edmodo. Also, teachers prompted students to actively ask questions, share knowledge, and make comments on peers' posts. In the face-to-face setting, students worked in groups to practice multimedia skills and create AR artifacts using Aurasma AR platform (http://aurasma.com),[1] while teachers facilitated scaffolding with guided discovery (Akcaoglu & Koehler, 2014).

Learning activities featured situated and spiral learning. To implement situated learning, students were grouped to participate in each activity to enable social interactions and participate in authentic learning activities. For example, one activity grouped students to practice photography by taking campus landscape photos. Students had hands-on experiences in photography and naturally interacted with group members. After class, their photos were showcased on Edmodo, which enabled online peer interactions and exchanges of photography knowledge and skills. This program's learning tasks were ordered with increasing difficulty to implement a spiral learning model (see online Appendix A).

In Phase 1 (online Appendix A), students learned basic knowledge and skills required to create AR artifacts in the subsequent phases. In terms of knowledge

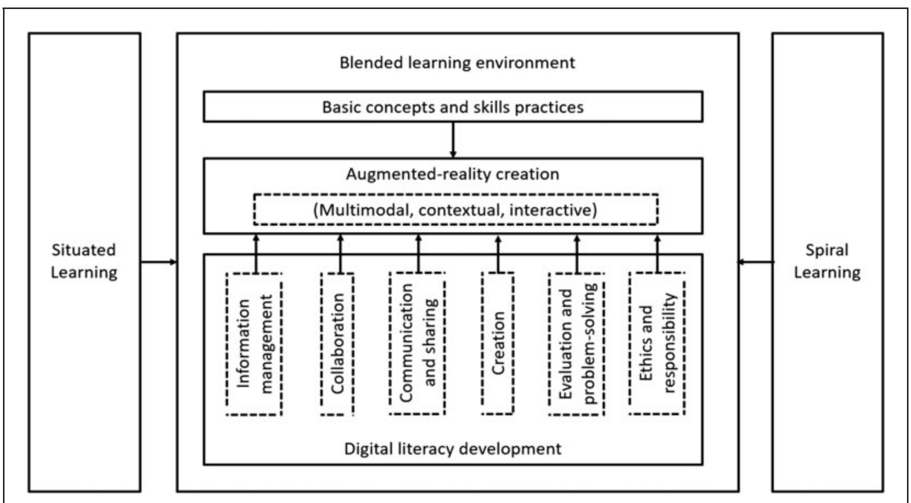

Figure 1. This study's instructional design framework.

concepts, students developed knowledge of information searching, evaluation, and management; and knowledge of Internet ethics, responsibility, privacy, safety, and netiquette. In terms of digital skills, students participated in several campus-based, collaborative learning activities, including photography, video recording, and multimedia editing. They also enacted information search and evaluation strategies in researching a controversial topic. Moreover, students' photography and video recording products were published on Edmodo to stimulate online discussion.

In Phase 2 and Phase 3, as shown in online Appendix A, students had two individual AR creation tasks, with increasing degrees of complexity, enabling learners to gradually reinforce and consolidate previous learning gains. In this study, AR artifact creation refers to using AR technology as a platform to assemble multimodal information (e.g., text, picture, video, audio, and animation) to represent a creator's ideas in a contextual and interactive way (Kolsch et al., 2006; Santos et al., 2014). The integrated multimodal information then becomes concurrently visible on real objects through the screen of Internet-connected mobile devices using an AR application (Azuma, 1997). For example, students created an AR student ID, which allowed students to comprehensively integrate knowledge and skills learned from the first phase while also representing their self-identity in a multimodal, contextual, and interactive way (see Figure 2). Given the complexity of creating an AR artifact, students were taught how to use a mind map to plan the structure of their AR artifact.

In the AR storytelling project, students revisited and applied their knowledge and skills obtained from creating their AR student ID. The creation of an AR storytelling artifact required students to sequentially present images as other AR image triggers communicated a meaningful story. For example, a student's AR story combined texts, figures, videos, and data from professional websites to explain how to take care of a cat in each stage of its life (see Figure 3). Readers/users scanned different images in the story that triggered the augmented information about cat care tips.

For Phase 4, as shown in online Appendix A, students comprehensively synthesized and integrated knowledge and skills learned in the previous three phases and collaborated with peers to create the final project, building an AR Campus Tour Guide System for the students' campus. The AR Campus Tour Guide System artifact would be officially adopted as a tool to assist guests and new students in learning about their campus. Students formed their own groups, took pictures of different locations on campus, and conducted peer students' and teachers' interviews in terms of campus life and school history. Then, students edited the multimodal information and assembled them to build the AR Campus Tour Guide System (see right portion of Figure 4). There were six locations on campus with attached image triggers (see left portion of Figure 4) that users could scan to see the augmented content through the AR Campus Tour Guide System on Aurasma, an AR application for mobile devices.

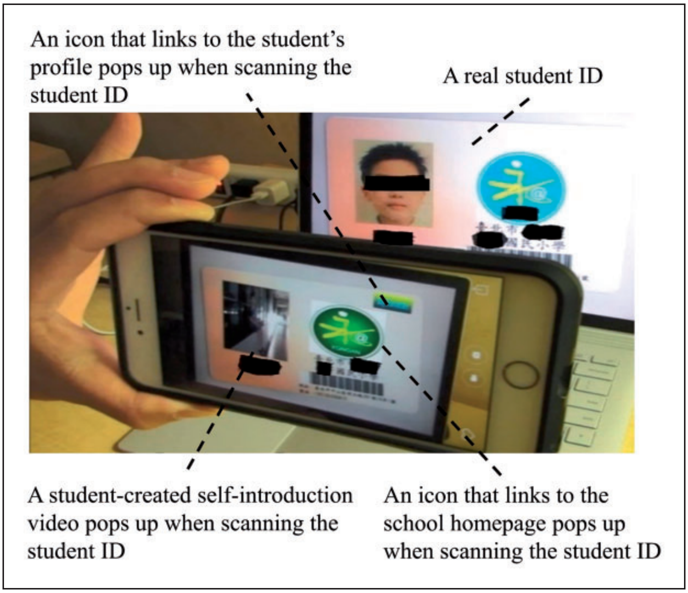

Figure 2. Example of AR student ID artifact.

Instrument, Data Collection, and Analysis

Questionnaire. To probe students' DL development, this study examined the six practices conceptualized earlier as DL: information management, collaboration, communication and sharing, creation, evaluation and problem-solving, and ethics and responsibility. Each practice was measured using pre- and post-test questionnaires, adapted from the survey used in the Ikanos project of the Basque Government (Spain) (2017) with a 5-point Likert scale. The original English version was translated to Chinese by the first author and back-translated by the second author to ensure reliability and validity of the Chinese-translated items. To evaluate the creation and collaboration aspect, we adopted six and five items respectively from the survey used by Jeng and Tang (2004) and Lin and Wang (1994) that had already been used in K-12 studies for evaluating learning performances in a digital learning environment (Hsiao, Chang, Lin, & Hu, 2014; Lai & Hwang, 2014; Wang, Huang, & Hwang, 2016). We made slight modifications of the items to match our participants' cognitive levels and life experiences. The DL test items were then examined by two experienced teachers and revised by the first author in accordance with the teachers' feedback. The final survey items and Cronbach's α value of each of the six practices is reported in online Appendix B. The students' pre- and post-questionnaire data were analyzed using paired-sample t tests to understand students' changes in the

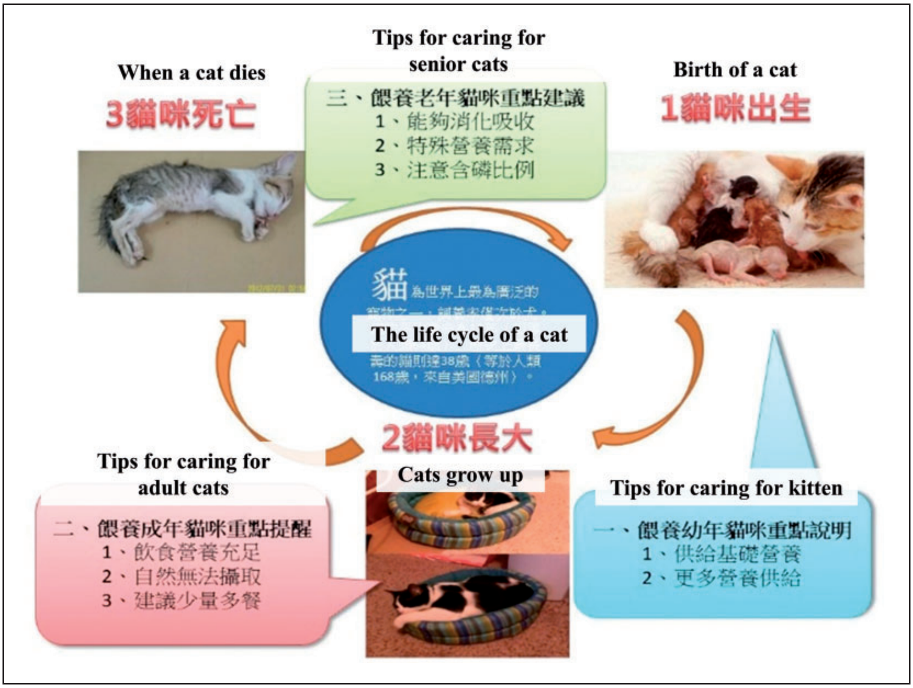

Figure 3. Example of AR storytelling artifact: How to take cats from birth to death.

six competencies of DL: information management, collaboration, communication and sharing, creation, evaluation and problem-solving, and ethics and responsibility.

Interview and observation. Both teachers were interviewed during and after the program (Weeks 8, 11, 14, and 20) to investigate how they perceived students developing DL as the program progressed with teachers' scaffolding, peer interaction, and engagements within the instructional design framework. Questions probed changes in students' DL practices, the role of AR creation and DL, social and group interactions, and students' application of previous learning in new activities. We randomly invited 16 students to participate in post-program interviews to understand how they perceived their DL development through social interaction and creating ARs. Questions probed their perceptions of DL and its six aspects, the role of AR creation and social and group interactions with DL development, and students' application of previous learning in new activities.

The students' learning activities in the classroom and on Edmodo were observed to better understand their situated and spiral learning processes.

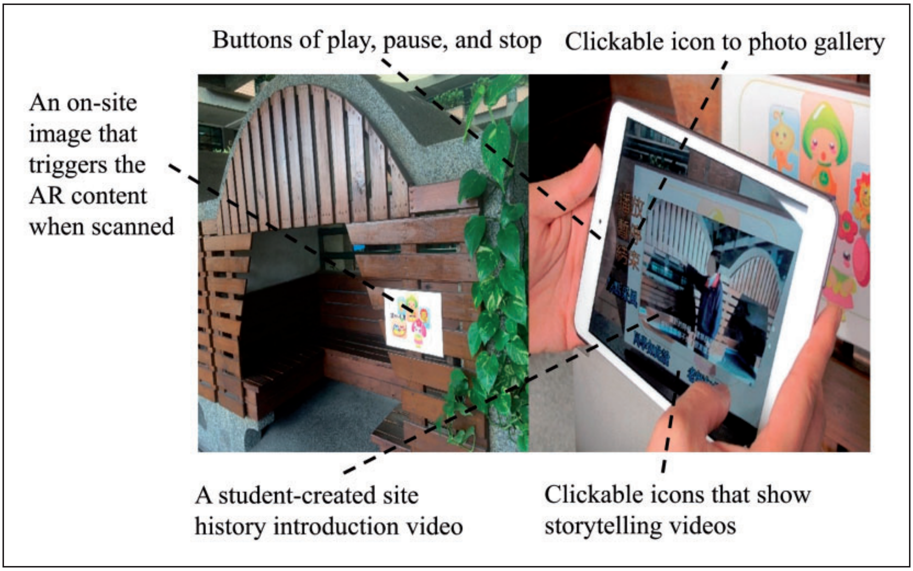

Figure 4. Example of the AR Campus Tour Guide System.
AR = augmented reality.

Our observation protocol focused on capturing the students' behaviors that manifested the co-construction and transfer of knowledge in different contexts with increasing sophistication. The development of the observation protocol was theoretically driven by the DL frameworks (Ferrari, 2012; Reynolds, 2016), concurrently referring to a validated Cooperative Learning Observation Protocol (Kern, Moore, & Akillioglu, 2007). The Cooperative Learning Observation Protocol articulated its applicability in observing group learning activities (Raphael, Bachen, & Hernández-Ramos, 2012; Salehizadeh & Behin-Aein, 2014) and was applied to observe elementary students' behaviors in a group design project setting (Luo, 2015). The observation protocol was reviewed by the two program instructors to ensure its appropriateness. The classroom observations were conducted by the first author during the program (Weeks 5, 10, 13, and 17), while the Edmodo observations were performed on a weekly basis by the first author.

The interview and observation data analysis aimed to verify and triangulate the data interpretation of the students' self-reported DL questionnaires through applying theory-driven codes (DeCuir-Gunby, Marshall, & McCulloch, 2011). The data were coded using a priori codes theoretically generated from a review of previous studies (Bruner, 1960; Ferrari, 2012; Lave & Wenger, 1991; Reynolds, 2016) by the first author. The coding results were checked with the

Table 1. Table of Codes, Number of Coded Data, and Examples of Interview and Observation Data.

Code	*N*	Example
Situated learning experience	24	We could not always find the appropriate time to have a face-to-face meeting, so we continued unfinished works at home and kept connected on Edmodo.[a]
Spiral learning experience	18	I learned some skills to present AR layouts to highlight a topic, inspired by my peers. I used this way to design my later AR storytelling.[a]
Information management	66	I became aware of the importance of naming files properly.[a] A student retrieved a video from a group shared profile to build AR content.[b]
Collaboration	102	Working with others helped me find what I do not know.[a] A group of students worked collaboratively to make a video.[b]
Communication and sharing	60	I would upload my works to the shared (cloud) folders and notify my group members via Edmodo. They would "like" me to show a confirmation.[a] A student shared a photo of a homemade tripod on Edmodo.[b]
Creation	90	I never thought I could use PhotoScape in that way.[a] A student showed a new idea on his or her artifact.[b]
Evaluation and problem-solving	78	We worked together on the problem and exchanged thoughts over phone calls.[a] Two or more students collaboratively conducted technical troubleshooting.[b]
Ethics and responsibility	36	After we reminded them of the problem, almost every student could appropriately provide a reference list with complete information.[a] A student posted forwarded information with complete resource.[b]

Note. AR = augmented reality.
[a]Interview data.
[b]Observation data.

two after-school program teachers and discussed with the second author to ensure reliability. A codebook is provided in Table 1.

Student individual AR project assessment. Students' individual AR projects (AR student ID and AR storytelling artifact) were assessed using a contextualized rubric originally designed for multimodal artifacts assessment (Burnett, Frazee, Hanggi, & Madden, 2014). The original rubric defined adaptable categories to evaluate a multimodal artifact, including rhetorical awareness, stance and support, organization, convention, and design for medium. These categories were contextualized to evaluate students' DL within five aspects: information management, communication and sharing, creation, evaluation and problem-solving, and ethics and responsibility. Each aspect had five levels with descriptive criteria for meeting each level. The two experienced teachers used this rubric to evaluate the students' individual artifacts after the first author trained them to use the rubric to grade student AR artifacts and their performances during the artifact creation process. The students were informed of the assessment criteria and rubric. To reduce biases by the teachers and contribute to interrater agreement, they practiced assessing five multimodal artifacts (student-created PowerPoint presentation) before evaluating the AR artifacts and discussed their results to facilitate evaluation agreement. The outcome of Cohen's kappa statistic (Table 3) presents a substantial agreement for each DL dimension. The assessment standards for the two artifacts were different, which reflected the expectations for increased AR complexity. For example, students were asked to use at least one type of special effect for their AR student ID and at least three types of special effects in the AR storytelling. We ran a paired-sample t test on the students' AR student ID and AR storytelling rubric scores to measure students' development of DL at different spiral time points.

Results

Both the analysis of the student questionnaires and the students' two individual AR projects indicated a statistically significant improvement in students' DL across the 20-week program. Students significantly improved their DL abilities in information management, collaboration, communication and sharing, creation, and evaluation and problem-solving (see Tables 2 and 3), though students did not significantly increase their knowledge of ethics and responsibility. We elaborate on the results of each area of DL in the following sections.

Information Management

Information management refers to the abilities to plan, identify, locate, access, retrieve, store, and organize information in a meaningful and systematic way. Table 2 shows a significant difference, $t(31) = -2.14$, $p < .05$, and moderate effect size between the students' self-reported information management ability before and after the program.

In terms of the role of spiral learning experiences in the development of information management ability, a significant difference was found between the rubric scores of the AR student ID creation and the AR story,

Table 2. Paired-Samples *t* Test for Pre- and Post-digital Literacy Questionnaires.

Variable	Test	*N*	*M*	*Mdn*	*SD*	Skew	Min	Max	*t*	Effect size
Information management	Pre-test	32	3.88	3.95	0.72	−.048	2.9	5.0	−2.14*	0.38
	Post-test	32	4.09	4.4	0.77	−.543	2.9	5.0		
Collaboration	Pre-test	32	3.4	3.4	0.61	.212	2.7	4.4	−4.23***	0.75
	Post-test	32	3.76	3.85	0.53	−.605	2.7	4.5		
Communication and sharing	Pre-test	32	3.79	4.0	0.72	.215	2.7	5.0	−2.22*	0.39
	Post-test	32	4.07	4.1	0.70	−.195	3.1	5.0		
Creation	Pre-test	32	3.83	3.7	0.34	.495	3.47	4.4	−4.20***	0.74
	Post-test	32	4.14	4.24	0.54	−.024	3.33	5.0		
Evaluation and problem-solving	Pre-test	32	3.83	3.67	0.56	.570	3.22	4.89	−2.62*	0.46
	Post-test	32	4.03	4.22	0.68	−.083	2.89	5.0		
Ethics and responsibility	Pre-test	32	4.33	4.17	0.46	.368	3.5	5.0	−1.50	0.27
	Post-test	32	4.47	4.67	0.50	−.971	3.0	5.0		

*$p < .05$. ***$p < .001$.

Table 3. Paired-Samples *t* Test for Student-Created AR Artifact Assessments.

Variable	Test	*N*	Kappa	*M*	*SD*	*t*	Effect size
Information management	AR Student ID	32	0.70	3.64	0.82	−2.12*	0.37
	AR Storytelling	32	0.73	4.00	0.77		
Communication and sharing	AR Student ID	32	0.92	3.84	0.78	−2.74*	0.48
	AR Storytelling	32	0.92	4.20	0.58		
Creation	AR Student ID	32	0.64	3.67	0.66	−2.74*	0.48
	AR Storytelling	32	0.68	4.09	0.69		
Evaluation and problem-solving	AR Student ID	32	0.81	3.57	0.81	−2.39*	0.42
	AR Storytelling	32	0.84	3.95	0.66		
Ethics and responsibility	AR Student ID	32	0.96	3.89	0.72	−1.09	0.19
	AR Storytelling	32	1.0	4.03	0.73		

Note. AR = augmented reality.
The variable "Collaboration" was not assessed for the student ID and storytelling artifacts because these were individual projects.
*$p < .05$.

$t(31) = -2.12$, $p < .05$, with a moderate effect size (see Table 3). In the second AR storytelling project, students strengthened their information management skills by learning from previous mistakes in the first project (AR student ID). For many participants, the AR student ID project was their first AR creation experience. The multimodal, contextual, and interactive features of AR artifacts required students to strategically plan, collect, produce, and assemble multiple digital components to create a complete and functional AR product. Typically, students encountered problems regarding how to organize and share the files using online applications. From the interview, we discovered that students were able to reflect on their mistakes and learn from peers in the first AR project, which informed better decision-making in the second AR storytelling project. One student explained how he improved information organization skills through applying prior knowledge and skills to the second task to avoid the same problem:

> After I submitted my AR student ID assignment, I found some bugs in my peers' Edmodo posts. For example, some links would not work properly, or a photo would block other content. I avoided the same problems when creating my AR storytelling artifact. (Student E)

One teacher articulated how the spiral learning experiences allowed students to develop information management ability by using mind maps:

> Many students were confused about how to use a mind map in the very beginning. After they applied mind maps in planning the AR student ID card and AR storytelling artifact, I noticed that every group could use mind maps fluently to plan their AR Campus Tour Guide System [the third and most complicated artifact project]. I also observed two groups use mind maps to keep track of each team member's progress, which shows they mastered this new way of managing the project progress and organizing information. (Teacher C)

The final group project experiences enabled students to authentically practice their information management skills via situated learning experiences. To collaboratively build an AR artifact in a group, students had to digitally store, locate, access, and retrieve group data. They also needed to make a consensus regarding ways to manage data to build and maintain a steady workflow. During this process, students developed concepts and skills of information management. For example, a student shared his learning:

> If you did not name profiles in a meaningful and consistent way, your group partners would fail to retrieve profiles or take longer time and delay the whole group's progress. After a couple of such experiences, I realized the importance of profile management. (Student H)

Another student reflected upon her data organization techniques:

> I was responsible for assembling all data to design the AR artifact of our final project. My peers, in the very beginning, put different types of data in the same

> folder, so I needed to categorize all data by myself, which wasted tons of time and exhausted me. I explained this situation and asked them to categorize data for me. Fortunately, they did everything perfectly. (Student D)

To complete the final group project that involved different digital components, students often worked separately and uploaded their works to a group shared folder. Students realized it was important to ask all team members to use the folder and to establish and follow group rules to improve the efficiency of information exchange and management. One teacher explained how the collaborative learning setting facilitated students' development of information management skills via situated learning experience, such as file organization and sharing:

> I thought the final group project provided an excellent chance to enable students to practice their information management ability. Students needed to complete different tasks separately, such as video recording, photography, multimedia editing, and the AR content design. They collaboratively organized different modes of data to introduce their campus with Aurasma. It was particularly important to remind students to consistently categorize files and to name folders shared by the same group. Otherwise, many disputes will arise during the group work. (Teacher C)

The design experience involving the multimodal representation feature of AR required students to form a strategy to facilitate the workflow for making an AR artifact in a group setting. In other words, students needed to find an optimal way to organize, store, retrieve, and share a variety of multimedia files to facilitate the collaboration with peers in the AR creation process. This point was illustrated by two student interviewees' comments at the beginning of this section. From the teacher's perspective, the multimodal representation feature of AR creation required students to think systematically in terms of how to assemble content in different formats in a meaningful way to communicate a topic. One teacher commented as follows:

> Pupils today are very familiar with how to create text, image, audio, and video using different technologies. However, they seldom have a chance to practice how to integrate different modes of data. I would think creating AR trained pupils how to manage different information modes to represent ideas effectively. (Teacher H)

Collaboration

Collaboration within DL refers to the ability to use digital tools to collaborate with others in online and face-to-face contexts to complete specific digital work. Our research data revealed a significant difference in students' collaboration, $t(31) = -4.23$, $p < .001$, with a large effect size between the beginning and end of the program (see Table 2). Working on a group project required every student team member to work closely to support each other and complete collaborative work with digital tools. The following teacher explained how the situated learning experiences required students to collaborate to build media content for their AR project:

> Videotaping the teacher's introduction of campus buildings required at least three students' joint efforts. Typically, one student would be the interviewer, while another student took care of the microphone, and the third student video recorded the interview. It was impossible to complete all these tasks at the same time by one single person. (Teacher C)

On the other hand, even the individual AR artifact showcase on Edmodo helped students become aware of the effectiveness of peer collaboration and raised their willingness to work with others. For instance, a student was impressed by the achievement of group work and stated how such experience impacted his performance in subsequent tasks:

> I initially made my AR student ID alone. I found two other classmates, and they created nice artifacts and won many votes [on Edmodo]. I knew they worked on the assignment together. So, I partnered with my peers on the second assignment [AR storytelling]. We also did a good job. (Student E)

In addition, a teacher articulated how the collaborative AR creation experience allowed students to learn the importance of collaboration to achieve a common goal:

> Students could understand the significance of collaboration because their work was interrelated. For example, if student A failed to complete a video editing task, student B would have no material to integrate into the AR artifact. On the other hand, student B's requests would also influence student A's work. (Teacher H)

Working in a group setting simulates an authentic environment that helped students practice how to use technologies to support group collaboration. For example, one student explained how he advanced collaboration skills with technologies through solving a real problem:

> That was the first time that I used e-mail and Google Drive to complete a group work. I was responsible for editing videos [of student/teacher interviews] with one of my peers. Originally, I planned to use e-mail to send videos to my partner, but the videos sizes were too large. I called my partner for help, and he taught me how to upload video to Google Drive and share a link with him. Although our teacher

> once taught me how to do that, I could not understand why we should learn it until I faced this problem. (Student L)

The spiral learning approach provided an opportunity for students to gradually realize the significance of collaboration and learn to work with others in constructive ways. One student stated his experience in this way:

> I found some peers could solve problems that I could not. I also learned a lot from my peers. I learned photography composition skills when I made my [AR student] ID with my classmates. I learned different ways to present AR layouts from my peers when I made my AR storytelling artifact with them. I gradually became willing to collaborate with others because I can learn very much from others. (Student K)

The interview data revealed that the design experience of creating multimodal AR artifacts facilitated students' collaboration skill development. During the process of producing, storing, and assembling different digital components to present a multimodal AR artifact, students sought help from their group members based on each member's specialty in a certain aspect. For example, to build the AR Campus Tour Guide System, members in a group needed to assume different roles, such as photographer, camera person, interviewer, multimedia editor, and AR designer. Classroom observations showed how students recruited team members by considering individual skills. A teacher articulated the process in this way:

> It was amazing to see some students played leading roles in organizing teams for the final project. These young leaders, like headhunters, strategically recruited their team members depending on what kind of workforce they need, like a multimedia editor or AR designer. You could also find some students with multiskill sets were the superstars. Every group was eager to have them. (Teacher C)

To design an interactive AR artifact using Aurasma, oftentimes students needed to work together to figure out how users apply this application to interact with the authentic environment. From our classroom observations, a typical workflow for a group was as follows:

- Students brainstormed what interactive feature Aurasma provided;
- Students identified the kinds of digital content that would help them effectively communicate their concepts to the end users and stimulate actions; and
- Students reviewed what widgets would help optimize users' experience of interacting with their AR artifact.

Students completed a test version of the final product, gathered together to test it with peers, and took notes of glitches that hindered smooth and efficient user interaction. A teacher explained how the task of designing AR's interactive representation increased students' awareness of collaborative work:

> The design of interactive actions in layouts was the most complicated task in the AR artifact creation process. For example, two actions of overlay representation—"After Overlay has faded in" and "After Overlay has started"—looked very similar and always confused students. Therefore, you would find students often working together to figure out how to implement specific actions of the AR layout. It was an excellent chance to allow them to understand why they should collaborate with others. (Teacher C)

Communication and Sharing

Communication and sharing refer to the ability to exchange information using online tools, while considering privacy, safety, and netiquette. The students' communication and sharing ability developed significantly, $t(31) = -2.22$, $p < .05$, with a moderate effect size between the beginning to the end of the program (see Table 2).

Regarding the contribution of spiral learning experiences on developing communication and sharing capacities, the students' skill of using online tools to communicate and share developed significantly, $t(31) = -2.74$, $p < .05$, with a moderate effect size from the AR student ID creation project to the AR storytelling artifact creation project (see Table 3). The ability to exchange information using online tools was demonstrated by students' learning to use online channels to convey their ideas, such as video sharing on YouTube. One student explained how he developed a communication and sharing ability by solving the technical problem of sharing videos on YouTube, applying his prior learning outcomes in the subsequent tasks:

> Aurasma had a 100MB limit on video size. To present large [sized] videos, I used YouTube to do that. I learned this method from YouTube when I created my AR student ID. YouTube is a fast way to share a video. I used the same way to present some large [sized] videos in my AR storytelling artifact and in our group's final project. (Student M)

The participation in the group project situated students to authentically practice the skill of using digital tools to communicate and share within a group.

A student explained how a group setting developed her and other group members' communication and sharing skills using technologies:

> The final group project really helped me understand how to use Google Drive to facilitate our group communication. I was responsible for taking pictures, and I often used my after-school time to do the work. After I took photos, my phone would auto-upload those pictures to my group's shared folder once it connected to my Wi-Fi at home. Then, everyone could see that. Gradually, there were more and more group members using the same way to share their videos or pictures. Initially, I did not know how to do it, but my friends taught me how to upload pictures to a cloud service. (Student N)

One teacher also indicated how working in an authentically collaborative environment facilitated students' technology-based communication and sharing skills through situated learning experiences:

> In a regular computer science lesson, students learned how to use communication technology, such as Google Drive or Google Doc. Working on group work and dealing with a real problem [with technology], students could really understand why they needed to learn these technologies and how these technologies help their communication and sharing. (Teacher H)

For netiquette learning, one student indicated how the public nature of social media improved her perception and enactment of netiquette: "I knew every account on Edmodo represented a real person. I would treat them politely as I did in a face-to-face way. If you treat others rudely, everyone would know about it. The [Edmodo] platform was so public" (Student F).

For the learning of digital safety and privacy, students were situated in authentic scenarios in which they need to take into account the importance of cyber safety and privacy while developing their AR artifacts. One teacher pointed out that while participating in this program, students had many chances to reflect on their digital behaviors:

> Students needed to register individual accounts for using different applications, such as Edmodo and Aurasma. Every time they registered a new account, we would remind students to avoid using the same password over multiple sites or using the birthday as a password. Also, students were advised to keep cyber security and privacy principles in mind when digitally exchanging information and distributing artifacts online. For example, when posting AR student ID on Edmodo, we would remind them to cover their student ID numbers. (Teacher C)

The design experience involving the multimodal representation feature of AR enabled students to hone their communication skills. Given that the final group project involved multiple digital components in different forms, students needed to constantly communicate and coordinate with peers to produce and compile different types of multimedia files to present a content-rich AR product meaningfully and harmoniously. One teacher illustrated this point in the context of the final project of creating the AR Campus Tour Guide System:

> Students initially discussed what site they wanted to introduce. Later, they would have a brainstorming activity to figure out a topic and decide each member's tasks. For example, to build the AR content of the Secret Garden, a group of students might send some members to interview peer students' perceptions of the Secret Garden, while the other members interviewed administrators to know why their school established the Secret Garden. (Teacher H)

Students developed digital communication and sharing skills when designing the contextual feature of an AR artifact. To make an AR artifact that represents information in specific contexts, students needed to think about what types of technology optimize the communication of an idea. For example, while building the AR Campus Tour Guide System, students needed to extract the contextual information—the history and stories of school buildings, evaluate the characteristics of different forms of multimedia presentation, and select the most suitable form to introduce a particular building in their campus. In other words, students had to determine what digital tools could help them effectively communicate and share contextual information to a wide range of audiences considering the constraints of technology, such as the performance of users' mobile devices and Wi-Fi speed on campus. One teacher illustrated this point in this way:

> When making the final project, we scaffolded students to discuss how to mix different digital tools to effectively involve audiences in the process of using their product [AR Campus Tour Guide System]. Audiences should be able to quickly obtain information they need without technical problems or irrelevant information. We hoped to empower students' ability to know the advantages and disadvantages of different tools in communicating and sharing their ideas. (Teacher C)

Creation

Creation referred to the ability to retrieve and reorganize previous knowledge and integrate obtained information to construct new knowledge or digital artifacts using digital tools. The students' creation practices in DL increased significantly, $t(31) = -4.20$, $p < .001$, with a large effect size from the beginning to the end of the program survey (see Table 2). Learning to design AR artifacts in a socially interactive environment situated students to work with and learn from peers to stimulate their creativity. For example, one student used her experience to explain:

> I saw my friends using the slow-motion model to introduce his favorite sport [when creating the AR student ID]. I thought it was a good idea to present a fast-moving thing, so I used the same strategy to show a cat's moves when creating my AR storytelling artifact. (Student G)

One student's creative use of a digital tool influenced another student's creative uses in a later assignment. Students' showcases of their creations on Edmodo exposed them to their peers' works, which helped them reflect on their own design process, and further enhanced their creative thinking. For example, a student shared: "Our teachers asked us to showcase our artifacts on Edmodo. One of my classmates covered Iron Man mask over his face [on his AR student ID artifact] using PhotoScape. I never thought I could use PhotoScape in that way" (Student G).

The spiral learning approach positively impacted students' creativity, $t(31) = -2.74$, $p < .05$, with a medium effect size from the early AR student ID creation to the later AR storytelling creation (see Table 3). The spiral learning experiences not only challenged students to find innovative ways to use familiar technologies but also allowed them to transfer their skills to creatively building and sharing other digital artifacts in daily life. One student shared his experience as follows:

> The experience of making [AR] student ID and [AR] storytelling artifacts helped me realize my smartphone was not just for playing video games and phone calls. I could use my smartphone to create so many interesting AR [artifacts]. After that, I even created a birthday card using AR [technologies] for my mom. My mom just needed to scan the card to watch my congratulations video. (Student O)

The experiences of designing with the multimodal and contextual representation features of AR played key roles in promoting students' creativity. This unique learning process engaged students in producing and organizing different types of multimedia content to creatively express their ideas and concepts, given certain contexts. One teacher explained how the program facilitated students' full engagement with the multimodal feature of AR: "The AR artifact creation involved students in assembling multimodal information to present ideas. Students could explore creative ways and technologies to present their ideas. In a regular computer class, students did not have such opportunities, restricted by class time" (Teacher H).

One student also shared a similar perspective by describing how the individual AR storytelling project stimulated her creativity: "Before this, I never had the experience of assembling different [types of] data to tell a story or to create something interesting. This learning activity inspired my creativity and showed me how technologies could help my creation'' (Student K).

Designing the contextual representation feature of AR also contributed to students' creativity. Built upon students' own experience, they used creative thinking and technologies to express their understanding and personal connection with a particular place/object. One teacher shared how the final project situated students in a learning process that required them to research and creatively and digitally express contextual knowledge of specific locations in their campus:

> Every student had already spent many years on campus and had very different understandings of specific sites. Building the AR Campus Tour Guide System to contextually introduce a site let students recall their memories. Take the Marine Palace as an example, different students might have different ideas to introduce the place. Along with the process of opinion exchange, the final project allowed students to share peer students' viewpoints and broaden their thinking scope, enabling their creativity development. (Teacher C)

Evaluation and Problem-Solving

Evaluation and problem-solving refer to the ability to identify appropriate technology and media to solve problems, search resources, and evaluate obtained information using digital tools. Students evidenced a statistically significant change in evaluation and problem-solving, $t(31) = -2.62$, $p < .05$, with a medium effect size before and after the program (see Table 2). The situated learning environment primarily facilitated students' development of evaluation and problem-solving abilities by providing the context in which students could work collaboratively to solve a real-world problem. For example, the English interface of Aurasma imposed a big challenge for students, given their limited English fluency level. Oftentimes, students needed to work together to figure out how to use particular functions in Aurasma. For example, one student shared his experience in using Aurasma:

> One time, I could not see my peers' AR content, although I had scanned their images a couple of times. I also checked if I forgot to follow their channels. My friends and I worked on it for a long time. We finally solved it. In the interface of Aurasma app, the ''unfollow'' button meant that you already followed someone. The language logic was weird to me. (Student G)

Working in a socially interactive environment also enabled collaborative efforts to critically evaluate the reliability of online resources that they might use to solve problems. One student shared his experience of a debate activity in learning to evaluate the quality of online information:

> The opposing side said Wi-Fi signals could kill plants. After we collaboratively tracked back their information sources, we knew their information was obtained from content farms. We doubted them and found many different perspectives to refute them. None of our information was obtained from a content farm. (Student N)

The spiral learning experiences significantly improved students' evaluation and problem-solving skills, $t(31) = -2.39$, $p < .05$, with a medium effect size between the first and second individual AR project (see Table 3). Two teachers elaborated on how students developed problem-solving skills and built confidence as they solved more problems by themselves in an authentic environment. One teacher emphasized how they moved away from step-by-step instruction and learning:

> Compared to the traditional cookbook-style computer science instruction, in this program, students needed to critically evaluate problems, propose solutions, and test their strategies by themselves. Students knew they could not get direct answers from [their] teachers. After several independent attempts at solving problems, they became more confident in the problem-solving tasks and enjoyed the learning process. (Teacher C)

The second teacher emphasized how they moved away from teachers serving as content experts with the answers to independent and group problem-solving:

> We hoped students would solve problems as a group rather than expecting answers from us. We scaffolded students to think back to what they learned in previous tasks and guided them to apply prior knowledge to come up with solutions to new problems. Through repeated practices, students gradually realized how to solve problems by themselves. (Teacher H)

In addition to teachers' comments, we also witnessed some students worked diligently with peers to solve a problem during classroom observations: A group of students encountered difficulties in setting certain layouts in Aurasma Studio. After a brief group discussion with each member contributing their thoughts, they split the task and sought potential solutions on YouTube and came back together to construct a viable plan.

The demands of designing multimodal AR artifacts required students to practice evaluation and problem-solving skills. To enrich their AR artifacts with different formats of information, students had to evaluate their topics and decide on what text, audio, and video files should be produced and included in their AR artifacts. While looking for relevant resources online, they honed their ability to critically evaluate online information and make rational decisions regarding inclusion criteria. In the meantime, they also encountered many problems while trying to organize and assemble their files to create the multimodal AR artifact, given the complexity of the final product. Within this complex process, there were multiple opportunities to solve problems individually and collaboratively. One student described several specific examples:

> We got so many problems, like the video quality was not good enough or interview recording included too much noise. It was also impossible to interview teacher/students again, so we just Googled those problems and tried to solve them with tutorials. I learned a lot from these experiences. (Student D)

The design experience involving the interactive information representation feature of AR motivated students to collaboratively solve problems. Given the steep learning curve of designing AR interactive functionality using the Aurasma app, students often supported each other to implement the app's interactive functionality. Moreover, to provide better user experiences, students were guided to evaluate users' needs and accordingly engaged users to interact with the content of their AR artifacts. In the product testing stage, we observed several groups of students evaluating user experiences of their draft products and solving identified problems to guarantee smoother user experiences. A teacher explained how the task of designing AR's interactive representation became a catalyst for promoting students' collaborative problem-solving:

> Creating AR artifacts was helpful for students' development of evaluation and problem-solving ability, particularly designing the interactive interface of Aurasma. Students needed to design from a user's perspective. The interface design work required students to have logical thinking ability. The English interface of Aurasma certainly added another difficulty, which made some students fall behind. At the time, peer support oftentimes provided the greatest help to solve the technical problems. (Teacher H)

Ethics and Responsibility

Ethics and responsibility refer to the ability to behave in an ethical, responsible, legally aware way when participating in digital interactions and using digital hardware and software. Unlike the other five DL practices described earlier, there was no significant difference, $t(31) = -1.50$, $p > 0.05$, in students' ethics and responsibility skills from before and after the program (see Table 2). The teachers attributed students' limited development in ethics and responsibility to their high entry knowledge levels, which resulted from previous learning experiences as well as the lack of learning opportunities for students to practice this aspect during this program. For example, Teacher C explained the historical focus on these practices: "I would think students' entry level of digital ethics and responsibility was quite high because we had emphasized these concepts since they were 3rd graders." Another teacher explained:

> Students had limited opportunities to develop their concepts of ethics and responsibility in this program. The only place of this program to facilitate their digital ethics and responsibility was to allow them to practice how to give credits to information resources in an appropriate way. (Teacher H)

However, data from student interviews suggested the situated learning experiences did help them develop their concepts of ethics and responsibility. One student observed that another student used a resource with no attribution.

> I saw my friend used a button that I had spent a lot of time searching the Internet for, and he did not inform the audience where he got the button. I believed he knew where to get the button from my reference list [of my AR student ID]. So, I told him about my bad feeling, but he just did nothing. (Student J)

Another student recognized the importance of attributing the source for materials:

> One of my peers showcased an interesting video embedded in his AR storytelling (artifact) on Edmodo. I could quickly get the video using his reference list. Putting reference data is very important to help your audiences. That was the first time I realized the importance of listing the reference. (Student C)

Our analysis of students' scores on the two individual AR creation projects also failed to show a significant difference, $t(31) = -1.09$, $p > 0.05$, in student growth in ethics and responsibility between the first and second project (see Table 3). According to one of the teachers, students did have opportunities to practice and improve ethical use of online resources through applying prior learning outcome in subsequent learning tasks. For example, the teacher explained how students improved their knowledge and skills of creating reference lists to credit information resources when creating an AR artifact with multimodal representation:

> Although students did know they should credit the information resources when they initially engaged in the AR student ID creation, the point was that they often forgot to provide complete information when they tried to use texts, audios, or videos obtained from the Internet. For example, most students only provided a webpage's title and/or URL in their reference lists. In other words, the authors and

> access date were forgotten. After we reminded them of the problem, almost every student could appropriately provide a reference list with complete information when engaging in the AR storytelling creation. (Teacher C)

While students learned about the ethical and responsible use of Internet-based information and resources, the experience was not deep enough to significantly shift the students' perspectives, as measured in the surveys or AR assessments.

Discussion and Conclusions

This study empirically examined the effectiveness of an instructional approach that combined situated learning and spiral learning in DL education at the elementary school level. For the first research question, we found that students improved five DL practices: information management, collaboration, communication and sharing, creation, evaluation and problem-solving, whereas limited development was detected in the ethics and responsibility practices. These learning outcomes were achieved through the situated learning and spiral learning approach as well as by students' engagement in creating multimodal, contextual, and interactive AR artifacts. Students were situated in a blended learning setting in which they were encouraged to learn in a socially constructivist way. The curriculum design enabled students to engage in multiple AR creation projects with increasing complexity that helped them practice and consolidate learned knowledge and skills over time and across several projects. The lack of significant development in ethics and responsibility might be explained by limited learning activities embedded in the curriculum that called upon students to consider ethical and responsible digital behaviors.

This study's evidence of the instructional effectiveness of AR artifact creation on DL education at elementary level responds to recent studies that advocate for the use of AR technology to facilitate DL education (Hagerman & Spires, 2017). In addition, this study adds insights to the research and instructional practice regarding the use of learning by design, which engaged pupils as AR content creators rather than consumers.

In terms of the integration of the spiral learning path, students applied what they previously learned to subsequent, more complex AR artifact creation projects, which improved their learning transferability and reinforced their DL accordingly. This instructional approach benefited elementary-level students' DL development in a similar manner as found among college students' learning processes (DiBiasio et al., 2001; Jaime et al., 2016; Vemuru et al., 2013). Students were able to reinforce target DL practices in a spiral way as they incorporated previous learning outcomes in multiple, related projects with increasing degrees of complexity. This study empirically extends the application of mixing spiral learning and PBL approaches from the college level to the elementary level of education.

In terms of the second research question, this study also investigated how the focus on AR technology associated with the learning-by-design pedagogy influenced students' DL. Students' authentic experiences of designing multimodal, contextual, and interactive AR representation features effectively facilitated their DL in different ways. For example, while creating the final project, the AR Campus Tour Guide System, students confronted multiple obstacles due to the complexity of integrating multimodal data, such as (a) needing to use creativity to decide on a focal topic and presentation approaches, (b) communicating and collaborating with peers either in online or face-to-face settings to produce the content, (c) figuring out an effective workflow to manage and share the content, and (d) solving various technical problems, never before encountered, while producing multimodal data involving a variety of digital tools. Ultimately, the study's results reveal how design involving the contextual representation feature of AR contributed to students' development of DL practices. For example, to enable contextual representation with AR technology in the individual and group AR artifacts, students creatively used different digital tools to communicate and share with audiences their understanding and personal connection with a particular object or place. The process of designing the interactive representation feature of AR developed students' ability to collaborate and evaluate and problem-solve. In the final project, given the steep learning curve of the AR app, students often needed to work together to figure out how to implement the specific interactive functionality. They also collaboratively evaluated how to apply AR's interactive representation to more easily involve users and engage in user testing to identify and solve the problem.

This study extends previous research on using AR in PBL by engaging students as creators. However, our research differs from empirical studies in terms of learning mode and participants. Previous studies focused on face-to-face instruction (Bower et al., 2014; Mathews, 2010), while our project used a blended learning mode. The combination of online and face-to-face social interactions among students played a vital role in their DL practices and development, particularly in their online collaboration and communication and sharing using digital tools. This outcome is consistent with prior research that investigated the blended learning effectiveness with Edmodo on sixth graders' digital multimodal literacy development (Thibaut, 2015). Further, we concentrated on DL development in elementary students instead of teacher education (Ke & Hsu, 2015). More important, we used the framework of DL to systematically measure students' development in six specific areas: information management, communication and sharing, creation, evaluation and problem-solving, ethics and responsibility, while other empirical studies emphasized critical thinking, creativity, critical analysis (Bower et al., 2014), and sociocultural views of literacy (Mathews, 2010). For future DL education research, this study discovered the relationship between the experiences of design with three different AR representation features (i.e., multimodal, contextual, interactive) and corresponding areas of DL development, indicating an emergent research direction to explore affordances of emerging technology when used in the learning by design as well as PBL pedagogy. For example, future research could investigate the affordances of virtual reality technology in DL education when this technology is applied to support learning-by-design pedagogy or PBL approach. Conceptually, DL is under development, and constantly involving new aspects and alternative DL frameworks exist, such as the International Society for Technology in Education standards (International Society for Technology in Education, 2015), so future research must always reconceptualize DL anew. Finally, we should not treat a student as a blank slate. Their preexisting DL should be considered in future DL instructional design. Therefore, future DL research should preassess a student's established DL and accordingly customize his or her learning experience.

We identified some obstacles during the implementation of our instruction: (a) language barriers, (b) online privacy concerns, (c) a lack of private virtual space for groups, and (d) limited opportunities for students to practices digital ethics and responsibility. First, Aurasma and Edmodo did not provide a Traditional Chinese interface, which contributed to a steep learning curve for students with lower English and Simplified Chinese fluency. This language barrier might have lowered students' learning motivation and online participation. Second, some students reported that they preferred private messaging tools to public posting on social media to communicate with peers. The social media platform we used, Edmodo, did not feature a private student-to-student chat interface. Third, students in different groups shared a common digital workplace on Edmodo in this study. Some students suggested a private virtual space where they could concentrate on their individual group's work would reduce the distractions of other groups' irrelevant information. Students also felt a private group space would increase privacy and make them feel more comfortable. Last, the only learning task directly concerned with digital ethics and responsibility was building reference lists to properly cite others' ideas.

There are three limitations to this study. First, the sample size in this study was 32. The research outcomes might have varied if the sample size was increased. For example, if the program had more participants, students might have had more opportunities to authentically practice their digital ethics and responsibility through more social interactions. Second, our program spanned 20 weeks. Students' learning experiences and outcomes may have changed as a result of increased familiarity with the AR app. For example, if the program has been extended to 40 weeks, students might have become even more familiar with the AR app and preferred to independently create AR artifacts, which might have led to decreased peer interactions. Third, our instruction was conducted in an after-school program, and participants self-selected to participate. Therefore, this study's results should be carefully interpreted and generalized. The research participants might have higher prior DL and motivation, compared with average students. Last, this study did not have a control group, which means further research is required to understand the effectiveness of creating AR on DL education, compared with other technology-enhanced project-based instruction, such as creative computing or Makerspace.

There are some implications of this study's instructional design for DL education and future research in this field. First, for instructional design practices, it would be worthy to explore alternative tools to facilitate peer communication such as instant messaging tools or social media platforms that provide private communication channels to encourage more peer conversation and reduce the risks of privacy issues. Also, it is important to consider the affordances of specific tools that support online collaboration of individual groups. The cascading layout of certain social media platforms might risk generating chaotic and distracting interfaces when multiple groups work together in the same space and when online conversations and sharing accumulate. To address this problem, private space for online interaction for each individual group might improve online participation and productivity. In addition, while planning the DL education curriculum, it might be helpful to consider emphasis on particular DL practices and examine if there are enough supporting learning activities for students to develop these DL practices. For instance, to facilitate students' ethics and responsibility of using digital tools, it is necessary to arrange a series of meaningful tasks to help students reflect on their digital behaviors related to their daily experiences. We encourage future research to examine the effectiveness of our mixing situated and spiral instructional design with students at different educational levels while concurrently taking account of their prior ICT skills and motivation. Future studies could explore the relationships between AR artifact creation and DL development in students across schooling levels and who have a range of prior ICT skills.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported in part by the 2016–17 Graduate Small Research Grant from the College of Education at The University of Texas at Austin.

Note

1. Aurasma has been rebranded as HP Reveal.

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Supplemental Material

Supplemental material for this article is available online.

References

Akcaoglu, M., & Koehler, M. J. (2014). Cognitive outcomes from the Game-Design and Learning (GDL) after-school program. *Computers & Education*, *75*, 72–81.

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, *20*, 1–11.

An, Y.-J. (2016). A case study of educational computer game design by middle school students. *Educational Technology Research and Development*, *64*(4), 555–571.

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*, *6*(4), 355–385.

Basque Government (Spain). (2017). *Digital competences self-diagnosis test*. Retrieved from http://ikanos.encuesta.euskadi.net/index.php/566697/lang-en

Bawden, D., & Robinson, L. (2002). Promoting literacy in a digital age: Approaches to training for information literacy. *Learned Publishing*, *15*(4), 297–301.

Baytak, A., & Land, S. M. (2011). An investigation of the artifacts and process of constructing computers games about environmental science in a fifth grade classroom. *Educational Technology Research and Development*, *59*(6), 765–782.

Bennett, S., & Maton, K. (2010). Beyond the 'digital natives' debate: Towards a more nuanced understanding of students' technology experiences. *Journal of Computer Assisted Learning*, *26*(5), 321–331.

Bennett, S., Maton, K., & Kervin, L. (2008). The 'digital natives' debate: A critical review of the evidence. *British Journal of Educational Technology*, *39*(5), 775–786.

Bonnardel, N., & Zenasni, F. (2010). The impact of technology on creativity in design: an enhancement? *Creativity and innovation management*, *19*(2), 180–191.

Bower, M., Howe, C., McCredie, N., Robinson, A., & Grover, D. (2014). Augmented reality in education – Cases, places and potentials. *Educational Media International*, *51*(1), 1–15.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher*, *18*(1), 32–42.

Bruner, J. (1960). *The process of education*. Cambridge, MA: Harvard University Press.

Burnett, R. E., Frazee, A., Hanggi, K., & Madden, A. (2014). A programmatic ecology of assessment: Using a common rubric to evaluate multimodal processes and artifacts. *Computers and Composition*, *31*, 53–66.

Cheng, K.-H., & Tsai, C.-C. (2013). Affordances of augmented reality in science learning: Suggestions for future research. *Journal of Science Education and Technology*, *22*(4), 449–462.

Chiang, T. H. C., Yang, S. J. H., & Hwang, G.-J. (2014a). An augmented reality-based mobile learning system to improve students' learning achievements and motivations in natural science inquiry activities. *Educational Technology & Society*, *17*(4), 352–365.

Chiang, T. H. C., Yang, S. J. H., & Hwang, G.-J. (2014b). Students' online interactive patterns in augmented reality-based inquiry activities. *Computers & Education*, *78*, 97–108.

Chou, C., Block, L., & Jesness, R. (2012). A case study of mobile learning pilot project in K-12 schools. *Journal of Educational Technology Development & Exchange*, *5*(2), 11–26.

Cope, B., & Kalantzis, M. (2015). The things you do to know: An introduction to the pedagogy of multiliteracies. In B. Cope, & M. Kalantzis, (Eds.), *A pedagogy of multiliteracies* (pp. 1–36). London, England: Palgrave Macmillan.

Creswell, J. W. (2013). *Research design: Qualitative, quantitative, and mixed methods approaches* (3rd ed.). Thousand Oaks, CA: Sage Publications.

DeCuir-Gunby, J. T., Marshall, P. L., & McCulloch, A. W. (2011). Developing and using a codebook for the analysis of interview data: An example from a professional development research project. *Field Methods*, *23*(2), 136–155.

DiBiasio, D., Comparini, L., Dixon, A. G., & Clark, W. M. (2001). A project-based spiral curriculum for introductory courses in ChE: Part 3. Evaluation. *Chemical Engineering Education*, *35*(2), 140–147.

Dunleavy, M., & Dede, C. (2014). Augmented reality teaching and learning. In J. M. Spector, , M. D. Merrill, , J. Elen, & M. J. Bishop, (Eds.), *Handbook of research on educational communications and technology* (pp. 735–745). New York, NY: Springer.

Ferrari, A. (2012). *Digital competence in practice: An analysis of frameworks*. Retrieved from http://jiscdesignstudio.pbworks.com/w/file/fetch/55823162/FinalCSReport_PDFPARAWEB.pdf

Gagne, R. M. (1968). Contributions of learning to human development. *Psychological Review*, *75*(3), 177.

Hafner, C. A. (2014). Embedding digital literacies in English language teaching: Students' digital video projects as multimodal ensembles. *TESOL Quarterly*, *48*(4), 655–685.

Hagerman, M. S., & Spires, H. (2017, April). *A systematic review of qualitative, classroom-based digital literacies research 2006-2016*. Paper presented at the Annual Meeting of the American Educational Research Association, San Antonio, TX.

Hill, A. E. (2014). Using interdisciplinary, project-based, multimodal activities to facilitate literacy across the content areas. *Journal of Adolescent & Adult Literacy*, *57*(6), 450–460.

Hsiao, H. S., Chang, C. S., Lin, C. Y., & Hu, P. M. (2014). Development of children's creativity and manual skills within digital game-based learning environment. *Journal of Computer Assisted Learning*, *30*(4), 377–395.

Hsu, H. P., Zou, W., Hughes, J., & Wang, C. T. (2018, April). *Develop elementary students' digital literacy by creating augmented reality artifacts in a situated and cumulative way*. Paper presented at the Annual Meeting of the American Education Research Association (AERA), New York City, NY.

International Society for Technology in Education. (2015). *ISTE standards for students*. Retrieved from http://www.iste.org/standards/for-students

Jacobs, G. E., Castek, J., Pizzolato, A., Reder, S., & Pendell, K. (2014). Production and consumption: A closer look at adult digital literacy acquisition. *Journal of Adolescent & Adult Literacy*, *57*(8), 624–627.

Jaime, A., Blanco, J. M., Domínguez, C., Sánchez, A., Heras, J., & Usandizaga, I. (2016). Spiral and project-based learning with peer assessment in a computer science project management course. *Journal of Science Education & Technology*, *25*(3), 439–449.

Jeng, J. H., & Tang, T. I. (2004). A model of knowledge integration capability. *Journal of Information, Technology and Society*, *4*(1), 13–45.

Kafai, Y. B. (2006). Playing and making games for learning. *Games and Culture*, *1*(1), 36–40.

Ke, F., & Hsu, Y. C. (2015). Mobile augmented-reality artifact creation as a component of mobile computer-supported collaborative learning. *The Internet and Higher Education*, *26*, 33–41.

Kern, A. L., Moore, T. J., & Akillioglu, F. C. (2007, October). *Cooperative learning: Developing an observation instrument for student interactions*. Paper presented at the 37th ASEE/IEEE Frontiers in Education Conference, Milwaukee, WI.

Kimbell-Lopez, K., Cummins, C., & Manning, E. (2016). Developing digital literacy in the middle school classroom. *Computers in the Schools*, *33*(4), 211–226.

Klopfer, E., & Squire, K. (2008). Environmental detectives—The development of an augmented reality platform for environmental simulations. *Educational Technology Research and Development*, *56*(2), 203–228.

Kolsch, M., Bane, R., Hollerer, T., & Turk, M. (2006). Multimodal interaction with a wearable augmented reality system. *IEEE Computer Graphics and Applications*, *26*(3), 62–71.

Lai, C. L., & Hwang, G. J. (2014). Effects of mobile learning time on students' conception of collaboration, communication, complex problem-solving, meta-cognitive awareness and creativity. *International Journal of Mobile Learning and Organisation*, *8*(3–4), 276–291.

Laine, T. H., Nygren, E., Dirin, A., & Suk, H.-J. (2016). Science Spots AR: A platform for science learning games with augmented reality. *Educational Technology Research and Development*, *64*(3), 507–531.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge, England: Cambridge University Press.

Lin, H. T., & Wang, M. J. (1994). *Creativity assessment packet*. Taipei, Taiwan: Psychological Publishing.

Lotherington, H., & Jenson, J. (2011). Teaching multimodal and digital literacy in L2 settings: New literacies, new basics, new pedagogies. *Annual Review of Applied Linguistics*, *31*, 226–246.

Luo, Y. (2015). Design fixation and cooperative learning in elementary engineering design project: A case study. *International Electronic Journal of Elementary Education*, *8*(1), 133–146.

Martin, A., & Grudziecki, J. (2006). DigEuLit: Concepts and tools for digital literacy development. *Innovation in Teaching and Learning in Information and Computer Sciences*, *5*(4), 1–19.

Mathews, J. (2010). Using a studio-based pedagogy to engage students in the design of mobile-based media. *English Teaching: Practice and Critique*, *9*(1), 87–102.

Moore, D. C. (2013). Bringing the world to school: Integrating news and media literacy in elementary classrooms. *Journal of Media Literacy Education*, *5*(1), 326–336.

Ng, W. (2012). Can we teach digital natives digital literacy? *Computers & Education*, *59*(3), 1065–1078.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York, NY: Basic Books, Inc.

Prensky, M. (2001). Digital natives, digital immigrants part 1. *On the Horizon*, *9*(5), 1–6.

Price-Dennis, D., Holmes, K. A., & Smith, E. (2015). Exploring digital literacy practices in an inclusive classroom. *The Reading Teacher*, *69*(2), 195–205.

Raphael, C., Bachen, C. M., & Hernández-Ramos, P. F. (2012). Flow and cooperative learning in civic game play. *New Media & Society*, *14*(8), 1321–1338.

Reynolds, R. (2016). Defining, designing for, and measuring "social constructivist digital literacy" development in learners: A proposed framework. *Educational Technology Research and Development*, *64*(4), 735–762.

Sadik, A. (2008). Digital storytelling: A meaningful technology-integrated approach for engaged student learning. *Educational technology research and development*, *56*(4), 487–506.

Saidin, N. F., Halim, N. D. A., & Yahaya, N. (2015). A review of research on augmented reality in education: Advantages and applications. *International Education Studies*, *8*(13), 1.

Salehizadeh, M. R., & Behin-Aein, N. (2014). Effects of cooperative learning plus inquiry method on student learning and attitudes: A comparative study for engineering economic classrooms. *European Journal of Engineering Education*, *39*(2), 188–200.

Santos, M. E. C., Chen, A., Taketomi, T., Yamamoto, G., Miyazaki, J., & Kato, H. (2014). Augmented reality learning experiences: Survey of prototype design and evaluation. *IEEE Transactions on Learning Technologies*, *7*(1), 38–56.

Shute, V. J., & Becker, B. J. (2010). *Innovative assessment for the 21st century*. New York, NY: Springer.

Stein, D. (1998). *Situated learning in adult education*. Retrieved from https://www.ericdigests.org/1998-3/adult-education.html

The New London Group. (1996). A pedagogy of multiliteracies: Designing social futures. *Harvard Educational Review*, *66*(1), 60–93.

Thibaut, P. (2015). Social network sites with learning purposes: Exploring new spaces for literacy and learning in the primary classroom. *Australian Journal of Language & Literacy*, *38*(2), 83–94.

Vemuru, S., Khorbotly, S., & Hassan, F. (2013, May). *A spiral learning approach to hardware description languages*. Paper presented at IEEE International Symposium on Circuits and Systems (ISCAS2013), Beijing, China.

Vuorikari, R., Punie, Y., Carretero Gomez, S., & Van Den Brande, G. (2016). *DigComp 2.0: The digital competence framework for citizens*. Retrieved from https://ec.europa.eu/jrc/en/digcomp/digital-competence-framework

Wang, H.-Y., Huang, I., & Hwang, G.-J. (2016). Effects of a question prompt-based concept mapping approach on students' learning achievements, attitudes and 5C competences in project-based computer course activities. *Journal of Educational Technology & Society*, *19*(3), 351–364.

Wu, H.-K., Lee, S. W.-Y., Chang, H.-Y., & Liang, J.-C. (2013). Current status, opportunities and challenges of augmented reality in education. *Computers & Education*, *62*, 41–49.

Yin, R. K. (2009). *Case study research design and methods* (4th ed.). London, England: Sage.

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